Development of sustainable energy technologies in changing institutional and socio-political contexts: the case of combined heat and power in the UK

Anton Sentić

A thesis submitted in partial fulfilment of the requirements of the University of Greenwich for the Degree of Doctor of Philosophy

June 2017

DECLARATION

I certify that the work contained in this thesis, or any part of it, has not been accepted in substance for any previous degree awarded to me, and is not concurrently being submitted for any degree other than that of Doctor of Philosophy being studied at the University of Greenwich. I also declare that this work is the result of my own investigations, except where otherwise identified by references and that the contents are not the outcome of any form of research misconduct.

London, __ October 2017

Anton Sentić, MSc *(student)*

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Dr. Anne-Marie Coles *(1st supervisor)*

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ACKNOWLEDGEMENTS

I would like to thank my supervisors, Dr Anne-Marie Coles and Dr Athena Piterou, for their ongoing and unwavering support throughout my doctoral journey, and the countless times they provided me with advice and guidance on approaching my tasks.

Furthermore, I would like to thank Dr Petros Ieromonachou, Dr Ian Clarke, Dr Andres Coca-Stefaniak and Dr Emanuele Lobina for their feedback to my numerous enquiries.

Outside the University of Greenwich, I would like to thank Professor Bernhard Truffer, Dr Jochen Markard, Professor Audley Genus, Dr Stephen Potter, Dr David Hawkey and Dr Colin Nolden for their feedback and guidance.

The planning and conducting of my case studies and interviews would not be possible without the support of Mr Jonathan Sibson, Mr Simon Goldsmith, Ms Fabienne Van der Velde, Ms Lynn Davis, Mr Scott Briance and further anonymous supporters. I would also like to extend my gratitude to all interviewees and contact persons, without whom this project would have been far more complicated. A special mention goes to Mr Russ Spencer, who provided me with a very interesting afternoon session explaining the systems behind running CHP schemes.

As the planning and execution of a project of this size requires professional and private support, I would like to thank my parents, Milkica Buric and Mate Sentic for their ongoing support throughout my doctorate, and the help and support provided in the earlier stages of my education that made it possible to reach out so far.

Unconditional, day-to-day support was provided by my partner, Ms Ramona Lescesen, whom I would like to thank for accompanying me through both good and hard times, and keeping an open ear for my thoughts, comments and complaints.

I would also like to thank Ms Maja Popov for her support in reviewing and proofreading the work, particularly during the stressful last days before the submission of this thesis.

Finally, I would like to thank the administrative staff at the University of Greenwich, first and foremost Ms Gillian Haxell, for their invaluable help in addressing my enquiries and thoughts over more than three years.

ABSTRACT

The emergence and development of innovative, sustainable ideas and their interaction with incumbent regimes is one of the key focal areas of Transitions Research. While many authors publishing in the field focus on analysing successful transition processes, a smaller group of scholars reviews less successful transitions, aiming to understand the reasons for the partial or complete failure of these processes. In this thesis, the author will follow in the footsteps of the latter group, utilizing two analytical approaches from the broader field of Transitions Studies in order to investigate the case of combined heat and power (CHP) technologies in the United Kingdom.

CHP in the UK has been the focus of multiple studies from different viewpoints, using a variety of theories and analytical approaches. The story of CHP has often been conflated with the development of district heating systems although, more recently, scholars have taken a broader perspective on the utilization of CHP technologies. This thesis will attempt to take a holistic approach to the CHP industry, investigating a broad range of CHP application areas.

The author will use a two-step analysis, starting with a system-focused technological innovation systems analysis of the CHP industry and then broadening the scope of the enquiry to include a broader context, using niche and regime concepts derived from the Multi-level perspective and Strategic Niche Management. The approach is based on a joint framework proposed in the literature (Markard and Truffer, 2008) but rarely applied on empirical cases. Besides investigating the reasons behind the peculiar performance of CHP in the UK compared to other European countries (Weber, 2014), the author will also address gaps in theoretical developments related to the niche concept and niche typology (Raven, 2006; Smith and Raven, 2012), and the applicability of transition pathways concepts (Geels et al., 2016) for multi-regime transitions.

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LIST OF ABBREVIATIONS

CHP	Combined Heat and Power
DECC	Department of Energy and Climate Change (disbanded in 2016 and replaced by the Department for Business, Energy & Industrial Strategy (DBEIS))
DH	District heating
DNO	Distribution Network Operator
ESCo	Energy Service Company
FiT	Feed-In Tariff
LA	Local authority
MLP	Multi-level perspective
OFGEM	Office of Gas and Electricity Markets
RHI	Renewable Heat Incentive
SNM	Strategic Niche Management
TIS	Technological Innovation Systems

1 Introduction

The modern world is facing major sustainability challenges in several domains, in particularly those connected to the provision of basic societal functions such as (electrical) energy, heating, water and sanitation and public and private transport (Markard et al., 2012). Air pollution and greenhouse gas emissions, resource shortages and price fluctuations, geopolitical instability, extreme weather and climate events, low efficiency and concerns about short- and long-term security of supply all represent significant challenges and hurdles to both the public and the private sector, with the increasingly globalised character of the world meaning that trans-regional and international cooperation in tackling and solving these challenges is more important than ever.

Focusing on the energy sector, public and private actors are caught between the pledge to reduce emissions and work towards maintaining a global warming target of below 2 degrees Celsius, and the need to re-work and re-structure their systems in order to tackle energy poverty, increasing uncertainty about the security of supply and the need to change energy generation and supply systems on the system level. Furthermore, changes in the world economy are bringing developing economies such as India and China forward, increasing the focus on engaging with sustainability issues in these countries compared to the programmes and actions already implemented in highly developed economies. Fuel prices and resource availability are fluctuating strongly, creating an uncertain outlook for oil-, gas- and coal-fuelled power plants already pressured by decarbonisation and efficiency increase requirements (IEA, 2015). In the United Kingdom context, wavering support for a shift to sustainable energy sources (Geels, 2014; Smith et al., 2014) coupled with a need for modernisation of the current, heavily gas-dependent energy sector (DECC, 2014), increasing energy supply uncertainty and pressures to maintain transnational emission goals and pledges all combine to create a highly uncertain situation with different actors supporting different solution approaches ranging from full decarbonisation to a switch to a nuclear energy-focused system, changing positions of government actors following shifts in the political orientation (Geels, 2014) and increasing international influence and pressures both by public and private sector actors. Therefore, it is hardly surprising that the overall state of the UK energy sector is one of uncertainty – while the need for change is certainly recognised (DECC, 2013; Ricardo-AEA, 2014) and transition pathways to a future energy system are investigated and proposed (RTP Engine Room, 2015), there is no final decision[1] on the development direction that is to be taken.

Compounding these issues on the government and industry side, potential solution-providers are also far from united and certain about the direction the system transition needs to take: multiple technological and structural innovations are competing with each other (Allen et al., 2008; RTP Engine Room, 2015) with no dominant design emerging so far. While some of the proposed solutions are in a fairly early stage of development and might not be technologically mature, such as fuel cells (Brown et al., 2007), other more developed technologies suffer from a lack of support or economic and infrastructural barriers (Wright et al., 2014). Combined heat and power generation (CHP), also called co-generation, is a potential technological solution belonging to that latter group: defined as the simultaneous generation of electric power and useful heat, the technology has a long history of development, being in use since the early 20th century (Russell, 1993). Despite being successfully applied in a number of countries in Central, Western and North Europe (Weber, 2003; Raven, 2007; Raven and Verbong, 2007; Weber, 2014), CHP was never used in significant numbers in the UK energy system (Russell, 2010), remaining constrained to a number of application niches and very often used in conjunction with heating networks, sharing the wavering interest of successive governments, public agencies and industries in shifting the provision of heat towards a network-based system (Hawkey, 2009, 2012, 2014). Other application areas include CHP in industry plants and non-industrial, commercial sites, CHP plants used in public sectors sites such as hospitals or universities, and domestic micro-generation CHP. Industrial use provides the by far largest share of the total electrical capacity generated by co-generation plants, accounting for about 80%, however, industry use of CHP is limited to a number of sector – the oil industry, the chemical industry, paper, publishing and printing and food, beverages and tobacco production. Non-industrial commercial use accounts for about 10% of the capacity,

[1] The “final decision” mentioned here might take the form of drafting targeted government policies, such as it was done by the German government on abandoning nuclear power generation in the wake of the Fukushima accident, or through strong and long-term signalling in the form of extensive subventions and support programmes for a certain technology or group of technologies

while all other application contexts generate the final 10% (DECC, 2015). The use of CHP also often necessitates the development of new business models, creating an additional barrier to producers and users used to operating within a centralised, top-down energy and heating system (Hawkes and Leach, 2008; Hannon and Bolton, 2015).

The history of CHP, and the cases of its limited success in the United Kingdom have been investigated within the Science and Technology Studies (STS) and Transitions theoretical schools through multiple studies including dissertations (Russell, 1986; Hawkey, 2009), research papers (Russell, 1993; Babus'Haq and Probert, 1996; Brown and Minnett, 1996; Skea, 1996; Russell, 2010; Weber, 2014) with more recent research focusing on distinct application areas such as CHP-DH (Toke and Fragaki, 2008; Hawkey, 2009, 2012 and 2014; Webb, 2014), industrial use of CHP (Hinnells, 2008) and domestic micro-CHP (Cockroft and Kelly, 2006; Sauter and Watson, 2007; Allen et al., 2008; Hudson et al., 2011). While some of these studies investigate the reasons behind the apparent relative failure of CHP in the UK, they also identify multiple causes for this failure, noting that often CHP technologies fell victim to combinations of unfortunate circumstances in the local and private sectors (Russell, 2012; Hawkey, 2014).

This research project will build on the insights generated by these studies, and will attempt to combine their results within a Transitions context, using recent theoretical developments within the Strategic Niche Management (SNM) and the Technological Innovation Systems (TIS) approaches to execute a functional and structural analysis of CHP technologies in the UK as a technological innovation system comprised of a number of niche application areas, focusing on the structure of these analytical constructs and the functions provided by them in order to review the implications on the history, current developments and future prospects of the technology in the UK.

In the second chapter, the author will undertake a review of Transitions Studies literature, focusing on the SNM and TIS analytical approaches, the underlying analytical constructs and the conceptual similarities. Drawing on the findings of the review, the author will identify a number of research gaps that will be addressed and discussed in the course of this thesis. The third chapter will be used to set out the research paradigm, outline the research design and present the research instruments.

In addition to that, the author will present and discuss the methodology, and provide a brief overview of the data sources used in the primary data collection phase.

The main objective of the fourth chapter is to introduce the chosen empirical case – CHP in the United Kingdom. At the beginning of the chapter, the author will present the technological concept, followed by a brief summary of the most common schemes and technological elements. In the second part of the chapter, the history of cogeneration in the UK will be presented in form of a timeline, separating a number of main development and diffusion periods.

In Chapters 5 and 6, the author will summarize the two main steps of the analysis. Starting with a system-centric review of the CHP industry through the scope of a TIS analysis, the scope of the observation will then be broadened to include contextual structures and dynamics in the form of a SNM-based review of niche-regime and inter-regime dynamics.

The findings of the analysis will then be discussed in Chapter 7, focusing on the three research sub-questions guiding the analysis. The main points of the discussion will also be reiterated in Chapter 8, together with a review of the limitations of this research study, and challenges for further research.

2 Literature review

In this chapter, the author will undertake a critical review of the concept of (sustainable) transitions, the main analytical approaches within the field, focusing especially on Strategic Niche Management (SNM) and the Technological Innovation Systems (TIS) approach. In the course of the review, the author will also define and review the commonly used analytical constructs, and investigate their theoretical and conceptual connections. The critique will extend into a discussion of recognised and potential research areas, a number of which will be addressed in this work.

2.1 Sustainable transitions

Sustainable transitions are defined as long-term, multi-dimensional and fundamental transition processes that cause established, incumbent socio-technical systems to shift towards more sustainable modes of production and consumption (Markard et al., 2012). Going beyond the scope of technological transitions, which focus on shifts within the technological dimension of a socio-technical system, sustainable transitions include, and to an extent focus on, changes in the governance dimension, changes to broader institutional contexts in which the transitioning system is operating (Smith et al, 2005) and changes to user practices (Markard et al., 2012). These processes include complex interrelations on different levels of aggregation (Markard and Truffer, 2008) involving established actors (incumbents) operating within the established system as well as actors supporting new, innovative technologies (Kemp et al., 1998; Geels, 2002, Raven, 2006), with agency taking place within the systems, between systems and on a system – environment level.

2.2 Development of transitions studies

Studies of sustainable transitions, system innovation and socio-technical regime changes saw several different development trajectories over the last 20 years. Drawing on insights from innovation studies, evolutionary economics (Nelson and Winter, 1982), the idea of technological paradigms (Dosi, 1982) and innovation systems research, transitions research has branched out into multiple distinct analytical approaches and research strands, focusing on distinct components of the transition process and utilizing a number of different analytical constructs.

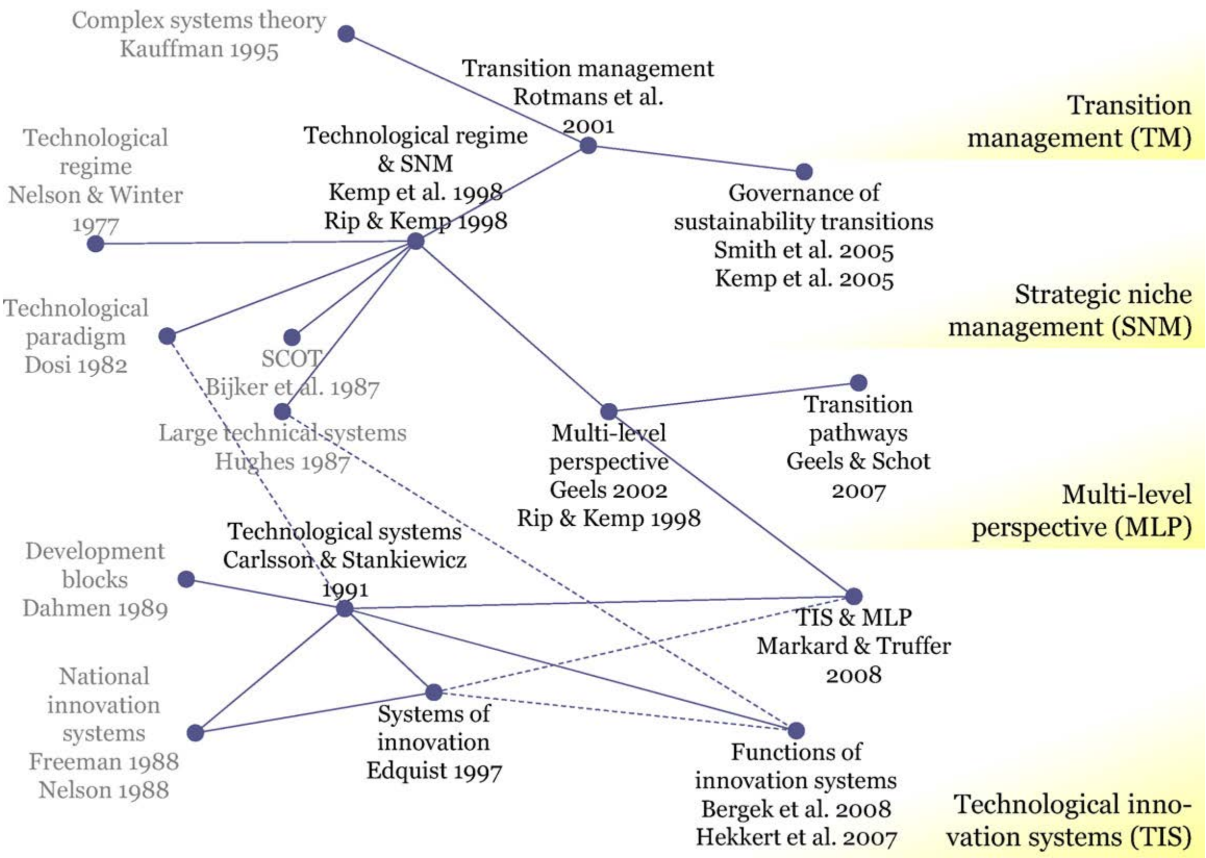

Figure 1: Map of key authors and research strands in the field of sustainability transition studies (Markard et al., 2012)

In itself a fairly recent research field, Transitions Studies draws on a number of research traditions, ranging from evolutionary economics and the conception of variation and selection processes for innovative technologies (Nelson and Winter, 1977), over different conceptualisations of innovation and technology systems (a term which will be discussed in more detail later in this chapter) including large technical systems (Hughes, 1987), national innovation systems, mainly utilized in Science and Technology Studies (STS) to neo-Schumpeterianism in the form of Kondratieff waves or the “long wave” theory of socio-technological development (Geels, 2010; Koehler, 2012). The general consensus among Transitions scholars posits a dual rooting in evolutionary economics and STS (Schot and Geels, 2008), although analytical excursions investigating conceptual similarities are not rare (Markard et al., 2012) and a number of research strands seem to have shifted between theoretical fields. One example would be the Strategic Niche Management perspective, which was initially conceptualized as a management approach within Constructive Technological Assessment (CTA) (Schot and Rip, 1996) but has shifted towards the bottom-up transitions approach of the multi-level perspective (Geels 2002, 2004).

Presently, four main research strands are identified within the research literature: – 1) the policy- and application based Transitions Management approach (Smith et al., 2005; Smith and Kern, 2007, Foxon and Pearson, 2008) reviewing the top-down governance and support of transition processes, as well as potential transition pathways (Geels and Schot, 2007; Geels et al., 2016); 2) the bottom-up, application-based Strategic Niche Management approach focusing on the creation and management of temporary protective spaces for innovative, sustainable technologies otherwise incapable of development and successful diffusion in selection environments created by incumbent regimes (Kemp et al., 1998; Raven, 2006; Smith and Raven, 2012). A third research strand revolves around the utilization of the multi-level perspective for describing transitions processes (Rotmans et al., 2001; Geels, 2002, 2004, 2005, 2010). Usually applied ex-post (Koehler, 2012), the multi-level perspective utilizes a set of analytical constructs at different levels of aggregation (niche, regime and landscape) in order to model and outline the actor interrelations, top-down and bottom-up dynamics and transformative journeys that are part of a successful sustainable transition. The fourth key approach is based on the concept of systems as analytical structures, particularly on the concept of technological systems (Carlsson and Stankiewitcz, 1991), which was developed into the concept of technological innovation systems (Hekkert et al., 2007; Bergek et al., 2008). Focusing on system-internal structures and the fulfilment of system functions, this approach is mainly utilized for assessment of the performance of specific technologies in one or more localities, and for informing sustainability and/or innovation policies (Bergek et al., 2015; Markard et al., 2015).

Those four main research strands are at least partially conceptually related and often used in conjunction; however, while there have been attempts at developing more explicit conceptual and analytical connections between the concepts and the analytical constructs utilized in them (Markard and Truffer, 2008; Papachristos et al., 2013, Walrave and Raven, 2016) or connecting Transitions frameworks to concepts from other research fields (Koehler, 2012; Planko et al., 2015), further development of theoretical connections and "conceptual bridges" is recognised as one of the main research challenges within the field (Markard et al., 2012).

2.3 Analytical constructs for researching sustainable transitions – system and regime

In this section the author will review a selection of different analytical constructs utilized within the broader field of sustainability transition studies, paying special attention to the constructs used in this research project – the (innovation) system, the (socio-technical) regime and the niche. While a broader overview of the different types of niches will be provided later in this chapter, as part of the review of the strategic niche management (SNM) school, the author will focus on the relationship between systems and regimes, and the role of these constructs in the broader research field.

Transitions researchers utilize a number of different constructs for the purposes of researching transition processes, which differ in a number of key characteristics as well as in their theoretical and methodological background. In general, a distinction can be made between a *multi-level approach* to transitions, which utilizes analytical constructs at different levels of aggregation (Geels, 2002, 2004; Raven, 2006; Markard and Truffer, 2008) undergoing processes of change and development caused by bottom-up pressures, internal agency and top-down influences by constructs at higher aggregation levels (Rotmans et al., 2001; Geels, 2002, 2004), and a *systemic approach* to transitions, where the core analytical construct is described as a *system*, a set of interrelated components, relationships and attributes working towards a common objective (Carlsson et al., 2002).

Contemporary research literature is rife with confusion about the concepts of *regime* and *system*, with some authors utilizing the concept interchangeably (Geels, 2011). In order to provide a usable overview of the two concepts, their definitions as well as conceptual and theoretical similarities and differences, the author will briefly discuss each of them and provide a number of definitions for the purpose of comparison.

The *regime* concept has its roots in the evolutionary economics approach, with Nelson and Winter (1982, p.258) describing a "technological regime" as a set of shared cognitive routines in a community of engineers, which guide their R&D activities and the direction of their innovative processes. This routine-based view has been extended by Rip and Kemp (1998) who introduced the category of rules, which are embedded more widely in the knowledge base, engineering practices, governance structures, skills and processes than the actor-bound cognitive routines described by Nelson and Winter (Geels, 2005). The *technological regime* concept is broadened by Geels (2002, 2004) towards a "socio-technical" regime, highlighting the role of actors and actor groups in carrying, codifying and enforcing these rules. Geels (2004) describes a *socio-technical regime* as the "deep grammar" of socio-technical systems, consisting of a rule set carried by a broad group of actors including scientists, users, policy-makers, societal groups, engineers and firms (Geels and Kemp, 2007). This extended view describes the regime as consisting of three interrelated sets of elements – rules (institutions) carried by actor networks, technological artefacts and supporting infrastructures (Raven, 2007; Geels et al., 2016). Regime elements are part of the production, consumption and governance domains (Konrad et al., 2008), with actors engaging in "game playing" aimed at the reproduction and/or modification of elements of the regime (Geels et al., 2016). In summary, there are two dominant conceptualizations of the regime – a narrow, rules-based view which considers actors and physical artefacts and infrastructures to be the interfaces through which the rules are (re)confirmed and reproduced, but not elements of the regime itself (Markard and Truffer, 2008), and a broader view incorporating rules/institutions, actors and technological components as regime elements (Konrad et al., 2008; Geels et al., 2016). Geels (2011) comments on the distinction between these two approaches by reaffirming the *regime* as being a purely rules-based construct, in line with the narrow definition, the broader construct incorporating actors and technological elements is the (socio-technical) system through which the rule set is reproduced.

Compared to the regime concept, the *system* concept within Transitions Studies draws upon multiple research strands, all of which comprise the broader Innovation Systems (IS) approach (Suurs, 2009). At its core, a system is described as a *"…set of interrelated components working towards a common objective. Systems are made up of components, relationships and attributes"* (Carlsson et al., 2002). Within this definition, components are the operating parts of the system: system actors and actor networks such as innovators, researchers, government bodies, businesses, financial institutions; institutions in the form of (codified) rules, regulations and shared heuristics and behavioural patterns (Hekkert et al., 2007; Bergek et al., 2008) and technological artefacts and supporting infrastructures (Carlsson et al., 2002; Hekkert et al., 2011).

Within the Innovation Systems approach, the common objective is the development and diffusion of innovations and innovation processes. Over time, multiple innovation system concepts were developed, differing mainly in the focus of the analysis. They include national systems of innovations (NIS) (Nelson, 1992); regional innovation systems (Hekkert et al., 2007; Bergek et al., 2008); sectoral innovation systems (SIS) (Malerba, 2002) and technological systems (Carlsson and Stankiewitcz, 1991; Carlsson et al., 2002), as well as related concepts such as large technological systems (LTS) approach put forward by Hughes (1987). A shared characteristic of these approaches is the differentiation between the principal unit of observation, the system, and the broader environment within which the system is operating (Bergek et al., 2015). System delineation *per se* is based on an analytical choice (Carlsson et al, 2002; Bergek et al., 2008; Suurs, 2009; Bergek et al., 2015). However, while this allows for a larger degree of freedom for the analyst, it can also cause issues when the relationships between multiple systems or the system and its environment are reviewed (Kern, 2015; Markard et al., 2015). The system's performance is established and measured as a function of the relationships between these components (Hekkert et al., 2007; Bergek et al., 2008; Suurs, 2009) as well as the attributes of the relationships and the components (Carlsson et al., 2002), which indicate the functionality of the system.

Of particular interest is the technological innovation system (TIS) concept, which is defined as a *socio-technical system focused on the development, diffusion and use of a particular technology*, in terms of the (physical) technology, generated knowledge or both elements (Bergek et al., 2008). As such, the TIS provides both the *innovation* and the *production function* for a focal technology (Markard and Truffer, 2008). The focal unit of analysis for a technological innovation system is a specific technology or technology/knowledge field (Bergek et al., 2008); the aim of the analyst reviewing the system is therefore to analyse and evaluate the development and diffusion of a specific technological innovation (Suurs, 2009). Compared to the other innovation system approaches listed above, the TIS delineation is not of a geographical nature (Bergek et al., 2008), with technological innovation systems extending past national borders; on the other hand, the single technology-specific focus of the TIS concept makes it a micro-oriented variety of the sectoral innovation systems (SIS) concept (Malerba, 2002), with sectoral innovation systems comprised of a set of interlinked technological innovation systems (Markard and Truffer, 2008; Suurs, 2009), which interact with the overarching SIS (Jacobsson and Bergek, 2011).

2.3.1 Comparisons between the technological innovation system and socio-technical regime

For the purposes of this thesis, the author will focus in more detail on the conceptual comparison between the socio-technical regime concept utilized in the multi-level perspective and related research strands, and the technological innovation system concept utilized in the TIS approach[2]. A number of researchers see these two concepts as interchangeable, which is highlighted as a potential criticism of the multi-level perspective approach (Genus and Coles, 2008; Markard and Truffer, 2008; Geels, 2011). While this is not necessarily true due to a difference in delineation and the structural elements of a regime compared to a system (Geels, 2011), there is nevertheless a certain level of conceptual similarity (Markard and Truffer, 2008; Geels, 2011).

The socio-technical *regime* is defined as a “deep structure” of shared semi-coherent rules embedded in and maintained by a set of actors and institutions (Geels, 2004, 2005; Geels and Schot, 2007; Geels, 2011). Actors and institutions are however not seen as elements of the regime, rather, they represent the interface through which the rules are established and reproduced in a state of dynamic stability (Geels, 2005). Following this conceptualization, regimes co-exist with actor networks and (socio-technical) systems as one of the inter-related analytical dimensions within the multi-level perspective approach (Geels, 2004; Geels and Kemp, 2007). There is however a clear distinction between the dimensions defined by the tangibility of the observed elements, with rules lacking a direct tangible manifestation beyond the results of their ongoing reproduction (Geels, 2011). The relationship between the analytic dimensions is summarized in the following figure:

[2] Both approaches are discussed in more detail in subsequent sections of this chapter

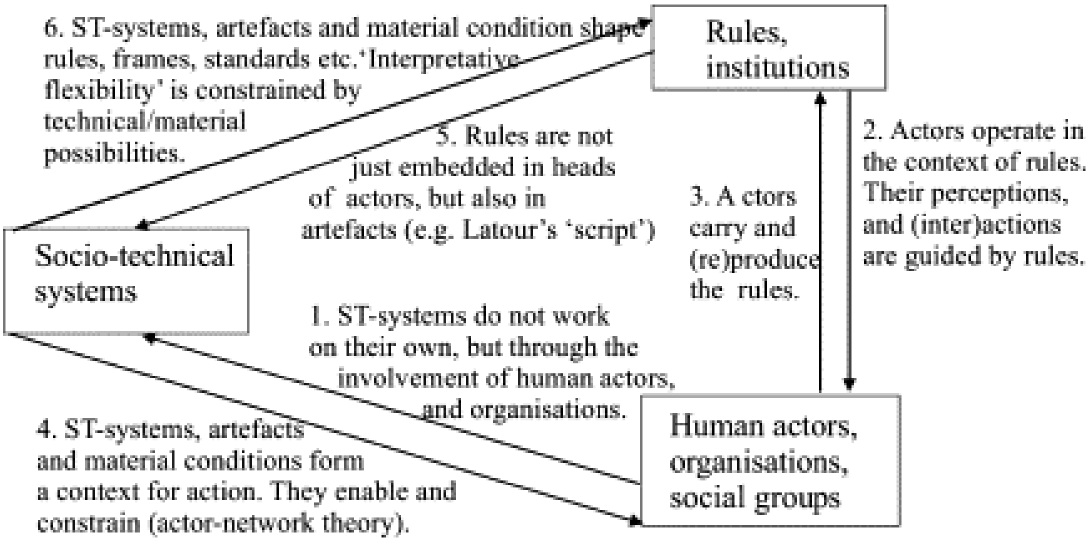

Figure 2: The relationship between the regime, actor networks and the physical system within the multi-level perspective (Geels, 2004)

It needs to be highlighted here that this applies to the narrow definition of the regime concept, while the broader definition of the regime, which includes tangible elements such as infrastructure (Weber et al., 1999, Hoogma et al., 2002), is more closely related to the system concept, and has been used in a way similar to the sectoral systems of innovation concept (Markard and Truffer, 2008).

On the other hand, the technological innovation system (TIS) is defined by its tangible elements: actors, networks and the institutions which provide the framework within which the actors are operating (Bergek et al., 2008), as well as the focal technology in the form of technological artefacts and supporting (tangible) infrastructure (Hekkert et al., 2011). While a regime on its own is not sufficient to form an analytical focus for a transition process (Geels and Kemp, 2007), the system is used as the baseline unit of observation in the TIS approach (Hekkert et al., 2007; Bergek et al, 2008), with the system's structure, the fulfilment of system functions and the existence of inducement and blocking mechanisms determining the progress of the technology's development (Hekkert et al., 2011; Markard et al., 2015).

With regard to their level of aggregation, the *regime* is considered to be at a high level of aggregation, while the *technological innovation system* can exist at a medium or high level of aggregation depending on its level of development (Markard and Truffer, 2008). Ultimately, the aggregation level of a given technological innovation system will also be dependent on the analytical choices made in the process of system delineation and boundary drawing (Carlsson et al., 2002; Bergek et al., 2008); a technological innovation system can be a micro-level construct, similar to the *niche* concept utilized in the multi-level perspective and related research strands, it can be regime-like if observed at a later stage of development, or anywhere in between (Markard and Truffer, 2008).

A further distinction between system and regime can be drawn by observing their role within the innovation process – while the system encompasses both the innovation and production parts (Hekkert et al., 2007; Markard and Truffer, 2008), the regime's role is mainly to stabilize (in a state of dynamic stability) existing structures (Geels, 2005) and enable incremental changes for regime incumbents (Geels and Schot, 2008; Geels et al., 2016) – radical innovations take place in niches and develop in a bottom-up process (Geels, 2002; Raven, 2006; Schot and Geels, 2008; Markard and Truffer, 2008).

Finally, the two concepts also diverge in the focus of the analysis – while a system analysis is mainly built on a structural analysis of tangible system components (Bergek et al., 2008; Hekkert et al., 2011) and an analysis of system functions supporting the innovation process and generated by system components (Hekkert et al., 2007), a regime analysis focuses on the underlying architecture of rules and rule-sets that guide actor agency and enable the ongoing reproduction of a socio-technical system (Geels, 2011).

2.3.2 The broader environment of transition processes: the landscape / external context

Transitions studies observe (sustainable) transition processes taking place within the broader contextual influences of the exogenous environment: political, macroeconomic, macro-social and societal factors. Changes of these factors can exert considerable influence on the development of (sustainable) innovations and on the dynamics and trajectory of transition processes; consequently, multiple research strands within the broader research field have developed conceptualisations which account for these external influences, and the effects they can have on actors, networks, institutions and technologies engaged in transitions (Geels, 2002, 2005;

Markard and Truffer, 2008; Markard et al., 2012; Bergek et al., 2015). In the following paragraphs, the author will briefly discuss the two approaches utilized by transitions scholars to delineate, describe and evaluate the broader environment. A more extensive analysis and discussion of the research strands utilising these approaches will be provided later in this chapter.

One possible conceptualisation of exogenous factors is the macro-level *landscape* concept utilized by the multi-level perspective (Geels, 2002, 2005) and Strategic Niche Management (Raven, 2006; Schot and Geels, 2008). In this concept, the landscape is defined as containing aspects of the wider environment which affect socio-technical development (Geels, 2005), shaped by deep structural trends (Geels, 2002). The term "landscape" is chosen by authors in order to reflect the material context and relative hardness of the construct – the landscape is, among others, defined by the presence of physical artefacts and infrastructures which may, or may not be utilized by actors engaged in transitions, but certainly shape the "playing field" within which transitions are taking place (Geels, 2002; Markard et al., 2008; Schot and Geels, 2008). While the landscape and its elements cannot be directly influenced by transitions actors (Geels, 2005), the opposite is certainly the case: landscape changes can have both positive and negative impact on transitions, forcing processes of change in existing structures and, at times, creating "windows of opportunity" for proponents of innovative technologies (Geels and Schot, 2007; Geels et al., 2016). The landscape view has been criticized for insufficient theorization, creating the risk of landscapes being used by analysts as "dumping grounds" for multiple contextual influences that cannot be related to transition actor agency (Geels, 2011). Van Driel and Schot (2005) have proposed a more differentiated view of the landscape concept, proposing the following classification:

(1) factors that do not change or change very slowly such as climate or geographical characteristics
(2) long term, persistent and directional change, such as the industrialization of a national economy
(3) rapid external shocks such as wars, large-scale natural disasters or commodity price crashes

For scholars using a system-based approach, the issue of system delineation, i.e. defining what is “inside” and “outside” of an observed innovation system is of high relevance for defining and designing the scope of analysis (Carlsson et al., 2002; Bergek et al., 2008). While initial system-based analytical approaches were focused largely on system-internal structures and dynamics, recent developments have exhibited an increased focus on the external system environment, characterised as the external context. In this approach, the system environment is not characterised as any sort of analytical construct, rather, external influences are described as structural and institutional couplings of system elements (actors, networks, institutions and technologies) across system borders (Bergek et al., 2015) which influence system-internal functionality. There have been attempts at coupling a system-based view with the regime-landscape view in the form of an integrated framework (Markard and Truffer, 2008), however, this development was only followed up in few studies (Wirth and Markard, 2011; Markard et al., 2015). A second possible approach to including external factors into an innovation system-based approach is by including multiple types of innovation systems, based on the perceived level of aggregation – a technology-focused technological innovation system (TIS) can develop as a part of a sectoral innovation system (SIS) or even multiple SIS. Taking geographical and political boundaries into account, both TIS and SIS can develop within and/or across national innovation systems (NIS) (Malerba, 2002; Markard et al., 2008)

2.4 The multi-level perspective

The initial development of the multi-level perspective drew on the idea of transition processes taking place between smaller innovation niches, where prospective technological innovations are developing (Kemp et al., 1998), and established technical systems / technical regimes (Nelson and Winter, 1982; Hughes, 1987). Rotmans et al. (2001) posited an analytical scenario for transition processes happening in a multi-layered system. In this scenario innovations are taking place in micro-level niches which are nested within and are interacting with meso-level regimes, where stable constellations of rules, search heuristics and institutions shape networks of incumbent actors who are utilizing and supporting established technologies (Geels, 2002, 2004). These processes are happening within a macro-level landscape (Rotmans et al., 2001) which is defined as the broader economic, societal and political context (Geels, 2002). The concept was subsequently further developed by Geels (2002, 2004, 2005, 2006a, 2006b, 2007) who developed the presently utilized concept of a multi-level perspective (MLP) as a middle-range theory (Geels, 2010, 2011) for describing long-term transition processes as a series of actor-network and institutional dynamics happening at the niche (micro), regime (meso) and landscape (macro) levels (Geels, 2002). The MLP is theoretically grounded in a number of concepts: evolutionary economics, sociology of technology, history of technology and innovation studies (Geels, 2005), while the main ontological foundation is a crossover between evolution theory and interpretivism (Geels, 2010). Following is a graphical representation of the analytical and heuristical concepts forming the multi-level perspective:

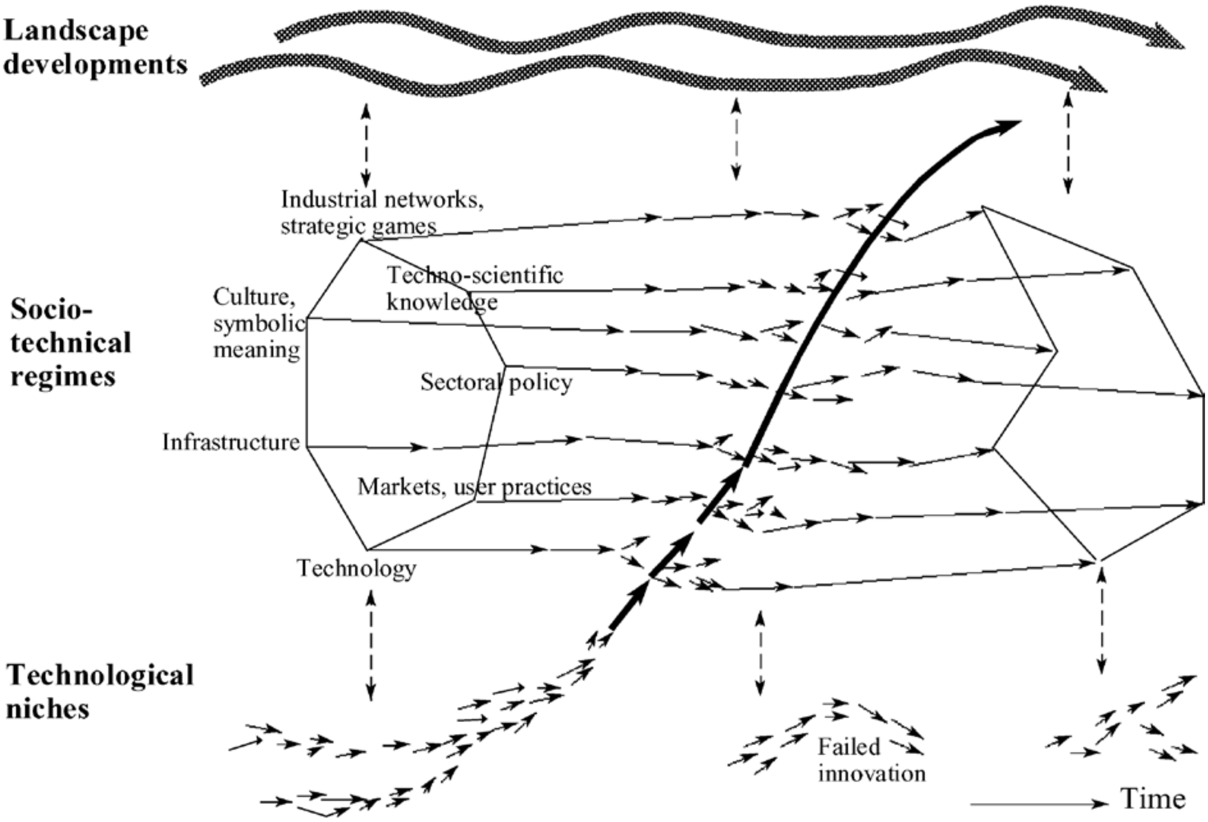

Figure 3: The multi-level perspective on technological transition processes (Geels, 2002, p.1263)

In the multi-level perspective approach, prospective new technologies are developing at the micro-level of aggregation in small, shielded spaces – technological niches (a far more detailed review of the niche concept and niche functions will be provided later in this chapter). Niches act as "incubators" for innovative technologies (Geels, 2007), enabling technological maturation, creation of shared trajectories and the development of supporting structures (Schot and Geels, 2008). Upon reaching a sufficiently advanced stage of development, niches and niche actors enter co-evolutionary process with incumbent regimes (Geels, 2006; Schot and Geels, 2008), the nature of these processes being somewhat dependent on both niche and regime stability (Raven, 2006). At the same time, the socio-technical regime itself can undergo processes of internal change and re-organisation (Geels, 2004, 2005; Geels and Kemp, 2007; Geels and Schot, 2007) while at the same time being exposed to pressures emanating from changes taking place at the landscape level (Geels, 2002, 2004). Depending on the development stage of the niche, the internal stability and change pressures within the regime, and the intensity of top-down landscape pressure, the regime may undergo an internal transformation process or engage in a broader transition process with the developing niche (Raven, 2006; Geels and Kemp, 2007; Geels and Schot, 2007; Geels et al., 2016). This transition process can take multiple forms, with a possible typology being proposed by Geels and Schot (2007) based on the *timing* and *nature* of niche-regime interactions. This typology is further refined by Geels et al. (2016), resulting in the following four pathways being proposed:

1. *Substitution pathway*
2. *Transformation pathway*
3. *Reconfiguration pathway*
4. *De-alignment and re-alignment pathway*

The substitution pathway represents what could be conceptualized as a “clear” transition process – niche technologies initially developed by actors different from the regime actors within protected spaces maintained and nurtured separately from the regime (Kemp et al., 1998) enter a transition process which culminates with the overthrow of established regimes (Geels et al., 2016). The overthrow process can take the form of a gradual, incremental change with limited institutional change, with niche technologies gradually adjusting to outperforming incumbent technologies within the selection environment created by the established regime (described as *fit and conform empowerment* by Smith and Raven (2012)) or in a more sudden, radical change, with niche actors developing concurrent institutions aimed to replace established regime structures (described as *stretch and transform empowerment* by Smith and Raven (2012)). It can be assumed that a successful substitution process necessitates a well-developed, stable niche (Raven, 2006, 2007; Schot and Geels, 2008).

In the transformation pathway, the main change processes are initiated by regime actors under the influence of internal and external (landscape) pressures (Geels et al., 2016); the aim of the regime actors being to ensure the reproduction of the regime into a more suitable configuration (Raven, 2006; Geels and Schot, 2007). This internal restructuring can be primarily incremental, with internal elements re-configured into new structures and configurations (Geels, 2004; Geels and Schot, 2007), but more radical restructuring of established structures is also a possibility, with regime actors reaching out towards niche innovations (Geels, 2016) and niches entering co-evolutionary (Geels, 2006) and/or hybridization processes (Raven, 2007) where elements of niche technologies are assimilated into the incumbent regime. The possibility for agency through niche actors is therefore somewhat limited (Geels, 2006), although a certain amount of process shaping might be possible (Raven, 2007; Smith and Raven, 2012).

The reconfiguration pathway differs from the substitution pathway in that while internal and external pressures necessitate a more radical regime change, niche technologies, actor-networks and institutions absorbed by the regime and combined with incumbent regime structures instead of replacing them altogether (Geels and Schot, 2007; Geels et al., 2016). Niche technologies may be taken over through hybridisation processes (Raven, 2007) though niche actors can retain a higher amount of control (Smith and Raven, 2012). Initially, this may take the form of modular innovation, although often existing incompatibilities between innovative and established technologies can create a need for further innovation. On the institutional level, changes are likely to start out as gradual adjustments followed by more substantial change (Geels et al., 2016). Consequently, transition processes following the reconfiguration pathway are likely to result in a period of reduced regime stability, potentially paving the way for follow-up niche technologies (Raven, 2006).

The fourth and final proposed pathway is the de-alignment and re-alignment pathway in which regimes are destabilized through sudden, large landscape shocks (Geels and Schot, 2007) at a moment where niche technologies and the supporting niche structures are not sufficiently developed and stable to engage on a substitution or reconfiguration pathway (Raven, 2006; Geels et al., 2016). Subsequently, multiple prospective niche innovations enter a competitive stage, with a dominant technology gradually emerging as the new regime incumbent (Geels et al., 2016). A specific characteristic of the de-alignment and re-alignment pathway is that there is little competition between niche and regime actors and structures, rather, the main competition takes place in a “vacuum” created by the dissolution of the previously incumbent regime (Geels and Schot, 2007). Co-evolutionary processes may take place between the niches (Geels 2005, 2006), and niche actors may play out different strategies (Raven, 2007).

It needs to be pointed out that the proposed pathways are not seen as deterministic, on the contrary, changing landscape contexts and actor agency may lead to shifts between pathways (Geels and Schot, 2007; Geels et al., 2016). Niche actors may follow specific strategies for technology development and niche empowerment (Smith and Raven, 2012), however, those strategies may not be played out in a sustained way, and might be changed and re-evaluated (Verhees et al., 2013).

Throughout its development, the multi-level perspective and its core analytical constructs, the niche, regime and landscape have been used to describe a variety of different transitions, focusing on historical processes in the early stages of the research strand's development (Geels, 2002, 2006a, 2006b; van Driel and Schot, 2005). Subsequently, the approach was utilized to describe more recent and even ongoing developments, through the focus of these studies was more on the niche-regime interaction and on inter-regime interaction (Raven, 2006, 2007; Konrad et al. 2008). In the following table, the author provides a brief overview of a number of MLP transitions studies, listing the focal technology and the observed sector, as well as the author and year of publication:

Observed *(transitioning)* **technology**	**Sector**	**Author**	**Year of publication**
Steam ships	Transport	Geels	2002
Grain elevators	Logistics/transport	Van Driel and Schot	2005
Sewer systems	Waste management	Geels	2006
Turbojet aircraft engines	Transport	Geels	2006
Waste management	Waste management	Geels and Kemp	2007
Rock'n'roll	Performing arts	Geels	2007

Biomass	Waste management, Energy generation	Raven	2007
Nuclear energy	Energy generation	Geels and Verhees	2011
UK electricity system	Energy generation	Geels	2014
German and UK low-carbon electricity transitions	Energy generation	Geels, Kern, Fuchs, Hinderer, Kungl, Mylan, Neukirch, Wassermann	2016

Table 1: Overview of a selection of published studies utilizing the multi-level perspective

The multi-level perspective is mainly used for the study of long-term historical transitions (Markard et al., 2012). This ex-post application and the potential data validity, as well as the analyst's interpretation of the data considering the nature of transitions, the actors and the process start and end points was subject to criticism (Genus and Coles, 2008). In light of this criticism, Geels (2011) has highlighted the illustration and exploration focus of MLP studies, while permitting that this type of analytical approach might not be the most suitable for systematic research. With initial attempts at broadening the scope of the MLP towards the development of a "grand theory" criticized by multiple actors (Genus and Coles, 2008; Smith et al., 2010), MLP was placed as a middle-range theory (MRT) (Geels, 2007, 2010, 2011). Studies of transition processes utilizing the multi-level perspective have covered multiple sectors, and focused mainly on long-term transition processes. While there is little agreement on "typical" lengths of transition processes, studies indicate that they can take between 15-20 years (Raven, 2006) and several decades, especially in the high-tech and IT sectors, coming close in their temporal dimension to the "long cycles" described by Kondratiev (Geels, 2002; Koehler, 2012). Geels (2011) reiterates the primary aim of the analytical approach being the description of *"…relatively rare, long-term macro-changes"*.

In addition to the discussions on the utilisation of the MLP and the scope of the proposed analytical approach discussed above, the multi-level perspective was subject to additional criticism, such as the lack of agency (Genus and Coles, 2008); the delineation and utilization of the regime concept, especially when used in parallel with the system concept (Genus and Coles, 2008; Markard and Truffer, 2008); a perceived bias towards bottom-up transition processes (Geels, 2011); lack of dynamics in and operationalization of the landscape concept (van Driel and Schot, 2005; Geels, 2011); and the utilization of a multi-level, “nested hierarchy” to describe processes which might be happening in a flat plane (Shove and Walker, 2010).

2.5 Protective spaces for sustainable innovations – Niches and Strategic Niche Management

In this section, the author will outline, explore and discuss the concept of niches as understood within the main schools of thought of Transitions Research, focusing on Strategic Niche Management (SNM) and the Multi-Level Perspective (MLP). While the term "niche" is widely used across a multitude of disciplines and can have different meanings, it is safe to conclude that something described as a niche implies a certain distance, seclusion, difference or protection from environmental, political, social and/or economic conditions considered to be standard in a particular system. Further characteristics of a niche are its relatively small size, limited boundaries and a group of users ready to engage with the technology or policy central to the niche, taking into account its potential disadvantages related to the level of development, acquisition/development cost and performance as a trade-off against perceived benefits of using this particular technology or policy (Levinthal, 1998; Kemp et al., 1998).

The Transitions Studies conceptualization of niches is primarily based on their functionality and the role they can play in transformative processes of larger socio-technical systems as protected spaces (Kemp et al., 1998, Raven, 2006, Smith and Raven, 2012), incubators and learning arenas (Schot and Rip, 1996; Raven, 2006 and 2007b) supporting the development and diffusion of promising sustainable technologies which would be struggling to develop in an open market environment due to their incompatibility with the dominant regime (Schot and Geels, 2008) and inability to withstand pressures from the selection environment generated by that regime (Kemp et al., 1998). Within niches, promising innovations can mature, increase their connections and alignment with markets (Raven, 2007b), develop expectations and storylines (Raven, 2006; Smith and Raven, 2012), build and expand actor networks (Ieromonachou et al., 2004; Raven, 2006), gain momentum and create a transition path (Raven, 2007; Schot and Geels, 2008) ultimately leading to regime reconfiguration through transition, transformation or complete de-alignment and re-alignment (Geels, 2005; Schot and Geels, 2008; Nill and Kemp, 2009).

The school of Strategic Niche Management (SNM) recognises the very low probability such processes to occur "naturally" and therefore proposes an actor-guided, proactive process encompassing the creation, development and controlled break-down of protective spaces (Ieromonachou et al., 2004), with different niche functions being either actively provided by niche actors and proponents or used through alignment with and incorporation of already existing processes, policies and (supportive) mechanisms (Smith and Raven, 2012). The roots of Strategic Niche Management lie within the school of Constructive Technological Assessment (CTA), where strategic niche management represented one possible CTA strategy, focused on the learning component of technological knowledge development - second-order learning (Schot and Rip, 1996) in particular. Subsequently, the focus of SNM research has broadened and shifted to the protective properties of niches (Kemp et al., 1996), the provision of protective functions with parallel development of actor networks and articulation of expectations (Raven, 2006), as well as protective, nurturing and empowering functions, with the latter aiming either to align the niche innovation development trajectory with the dominant regime through a series of alignment and co-evolutionary processes, or at increasing the momentum of the niche innovation with the goal of disrupting the regime and forcing a transformation and re-alignment process (Smith and Raven, 2012). This extension of the focus of SNM led to a widening of its scope, changing from an initially inward-looking perspective focused on strengthening and supporting niche-internal processes to a more outward-looking perspective where some of the main aims are related to developing and empowering the niche in relation to its environment.

In the course of its relatively short history, SNM approaches have been used to analyse a number of different transition processes, most of them focusing on sustainable technologies. Historical empirical studies cover technologies such as the application of white lead and madder in the 19th century Netherlands (Schot, 1998), early experiments on biofuels and biogas (Geels and Raven, 2006; Raven and Geels, 2010) or reconfigurations of national electricity regimes (Raven, 2006). Strategic Niche Management principles are used to both describe and provide prescriptive recommendations for the development and diffusion of sustainable technologies, including sustainable transport models (Weber et al., 1999); organic food and eco-housing (Smith, 2007), biofuels (van der Laak et al., 2007); Jatropha production for different uses (Caniels and Romijn, 2008); multiple new/sustainable energy projects (Raven et al., 2008); eco-industrial park concepts (Adamides and Mouzakitis, 2009);

aquifer thermal energy storage (Coenen et al., 2010); biomass gasification (Verbong et al., 2010), alternative fuel vehicles (Kwon, 2012); solar photovoltaics (Verhees et al., 2013; Smith et al., 2014); and hybrid-electric heavy vehicles (Sushandoyo and Magnusson, 2014). The concept of technological niche was further developed from being technology-centric to focusing on policies and social constructs in several studies, such as the Strategic Niche Policy Management conceptual study by Ieromonachou et al. (2004) or agricultural cooperatives experimenting on different models of sustainable nutrient management and agricultural governance (Hermans et al., 2013). Recent research has also investigated the institutional elements of niches and the need for top-down protection and guidance present in Strategic Niche Management approaches by focusing on grassroots innovations in the energy sector (Seyfang et al., 2014).

While other sectors are also taken into account, a focus on the sustainable energy and sustainable transport sectors can be identified, although this could be justified by the high relevance of these sectors in most sustainability-oriented technological change and policy development processes. Following is a brief overview of a selection of SNM-centric case studies published in academic journals, showing the observed sectors and the innovations themselves:

Sector	Case	Author(s)	Year
Energy	Biomass co-firing in Dutch power plants	Raven	2006
	Biogas development in the Netherlands	Geels, Raven	2006
	Biofuel policy development	Van der Laak, Raven, Verbong	2007
	Meta-analysis of 27 new energy projects	Raven, Heiskanen, Lovio, Hodson, Brohmann	2008
	Aquifer thermal energy storage	Coenen, Raven, Verbong	2010
	Biogas development in Denmark and the Netherlands	Raven, Geels	2010

	Biomass gasification in India	Verbong, Christiaens, Raven, Balkema	2010
	Solar PV in the Netherlands	Verhees, Raven, Veraart, Smith, Kern	2013
	UK community energy schemes	Seyfang, Hielscher, Hargreaves, Martiskainen, Smith	2014
	Solar photovoltaic electricity in the UK	Smith, Kern, Raven, Verbong	2014
Transport	Workbook on SNM based on 16 transport case studies	Weber, Hoogma, Lane and Schot	1999
	Road access charging scheme in Durham (UK)	Ieromonachou, Potter, Enoch	2004
	Alternative fuel vehicles	Kwon	2012
	Volvo heavy hybrid vehicles	Sushandoyo, Magnusson	2014
Manufacturing	White lead and madder in 19th century Netherlands	Schot	1998
	Organic food production and eco-housing	Smith	2007
Other	Use of Jatropha plant	Caniëls and Romijn	2008
	Industrial ecosystems	Adamides and Mouzakitis	2009
	Body disposal practices	Monaghan	2009
	Environmental cooperatives in agricultural production in North Frisia	Hermans, van Appeldoorn, Stuiver, Kok	2013

Table 2: Overview of academic case studies using elements of the SNM perspective

Whereas this selection shows an abundance of descriptive applications of SNM approaches, there is a recognised lack of prescriptive use of SNM – while it is almost certain that some elements of SNM have been used in transition-related projects in Northern and Western Europe, there is a lack of documented cases and analysis of such projects (Schot and Geels, 2008).

2.5.1 Niche types

While niches are generally seen as protected experimental environments – loci for the development of radical innovations (Raven, 2006) which exist on a low levels of aggregation (Geels, 2002; Markard and Truffer, 2008), there were several attempts at developing more detailed niche typologies, defining and outlining several categories of niches: technological niches (Van de Belt and Rip in Ieromonachou et al., 2004; Raven, 2006; Geels and Raven, 2006; Coenen et al., 2010, Smith and Raven, 2012); market niches (Levinthal, 1998; Raven, 2006; Smith and Raven, 2012); policy niches (Ieromonachou et al., 2004) and R&D niches (Raven, 2006). This typology is not final, and there is no complete clarity about the characteristics, properties and functions which assign a niche to a particular type. Although it will be demonstrated that the role, function and processes associated with niches have been investigated and expanded over time, the main protective function has remained virtually unchanged from the initial considerations (Schot and Rip, 1996; Levinthal, 1998; Schot, 1998; Kemp et al., 1998). In the following paragraphs, the author will provide a short outline of the four listed niche types.

2.5.1.1 Technological niches

The initial idea of technological niche was closely connected to the need for protection of radical innovations (Schot, 1998) in order for them to be able to mature and overcome their initial weaknesses (Schot, 1998; Geels, 2002) in a protected space where barriers to development (Kemp et al., 1998) caused by established structures (Smith and Raven, 2012) are not present or are present only to a limited extent. This idea was further reinforced by research on sustainable innovations (Kemp et al., 1998) where the need to survive in a market environment is further exacerbated by relative economic inefficiencies of sustainable solutions (Markard et al., 2012) as well as technological lock-in of incumbent techno-industrial complexes (Unruh, 2000).

Prospective technologies, sustainable or other, can be described using Mokyr's (1990) notion of "hopeful monstrosities" – they might offer solutions for functions and societal needs, but their initial performance is rather unrefined and discouraging. Therefore, the initial notion of a *technological niche* was that of a protected space which could act as an incubator for a fledgling technology, with the protection granted through policy measures and financial support (Kemp et al., 1998, Raven, 2006; Geels and Raven, 2006). Protection and development support through financial subsidies is identified as one of the main characteristics of technological niches by Raven (2006, 2007a), Geels and Raven (2006), Van der Laak et al. (2007) and Smith and Raven (2012). There is a strong focus on the experimental nature of technological niches (Schot and Rip, 1996.; Kemp et al., 1998; Geels, 2002; Ieromonachou et al., 2004; Raven, 2006; Caniels and Romijn, 2008a). This focus can also be used to distinguish the notion of technological niche from that of a market one - the technological niche in many cases does not have a clear application area (Van der Laak et al., 2007) which needs to be determined in experimental conditions (Raven, 2006) or through a process of niche accumulation where the technology is used in several subsequent application scenarios (Raven, 2007b). Effectively, the niche functions as its own proto-market where future market conditions are determined in a co-evolutionary process involving market structures and innovation proponents (Van der Laak et al., 2007; Caniels and Romijn, 2008b).

Summarizing the above, a *technological niche* following the Strategic Niche Management school within Transitions Studies and especially Sustainable Transitions Studies could be described as a *protected space centred on a radical, possibly sustainable innovation focusing on protecting the innovative technology by means of public and/or private financial subsidies and public policies while at the same time providing an arena for undertaking localized experiments facilitating learning effects, especially second-order learning among niche proponents, early users and innovators.* There is no clear market for the innovative technology; a market needs to be formed within and through the niche, through market creation the niche will further evolve into a market niche.

2.5.1.2 Market niches

Market niches are primarily represented as specific application domains (Levinthal, 1998; Schot, 1998; Raven, 2006) where the niche technology, and its relative functional and economic inefficiencies are supported by accepting user-actors (Smith, 2007), specific locations decreasing the impact of these inefficiencies or increasing the relative gains from the specific performance offered by the focal niche innovation (Van der Laak et al., 2007) and selection pressures different from the ones created by the incumbent regime (Schot and Geels, 2008). Compared to the proto-markets developed in technological niches, market niches tend to fill in already existing spaces, or develop out of the incumbent regime following an initially minor divergence in the mainstream selection environment (Levinthal, 1998). Following this initial disruption, market niches tend to develop their own trajectories, and invade other niches or re-converge with the mainstream market through fusion, hybridisation or transition (Raven, 2006). An alternative approach defines market niches as a later-stage form of technological niches, which are transformed through the successful fulfilment of three distinct internal processes: articulation of expectations and visions; the building of social networks; and successful multi-dimensional, second order learning processes (Kemp et al., 1998; Schot and Geels, 2008). This approach was further refined by conceptualizing niche development as a sequence of unstable local-level niche experiments exchanging knowledge with a developing market niche, which is characterised by a wider reach and a higher level of stability ensured by defined, shared rules (Schot and Geels, 2008). Finally, market niches are recognised as spaces providing limited but commercially viable application opportunities for their focal (sustainable) innovation and technologies (Smith et al., 2014). Once market niches have been formed and/or identified, a promising innovation can continue to mature and gain momentum in order to achieve a level of cohesion, stability and performance sufficient to trigger a transformative process by following different pathways. One potential strategy is to apply the technology in different niche markets in order to strengthen technology/market combination – this relates to the proposition of niches entering other niches (Levinthal, 1998; Raven, 2006, 2007). A second strategy has the niche enter a co-development process with the incumbent regime, ultimately arriving at a new, hybrid configuration in which the niche innovation was merged with the dominant market technology (Raven, 2007).

2.5.1.3 Policy niches

Compared to the first two niche types discussed above, policy niches are defined by the focal innovation, which is a novel (sustainable) policy instead of a technological innovation. While the ultimate goal of policy niche management is comparable to strategic niche management – causing a regime shift towards a more sustainable configuration by implementing a focal policy, or a modified variation thereof, into the incumbent regime, policy niches invariably require a deeper focus on social processes and interaction between actors due to the strong social component of niche development processes (Ieromonachou et al., 2004). Successful development of policy niches starts from individual, experimental cases, which merge to form policy niches. Following the strategic niche management process, the protective properties of these niches are gradually dismantled upon reaching a certain level of acceptance and stability (Kemp et al., 1998.), transforming policy niches into adoption niches. From these adoption niches a regime change is initiated, with regime rules, structures and practices re-configuring in order to match the new policies (Ieromonachou et al., 2004). While strategic niche management of innovative, sustainable policies has not been widely used, empirical work has shown its potential applicability in the future.

2.5.1.4 Research and development niches

This type of niche represents a variation of the more widely used technological niche concept, and is not taken into account by all niche researchers. While both technological niches and R&D niches refer to protective spaces, they differ by existing at different stages in the evolutionary process (Nelson and Winter, 1982): the technological niche exists between the variation and selection stage, and invariably becomes dependent on (proto-) market creation and market success, while a R&D niche is selected based on expectations only, with potentially a long time period between the start of R&D activities focusing on the innovation and market entrance (Van den Belt and Rip, 1987 in Raven, 2006). The R&D niche can therefore be considered a predecessor of the technological niche in a sequential niche development process. However, it needs to be assumed that R&D niches can be created and thrive only in conditions where significant amounts of research and development work can be undertaken without the expectation of swift returns in the form of practical applications and market-ready technologies.

From among the four described niche types, it is the Transitions Studies and especially Strategic Niche Management that focus on the development, management and analysis of technological niches and their transformation into market niches. It should be noted that the distinction between *technological niches* and *market niches*, as well as the focus on the evolution from fledgling technologies to market niches and regime challengers is more present in Strategic Niche Management. While Multi-Level Perspective proponents lean towards a more general description of the niche as a protected, experimental space serving as a technology incubator, they still use the term *technological niche* (Geels, 2002 and 2004; Geels and Kemp, 2007). With the conceptual connection of technological niches and market niches as stages in a sequential development process (Geels and Schot, 2008) with technological niches preceding and/or augmenting market niches (Smith et al., 2014) there is a reduced need for the distinction in later studies, with niches being generally observed as protective spaces (Markard et al., 2012) providing shielding, nurturing and empowering functions to the focal innovation (Smith and Raven, 2012).

2.5.2 Strategic niche management

The initial idea behind development of the Strategic Niche Management (SNM) approach was the question why a large number of sustainable innovations, some of whom show high potential at the start, never manage to leave the experimentation stage and, ultimately, enter the market (Kemp et al., 1998, Raven et al., 2008, Coenen et al., 2010). The inability of even promising innovations to enter the mainstream is attributed to the presence of an incumbent technological regime, which is a theoretical concept rooted in evolutionary economics, first described by Nelson and Winter in 1977. A technological regime is described as a complex of scientific knowledge, engineering practice, skills and procedures, institutions and infrastructures centred on a dominant design and reinforced by rules, beliefs and (scientific) search heuristics (Kemp et al., 1998), existing at a medium to high level of aggregation (Markard and Truffer, 2008). The incumbent regime is characterised through the presence of a dominant design, or parallel dominant designs, a shared development trajectory and shared rules (Geels, 2002) and a relatively high degree of stability (Raven, 2006). The regime creates a selection environment that acts as a barrier for non-regime technologies and especially for new and promising innovations which may face difficulties completing with established regime technologies or achieving significant market shares. This barrier can be manifested in the form of multiple selection processes related to one or more of the regime's components, and can relate to specific regime actors, actor groups, institutions and the availability of technological and/or human resources (Geels, 2002; Smith, 2007).

A typology of barriers has been proposed by Kemp et al. (1998), while a revised and adjusted typology was proposed by and Smith and Raven (2012). In order to provide an overview of both typologies, the author has summarized the barriers and identified selection processes in the following two tables:

Barrier / regime dimension	**Selection processes**
Technological factors	Availability/existence of complementary technologies/infrastructure; economies of scale affecting production
Government policy and regulatory framework	Lack of clear government goals, lack of directed support for R&D activities, existing regulatory framework unsuitable for new technologies
Cultural and psychological factors	Established psychological constructs related to a particular established technology or expectations related to the fulfilment of a societal function
Demand factors	Lack of user-side demand due to unclear expectations, high prices
Production factors	Unwillingness of large actors to introduce innovative technologies; sunk costs related to production of established technologies
Infrastructure and maintenance	Lack of necessary infrastructure, lack of actors trained in the maintenance of the new technology
Undesirable social and environmental effects of new technologies	New issues created through the use of innovative technologies, possibility of rebound effects (Berkhout et al, 2000; Herring and Roy, 2007)

Table 3: Barriers identified by Kemp et al. (1998)

Barrier / regime dimension	Selection processes
Established industry structures	Established network relations, user-producer networks, shared routines and heuristics, existing (labour force) capabilities and allocated resources
Dominant technologies and infrastructures	Technological standards and infrastructural arrangements
Established knowledge base	Guiding principles and learning processes geared towards incremental change; lack of resources for R&D; lack of knowledge exchange platforms
Markets and dominant user practices	Stabilised market institutions, supply and demand functions, price mechanisms, user routines
Public policies and political power	Existing regulations, policy networks, role of policy-makers within the incumbent regime
Cultural significance attached to a specific regime	Symbolic representation of regime or its elements; users with established psychological constructs

Table 4: Barriers identified by Smith and Raven (2012)

It should be noted at this point that not all of these barriers are external to the prospective innovation, with technological factors being directly related to lack of performance, or testing in mass use conditions, and production factor barriers depending on the willingness and ability of producers to develop the innovation to a market-ready state and start mass production while facing cost issues. Adding to the latter, established manufactures will often demonstrate unwillingness to invest into the production of an innovative product if it cannot be successfully introduced into a mass market. Infrastructure factors can also partially be related to the technology itself, especially in cases where the innovation requires alterations of the existing infrastructure or even the development of a new one (for example, hydrogen-based power sources for vehicles, or large-scale utilization of battery electric vehicles) and when there is a lack of advocacy from the innovation's proponents, or consent about the responsibilities for developing the new infrastructure. Further barriers related to the innovation itself are connected to potential undesirable societal and environmental effects such as increased land use and uncertainty about the allocation of arable land used for producing biofuels, or rebound effects in the transport sector caused by the higher cost-efficiency of low- or zero-emission vehicles (Kemp et al., 1998).

Other barriers are external and more related to the regime or the wider economy and society: government policy and existing regulatory frameworks can create uncertainty about the desirability of a prospective innovation; not provide a sufficient level of support in the form of regulatory policies and public funds (Verhees et al., 2013); or even outright block the diffusion of new technologies through creating an unfriendly public environment (Geels, 2014). Demand factors are directly related to market demand for the innovative product or service, related to users' preference, risk aversion, willingness to pay (Kemp et al., 1998) and public and private acceptance (Sauter and Watson, 2007). This is especially important when considering the need for diffusion and entering the main market; while a sustainable innovation might survive within the confines of a market niche, it will never have a chance to fulfil its potential of changing configurations of socio-technical regimes on a larger scale unless it enters a transition process with the incumbent regime.

A further barrier comprises infrastructure and maintenance factors. Unless the niche innovation is able to use the existing infrastructure without significant drawbacks or if it manages to enter a co-evolutionary, hybridisation process (Raven, 2007; Geels and Schot, 2008) with the incumbent regime, partial or even full reconfiguration of the existing infrastructure will be necessary. This is particularly problematic in cases where regime actors have large amounts of sunk investments in the existing infrastructure (Kemp et al., 1998). Finally, on a societal level, cultural and psychological factors related to the incumbent technology, the developing innovation, or both can be a significant barrier for diffusion and development. Users tend to form psychological constructs based on form and performance of an incumbent technology, and its provision of a societal function, and might exercise caution to the point of outright rejection of a new entrant which challenges, or does not fit into those constructs. Examples can be battery-electric cars, which were often derided as challenging the notion of freedom of movement connected with conventional cars (Kemp et al., 1998), or domestic micro-generation schemes for renewable technologies which did not fit into the domestic space/house construct of more conservative users (Allen et al., 2008).

In order to ensure that innovations have the support required to overcome these barriers so they can develop towards a transition trajectory, protective spaces need to be created where budding innovations can develop and diffuse without being exposed to the rigours of and probable rejection by the incumbent selection environment (Kemp et al., 1998, Raven, 2006, van der Laak et al., 2007, Schot and Geels, 2008, Smith and Raven, 2012). Those spaces are referred to as (technological) niches and they are developed, proactively managed and finally disbanded in a controlled fashion after the focal innovation reaches a development stage, enabling it to successfully diffuse within the regime selection environment, or trigger a transformative process within the incumbent regime (Schot and Geels, 2008).). This final stage is seen as having special importance for the eventual transition of niches to the mainstream regime, since potential over-protectiveness towards niche technologies might prevent them from becoming competitive in an open market setting and potentially become costly “white elephants” (Kemp et al., 1988, Schot and Geels, 2008, Smith and Raven, 2012). Breakdown of protection can also happen as a consequence of persistent disappointing performance or very low prospects of a successful transition (Kemp et al., 1998). Development and evolution of technological niches takes place through direct and indirect action by a number of niche actors supporting or holding a stake in the focal innovation. Depending on their closeness to the innovation and the strength of the connection, they can be separated into *partners*, who are actively involved in the development and management of the innovation, and *actors*, who take a more indirect role in the development and diffusion process but still provide their input and/or take action at different stages (Ieromonachou et al., 2004).

2.5.3 Niche functions

As the technological niche develops, a technological trajectory is formed through an internal accumulation of joint knowledge, shared rules, heuristics, expectations and models present on a global level and local experiments designed through practical application of this knowledge. The experiments subsequently feed back knowledge acquired by localized learning to the global level (Geels and Raven, 2006; Raven and

Geels, 2010). Ultimately, the emerging global trajectory might evolve into a market niche (Hoogma et al., 2002; Schot and Geels, 2008). This evolutionary process, spanning variation and selection procedures, is expected to take a certain amount of time, ranging between two (Raven and Geels, 2010) and up to five decades (Coenen et al., 2010). Success is in no way guaranteed, with niche technologies being prone to suffering disruptions ranging from setbacks to complete failures at any stage of the process; sustainable technologies are often at even higher risk (Raven and Verbong, 2004; Geels and Raven, 2006; Verbong et al., 2010; Verhees et al., 2013; Smith et al., 2014). In the initial development of the SNM concept, three main internal niche processes have been identified (Kemp et al., 1998, Raven, 2006, Van der Laak et al., 2007, Schot and Geels, 2008):

1) Coupling, building and articulation of expectations and visions

2) Learning processes (Raven, 2006; Schot and Geels, 2008)

3) Formation and building of social networks (Raven, 2006)

Each of these main processes has undergone further exploration and development in the last decade of SNM research, with the initial focus of strategic niche management being on the creation of experimental settings and facilitation of learning processes, especially second-order learning (Schot and Rip, 1996.). Further development of the field led to a focus on the relative weakness of promising (sustainable) innovations in the face of market pressures and regime stability and resistance, manifested through a selection environment comprised of a number of innovation-internal and external barriers which were outlined above. This weakness necessitates the development of a protective, shielded environment in which the focal innovation could develop until it has reached a state of development that will allow it to persist or even thrive in “normal” market conditions (Kemp et al., 1998). The protective function of niches was further explored by Smith and Raven (2012), who have proposed an extended taxonomy of niche functions, separating them into active and passive shielding, nurturing which encompasses all three processes identified above: articulation of expectations and visions; learning processes and network development; and empowerment which can take the form of “fit and conform” empowerment and “stretch and transform” empowerment. The table below provides a short overview of the development of niche functions over time, focusing on a selection of frequently cited papers based on a literature review of the transitions sector undertaken by Markard et al. (2012) with the addition of a number of papers cited in SNM literature and extensively used by the author of this thesis:

Author/s (Year)	Identified niche functions
Kemp et al. (1998)	Coupling of expectations, Articulation process, Network formation
Weber et al. (1999)	Coupling of expectations, Learning processes, Network formation
Raven (2006)	*(development of)* Expectations, Social Network, (deep) Learning Processes
Schot and Geels (2008)	Articulation of expectations and visions, Building of social networks, Learning processes at multiple dimensions
Verbong et al. (2010)	Social network composition, Shaping of expectations, Learning processes
Smith and Raven (2012)	Shielding of innovations (active and passive), Nurturing (articulating expectations, developing social networks, broad learning processes), Empowerment (empowerment to fit and conform, empowerment to stretch and transform)
Smith et al. (2014)	Shielding, nurturing, empowerment
Verhees et al. (2015)	Shielding, nurturing, empowerment

Table 5: Overview of niche functions identified in SNM research papers

This summary indicates that the initial niche-internal typology of functions was extended to include functions and activities which were primary oriented towards the niche environment, both in shielding the niche actors and the focal innovation from selection pressures, and in empowering the innovation by accelerating its maturation and diffusion (Smith and Raven, 2012), ultimately enabling it to embark on a transition pathway towards the incumbent regime (Schot and Geels, 2008). However, recent research has indicated that this typology might need further refinement, both with relation to the temporal succession and separation of the different phases and the separation of the individual functions (Verhees et al., 2013; Smith et al., 2014). In the following sections, the functions defined by the extended typology developed by Smith and Raven are discussed and presented in more detail.

2.5.3.1 Shielding

The main rationale behind the shielding function lies in the recognised necessity of shielding the promising, yet immature, innovations against a selection environment created by the mainstream regime (Kemp et al., 1998), with especially path-breaking innovation suffering from a structural disadvantage relative to the stable, established structure of the incumbent regime (Smith and Raven, 2012). Within this context, unprotected innovations will be severely affected in their ability to develop, create supportive structures and gather momentum, necessitating the creation of spaces with a distinctive selection environment both separate from the mainstream one and supportive to the development of the focal innovation (Levinthal, 1998). This selection environment will *shield* the innovation from selection pressures and regime resistance. SNM recognises two different forms of shielding – passive shielding where generic protective spaces pre-dating deliberate mobilisation by niche actors and advocates are exploited in order to shelter the niche innovation; and active shielding where protective spaces are created by deliberate and strategic choices and actions by niche actors and advocates supporting a specific, potentially path-breaking innovation (Smith and Raven, 2012).

These protective spaces can shield the innovation against one or more selection pressures, and can extend beyond a purely protective function towards providing nurturing and empowering functions. Examples of passive shielding include geographical spaces suitable for application of a particular innovation due to local-specific environmental, social and/or economic factors (Smith et al., 2014) or the presence of a generic supportive programme for sustainable technologies which is exploited by the proponents of a specific niche technology to protect it from the full pressures of the mainstream selection environment. Active shielding, on the other hand, is designed and created by means of deliberate action of niche actors, for example through lobbying for increased solar subsidies (Verhees et al., 2013) or directed state-level support for a specific technology (Veraart et al., 2010). Shielding can take place at various levels of a niche's development cycle, and invariably needs to be reduced once the focal innovation nears market-readiness in order to avoid a situation of niche "lock-in" where the niche technology stabilizes, yet still remains uncompetitive outside of a small niche market (Kemp et al., 1998; Raven, 2006).

2.5.3.2 Nurturing

The nurturing function encompasses the various internal actions aimed at strengthening the niche innovation, which were seen as central to the process of SNM in earlier studies (Kemp et al., 1998; Weber et al., 1999; Raven, 2006; Schot and Geels, 2008). Main nurturing functions are the *articulation of expectations and visions* for the focal technology, multi-dimensional and multi-stage *learning processes* and the creation and development of *social actor networks* ensuring broad and deep support (Smith et al., 2014) for the niche. Nurturing through learning relates to the focus of SNM as a strategy applied within the Constructive Technology Assessment (CTA) approach, where support for deep (second order) learning processes was the focal point of the strategy (Schot and Rip, 1996). The importance of second-order learning, causing changes in cognitive frames and assumptions, over the first-order learning, centred on the accumulation of facts and data for the successful development of niches was further emphasized by Schot and Geels (2008), who also highlighted the multi-dimensional nature of learning processes related to the structural components of the niche and a prospective future regime. The articulation of expectations and visions plays a crucial role in gathering public support and momentum as well as providing guidance for the search (Hekkert et al., 2007; Bergek et al., 2008) and shaping the development trajectory of the niche (Schot and Geels, 2008). Further effects are the attraction of resources and investments, the reduction of uncertainty and the building of legitimacy (Verhees et al., 2013). Finally, the development of actor networks supports niche development by increasing the number of entrepreneurial activities, improving the exchange of knowledge and broadening the scope of accessible experimental areas and/or niche markets (Kemp et al., 1998; Hekkert et al., 2007). While initial small supporting networks can develop autonomously, their broadening and deepening might require support by industry and state actors (Kemp et al., 1998). Finally, network actors can add their own vision to shape niche expectations, and develop the niche trajectory (Raven, 2006), and the structure and strength of actor networks can directly relate to the development prospects of a niche, with neither weak nor very strong networks being preferable (Caniëls and Romijn, 2008). The nurturing function of a niche has been extensively researched from a systemic perspective in the Technological Innovation System (TIS) literature, especially within the analysis of key system functions related to the development of the focal innovation/technology (Hekkert et al., 2007; Bergek et al., 2008), the conceptual connections being recognised in SNM research (Smith and Raven, 2012) and forming a relevant part of the theoretical discussion in this work.

2.5.3.3 Empowerment

The concept of niche empowerment describes active support of transition processes and expansion of the niche technology to the incumbent regime, increasing the niche's "competitiveness" and advancing it along its transition pathway. Empowerment of niche innovation can be implemented in two forms and following different aims: empowering to fit and conform, where the niche innovation is made competitive with regime practices inside the current selection environment; and empowering to stretch and transform, where the innovation is aimed at undermining incumbent regimes and transfer niche-derived reforms to the selection environment, changing it in the process (Smith and Raven, 2012). Fit-and-conform empowerment is considered to take a more inward-oriented approach, focusing on improving the innovation's and the niche's performance in order to increase its competitiveness in the incumbent selection environment (Smith et al., 2014). It can be related to strategies such as the niche hybridisation approach, with the niche developing towards becoming part of the regime (Schot and Geels, 2008). Related to earlier SNM approaches, successful fit-and-conform empowerment results in a breakdown of the protective properties of a niche, once the innovation is able to compete in the incumbent selection environment (Kemp et al., 1998). However, the processes enabling this type of empowerment also include the risk of disempowering the innovation in terms of its initially expected (sustainability) performance, and uncertainty about the ability of developing performance improvements which will allow the protective properties to be broken down without endangering the competitiveness of the innovation (Smith and Raven, 2012). Stretch-and-transform empowerment, on the other hand, takes a more outward-looking approach, aiming to change the existing selection environment by transferring elements of the niche's protective properties and internal structures into the incumbent regime, which is consequently transformed into a new configuration more conductive to the development and diffusion of the niche innovation (Smith and Raven, 2012; Verhees et al., 2013; Smith et al., 2014). Compared to fit-and-conform empowerment processes, niche protection does not need to be fully broken down as it is assimilated into the (changed) regime instead (Verhees et al., 2013). Actors will aim to institutionalise niche practices, however, as yet there is no systemic investigation of the institutionalisation process. While stretch-and-transform empowerment allows the niche innovation to retain its initial expectations and visions, as well as its potential (sustainability) performance, there is also a risk of protectionism by niche actors maintaining protective functions shielding a poor or failed innovation (Smith and Raven, 2012). Despite the clear theoretical delineation of the two approaches, recent empirical research has observed that “fit and conform” and “stretch and transform” processes in practice may not be separable into distinct components, with many elements of the processes played out simultaneously, following pragmatic approaches by niche actors (Verhees et al., 2013, Smith et al. 2014).

2.5.4 Niche-regime interactions

The potential of niches to grow and undertake a successful breakthrough to the regime was investigated by Raven (2006), who developed a niche taxonomy based on this potential by distinguishing niches and regimes based on their internal stability. In the taxonomy, represented by a 2x2 matrix, niche stability is determined by the success (or failure) of the three internal niche processes, while regime stability is determined by internal tensions and external influences from the socio-technical landscape level. Based on their own stability and the stability of the incumbent regime, niches can therefore be distinguished into “dead-end streets” (low niche stability and high regime stability; very limited potential for growth and breakthrough); “missed opportunities” (low niche stability and low regime stability; breakthrough is possible but requires high efforts); “promising technologies” (high niche stability and high regime stability, good chances for breakthrough but inevitable competition with regime actors); and “problem solvers” (high niche stability and low regime stability, rapid breakthrough with support by regime actors can be expected). However, it must be noted that this definition of regime stability is somewhat limited and might be incomplete; in addition to that, niches might be influenced by more than one regime at a time (Raven, 2006, Schot and Geels, 2008). Further research of niche stability has also shown that even though a (moderate) level of regime instability is necessary for a successful niche breakthrough, an inherently highly unstable regime is as detrimental to niche development as a highly stable one (Verbong et al., 2010). Consideration must be given here to the fact that niche-regime interaction can take on different forms: while in some cases niche innovations might be adopted by regime actors to solve certain problems within the regime (Raven, 2006), in other cases regime actors might pick up individual niche lessons and incorporate them to the incumbent regime without translating the niche itself, which might have continued its existence in the form of a stabilized market niche (Smith, 2007). In the latter case, translation processes between the niche and the regime play an important role; these processes are vital for the successful transfer of sometimes strongly differing practices. Translations are often expressed through learning processes, with one important requirement being sufficient flexibility on the niche side of the translation for regime actors to consider possible successful application of lessons within the regime. Three different kinds of translations are identified: translations of sustainability problems; translations that adapt lessons; and translations that alter contexts (Smith, 2007). Following the niche function taxonomy set forward by Smith and Raven (2012), niche-regime interactions also depend on the functions provided by the niche, based on strategies followed by niche actors and proponents (Schot and Geels, 2008). Depending on the type(s) of niche empowerment pursued, niches can aim to enter co-evolutionary processes with incumbent regimes, resulting in hybrid configurations with the niche technology becoming part of the regime and successfully competing in its selection environment (Verhees et al., 2013). Alternatively, niche innovations can also attempt to enter transformative pathways (Geels and Schot, 2007), re-configuring the regime by transferring parts of the niche’s internal structure and protective functions (Smith and Raven, 2012; Smith et al., 2014).

2.5.5 Future challenges for Strategic Niche Management

As a further point towards the analytical application of SNM theory, it may be worthwhile noting that some of the more recent case studies have found only scarce evidence of actors engaging in planned, strategic niche management activities (Verhees et al., 2013, Smith et al., 2014). This especially seems to be the case in studies where the observed technology has encountered significant resistance and/or adverse contexts, forcing proponents of the innovation to adapt their actions and measures to match the current political and socio-technical climate (Verhees et al., 2013). One possible conclusion from those observation is that niche actors have to display high flexibility as well as strong negotiating skills, which enable them to carefully shape and adapt expectations, thus avoiding entering a hype-disappointment cycle (Geels and Raven, 2006, van der Laak et al., 2008, Raven et al., 2008) and adapting local experiments to stakeholder expectations and local contexts (Raven et al., 2008). Recent research has highlighted the role of local, less formal actors through grassroots innovations and innovation networks, but at the same time highlighted that standard SNM procedures might not be suitable/sufficient for nurturing and developing those innovations (Seyfang et al., 2014). Additional empirical studies might lead to a deeper understanding of strategy changes and SNM processes and the role and intentions of niche actors in supporting them.

A second relevant pathway relates to investigating theoretical connections between the Transitions Research approaches of Strategic Niche Management (SNM) and Technological Innovations Systems (TIS). Even though they observe the development of promising innovations on different structural levels of accumulation – low for SNM and medium to high for TIS (Markard and Truffer, 2008), there are significant conceptual connections between niche processes and functions and TIS functions, especially related to inward-oriented processes aimed at strengthening the performance of the niche/system and the focal innovation (Smith and Raven, 2012). Following a conceptual framework proposed by Markard and Truffer (2008), niche-system interactions can be reviewed on a structural and functional level, contributing towards the development of a combined framework.

Finally, a third challenge for future SNM research relates to the relative lack of research on its prescriptive applications – while a multitude of studies applies SNM concepts *ex post* while investigating the development of promising, often sustainability-related innovations (Schot and Geels, 2008), there is a lack of academic and practice-oriented studies on planned applications of Strategic Niche Management approaches in the development and diffusion of promising sustainable technologies in local, regional and global contexts both in the developed and developing countries. While such a study would require continuous interaction of the researcher and a technology niche over a long period, as well as the opportunity to shape and co-develop actions taken by niche actors, and is therefore beyond the scope of a doctoral research project, this call for action should be taken up by other academic and non-academic researchers who have access to the required resources and positions.

2.6 The Technological Innovation Studies (TIS) approach

The second research stream reviewed in this chapter is the Technological Innovation Studies (TIS) approach, where the central aim of the analysis revolves around the evaluation of the performance of an innovation system centred on a specific technology (Markard et al., 2015). Initially based upon the technological system concept first developed by Carlsson and Stankiewitcz (1991), who defined a technological systems as a

"network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilization of a technology" (Carlsson and Stankiewitcz, 1991)

This concept was refined to address emerging technologies by focusing on the *generation* and *diffusion* of the core technology, and developing an analytical framework to measure the performance of the technological *innovation* system through analysing its structure and the fulfilment of a number of key system functions (Hekkert et al., 2007, 2011; Bergek et al., 2008). A second aim of the technological innovation systems (TIS) analysis was to provide guidance and recommendations for policymakers supporting the development of an innovative technology by identifying barriers to improved system performance, as well as supporting policies and other institutional tools defined within the analytical approach as inducement and blocking mechanisms (Bergek et al., 2008). Two sets of system functions were developed in parallel by Hekkert et al. (2007) and Bergek et al. (2008), with both sets subsequently utilized by researchers undertaking TIS analyses of case studies (an overview of several more recent studies will be provided later in this section). The author will outline both sets of functions in the table below, comparing the individual functions of the two sets on a like-for-like basis in order to highlight the similarities between the two sets. In the following, strongly similar or identical functions will be listed next to each other, while functions without a direct equivalent will be set in separate rows. It needs to be noted that the function overview in this table does not follow the order proposed by original authors. The left side of the table (Hekkert et al.) representing the first proposed set of function is left in the original order, while the order of the second set of functions (Bergek et al.) is changed accordingly.

System functions identified by Hekkert et al, (2007)		System functions identified by Bergek et al. (2008)	
System function	Performance indicators	System function	Performance indicators
F1 Entrepreneurial activities	Number of new entrants, diversification activities by incumbent actors, variety of experimentation	F3 Entrepreneurial experimentation	Number of new entrants, diversification activities in established firms, number of different application types/projects
F2 Knowledge development	Number of patents, R&D activities performed, investments in R&D, evolution of the knowledge base		
F3 Knowledge diffusion through networks	Number of networking events devoted to the focal technology, number of academic and non-academic publications, size and accessibility of the network system		
F4 Guidance of the search	Specific development targets set by governments or industries; creation of incentives for developments of specific technologies or knowledge fields; development of expectations towards specific	F2 Influence on the direction of search	Incentives for specific development trajectories, extent of regulatory pressures, articulation of interest by leading actors

	performance/development targets		
F5 Market formation	Number of developed/developing niche markets; existence of market institutions; market development phase and projections; policy support for market development	F4 Market formation	Creation of demand profile(s), development phase of the market, users and user demand functions, institutional support for market development and growth
F7 Creation of legitimacy/counteract resistance to change	Number and activity level of lobbying groups; establishment of technological legitimacy for key actor groups; stakeholder expectations; resistance by incumbent actors	F5 Legitimation	Legitimacy of the focal technology for key stakeholders, activities within the system which can influence legitimacy
F6 Resources mobilization	Availability of financial resources (funding, incentives, venture capital) for R&D and business developments; availability of trained specialist staff; availability of required technological infrastructure	F6 Resources mobilization	Availability of capital, in particular seed and venture capital, availability and quality of human resources (specialist staff trained to work with focal technology), availability of complementary assets (products, services, network technologies)

		F7 Development of positive externalities	Emergence of pooled labour markets, specialized intermediate goods and services providers, existence and volume of information flows and knowledge "spill-overs"

Table 6: Like-for-like comparison of system functions defined by Hekkert et al. (2007, 2011) and Bergek et al. (2008)

The above summary indicates a high level of conceptual similarities between the two sets of functions, which are focusing on a number of key development areas – the availability, accessibility and transferability of knowledge; the activity level of entrepreneurial actors; the existence, breadth and development phase of a market for the focal technology; the existence of institutional support for and system actor consensus on preferred development trajectories, as well as clear expectations from key stakeholders; the availability of financial resources (both in the form of R&D funding and venture/seed capital), human resources and infrastructure and complementary/supporting technologies; and finally the creation of legitimacy, public support and acceptance and the utilization of positive externalities developed through the system's own growth. In practical terms, these similarities have allowed a number of analysts to implement studies utilizing either of the function sets, or even a derived version combining both (Negro et al., 2008; Suurs et al., 2008; Praetorius et al., 2010; Hudson et al., 2011; Sanden and Hillman, 2011).

2.6.1 Implementing a TIS analysis

The implementation of a technological innovation system analysis consists of five key steps: determination of the focal TIS, where the analyst is required to undertake a number of case-specific choices to determine the breadth, depth and spatial limits of the analysis (Bergek et al., 2008); structural mapping of the TIS with the aim of identifying actors, networks and institutions (Bergek et al., 2008) and technological trajectories (Hekkert et al., 2011); functional mapping and functional analysis of the seven key system functions outlined in Table 5: Entrepreneurial experimentation and production; knowledge development; knowledge exchange; guidance of the search; market formation; resource mobilization; counteracting resistance to change and legitimacy creation (Hekkert et al., 2007, 2011; Bergek et al., 2008): ; assessing the development phase of the focal system (Bergek et al., 2008; Hekkert et al., 2011); identification of internal, structural causes for functional barriers (Hekkert et al., 2011) respective identification of inducement and blocking mechanisms (Bergek et al., 2008); and, concerning the second main aim of the TIS as a policy development aid, identification of obstacles to policy goals/key policy issues (Bergek et al., 2008; Hekkert et al., 2011). The following table will compare the main analytical steps from the approaches put forward by Bergek et al. (2008) and Hekkert et al. (2011):

TIS analysis – Analytical steps	
Bergek et al. (2008)	*Hekkert et al. (2011)*
1)Defining the focal TIS - Choice between *knowledge field* or *product/artefact* - Choice between *breadth* and *depth* (level of aggregation of TIS) - Choice of *spatial domain* (what are the spatial borders of the TIS?)	**1) Structural analysis** Identification of the *actors, networks, institutions* and *technological factors* forming the focal TIS Mapping of the components, especially the actors, in order to determine the key actors in industry and research; mapping the demand for/supply of education, the state of the market, politics and policy goals. Identification of intermediaries. Mapping of neworks
2) Structural analysis of focal TIS	**2) Determining the development stage of the focal TIS**

Identification of relevant *actors, networks* and *institutions*	Determining the development stage of the focal TIS based on the results of the structural analysis and considering the results of the functional analysis undertaken in step 3 – TIS can be in *pre-development, development, take off* or *acceleration phase*
3) Functional mapping using the 7 TIS functions Describing the functional pattern of the TIS, assessing fulfilment of individual functions	**3) Functional analysis using the 7 TIS functions** Describing the functional pattern of the focal TIS, measuring fulfilment of individual functions and review of functional patterns characteristic for particular development phases
4) Assessing the functionality of the TIS and setting process goals Defining the phase of development of the focal TIS based on results of structural and functional analysis – TIS can be in *formative phase* or *growth phase* Comparing focal TIS with similar TIS/TIS fulfilling a similar societal function in other localities Specify policy goals (aims for the development of the system functional pattern)	**4) Analysis of structural causes for functional barriers** Identification of system functions forming barriers through weak fulfilment. Identification of structural components causing weak fulfilment of functions Description of the relationship between the (structural) cause and the barriers
5) Identify inducement and blocking mechanisms Identification of internal and external inducement and blocking mechanisms	**5) Obstacles for policy goals** Determining the policy goals of the focal TIS and through them, the optimal configuration of the system

influencing the fulfilment of the system functions; identification of structural weaknesses	Identification of the most important barriers to the achievement of the policy goal
6) Specify key policy issues Specification of key policy issues which need to be addressed in order to influence mechanisms towards continuous development of focal TIS based on the policy goals set out in step 4, and the identified inducement and blocking mechanisms	

Table 7: Comparison of TIS analytical steps based on Bergek et al. (2008) and Hekkert et al. (2011)

The comparison of the two analytical approaches indicates significant overlaps in the key analytical steps, with both approaches including a structural analysis of the focal TIS, a functional analysis in the form of a review of the fulfilment of a set of system functions, and a barrier analysis with the main aim of identifying internal (structural) barriers as well as external inducement and blocking mechanisms which may impact the fulfilment of system functions, the development of the system and achieving the broader policy goals.

The analytical approach proposed by Bergek et al. (2008) puts an additional focus on the determination and delineation of the focal system, an approach whose importance is reflected in subsequent criticism on delineation of TIS and the spatial dimension of a TIS analysis (Bergek et al., 2015; Markard et al., 2015). Furthermore, there is a significant focus on the policy-informing role of a TIS analysis, which is important for any prescriptive use of TIS findings in policy-led transitions processes (Loorbach and Rotmans, 2010; Shove and Walker, 2010). This highlights the close relationship of transitions research and transitions-based policymaking, but also draws criticism related to potential analyst bias and the practical usability of recommendations made by TIS analysts (Markard et al., 2015).

The approach outlined by Hekkert et al. (2011), while following the same set of key steps, puts increased emphasis on the structural and functional analysis stages, particularly on the fulfilment of system functions, functional patterns and feedback cycles specific for particular stages of the TIS development process. This approach is in line with the research on function interrelations - “virtuous” and “vicious” cycles and “motors of innovation” as identified by Suurs (2009) and expanded upon by Walrave and Raven (2016). This element of a TIS analysis will be investigated in more detail in the following section.

Overall, and compared with some of the currently developing approaches within the broader field of Transitions Research, TIS analysis offers a clearly defined analytical approach which might make its application by analysis both more structured, and potentially also more suitable for ex-ante approaches aimed at informing public policy. This undoubtedly, at least partially, accounts for the current popularity of TIS as an analytical tool (Markard[3] et al., 2012; Bergek et al., 2015; Markard et al., 2015), with multiple empirical research studies being published based on partial or full utilization of the TIS approach (Negro et al., 2007, 2009; Suurs et al., 2009; Praetorius et al., 2010; Hudson et al., 2011; Sanden and Hillman, 2011; Lovio and Kivimaa, 2012 among others). At the same time, the TIS approach has been criticised in a number of areas (Markard and Truffer, 2008; Geels, 2011; Smith and Raven, 2012; Kern, 2015; Markard et al., 2015). The main criticisms, as well as potential areas for further research will be discussed in more detail later in this chapter.

2.6.2 Interrelations between system functions

In addition to assessing the fulfilment e.g. performance of the individual system functions, the TIS approach also acknowledges the interdependence and connections between the actors, institutions and networks fulfilling the different functions by reviewing the interrelations between the functions (Hekkert et al., 2007), identifying positive feedback cycles, “motors of innovation” (Suurs, 2009) and negative feedback cycles, “vicious cycles” (Hekkert et al., 2007). While the former are seen as desirable,

[3] Markard et al. (2015) note that for the period of 2008-2014, 80 papers are reported by the Scopus database as containing the term “Technological Innovation Systems” in their title and/or keywords

even integral to sustained system development (Suurs, 2009; Hekkert et al., 2011), the latter are recognised as hindering or even stopping the development of a TIS (Hekkert et al., 2007), resulting in system weaknesses (Jacobsson and Bergek, 2011) and instances of system failure (Klein Woolthuis et al., 2005). Suurs (2009) proposed a typology of "innovation motors" based on a number of case studies, identifying the following positive feedback cycles influencing TIS development:

Innovation motor	**Dominant functions** ***(functions based on the typology proposed by Hekkert et al. (2007))***
Science and Technology Push motor (STP motor)	Knowledge development (F2), Knowledge diffusion (F3), Guidance of the Search (F4), Resource Mobilisation (F6)
Entrepreneurial motor	Entrepreneurial activities (F1), Knowledge development (F2), Knowledge diffusion (F3), Guidance of the Search (F4), Market Formation (F5), Resource Mobilisation (F6), Creation of legitimacy/ Counteract resistance to change (F7)
System Building motor	Entrepreneurial activities (F1), Knowledge development (F2), Knowledge diffusion (F3), Guidance of the Search (F4), Market Formation (F5), Resource Mobilisation (F6), Creation of legitimacy/ Counteract resistance to change (F7)
Market motor	Entrepreneurial activities (F1), Knowledge development (F2), Knowledge diffusion (F3), Guidance of

	the Search (F4), Market Formation (F5), Resource Mobilisation (F6)

Table 8: Typology of "innovation motors" (Suurs, 2009)

While a number of negative feedback loops was also identified, there is presently no developed typology; this is partially a result of insufficiencies of systematic nature of “vicious cycles” which can be caused by specific instances of localized or situational agency, or constellations within the institutional framework (Hekkert et al., 2008; Suurs, 2009; Jacobsson and Bergek, 2011; Bergek et al., 2015).

Generally speaking, recognised positive interrelations are considered to be supportive inducement mechanisms, with the focus of TIS analysts being on sustaining them and identifying potential sources of additional institutional support (Bergek et al., 2008), while negative feedback cycles represent challenges which must be addressed either through system-internal changes or by utilizing targeted policies for external support. Recent research has extended on the conceptual connection of the TIS function feedback cycles to system dynamics (Walrave and Raven, 2016), drawing on transition pathway theory (Geels and Schot, 2008; Geels et al., 2016) and the four types of innovation motors identified by Suurs (2009) in order to develop a quantitative model for forecasting TIS diffusion and development behaviour.

The performance, or level of fulfilment of individual system functions, as well as the presence of specific positive interaction patterns are seen as indicative for the TISs development phase, with Hekkert et al. (2011) proposing four distinct development phases characterized by the dominance of particular functions. Those phases are pre-development, development, take-off and acceleration. In the pre-development phase, the dominant functions are knowledge development and sustained knowledge exchange and diffusion, supported through available resources and shaped by evolving search patterns and development aims. In the development phase, the accumulated knowledge is manifested through experimental/pilot projects, requiring a sustained flow of resources and actors-entrepreneurs willing to support the fledgling technology. Therefore, entrepreneurial experimentation is considered the key function for this phase, and needs to be supported by the other six system functions. The transition to the take-off phase marks a shift in the role of these early entrepreneurs.

With the early projects being successful, they need to change from entrepreneurs-innovators into the role of system builders (Hekkert et al., 2011), creating legitimacy for the focal technology and interacting with institutions and public actors in order to create legitimacy (Hekkert et al., 2008). In the final – acceleration - phase, the focus of system development is on market development, growth and sustained diffusion, with expectations and visions generated by multiple, even system-external stakeholders influencing future development.

Bergek et al. (2008), on the other hand, separate the system development into two phases – a formative phase and a growth phase, which are identified through a performance assessment of a series of indicators. For instance, the formative phase is characterized by high uncertainty regarding the viability of the technology, its technical performance and expectations for future development trajectories (Kemp et al., 1998), necessitating intensive knowledge development, hands-on experimentation and introduction of variety by applying the technology in different settings and testing multiple potential development routes. A system that has reached its growth phase has started to become self-sustaining, with articulated expectations, consensus of key actors on development trajectories and an existing user pool of innovators and early adopters (Rogers, 2003, p. 282). The focus shifts to system expansion through sustained marked growth and large-scale technology diffusion (Bergek et al., 2008). Resource mobilization becomes even more important due to increased demand, with initial R&D and prototyping resources unable to support a sustained, long-term growth process.

2.6.3 TIS and external context

While the TIS approach is broadly recognised for its capacity to analyse and evaluate system structures and processes/functions (Hekkert et al., 2007; Bergek et al., 2008; Bergek et al., 2015), one of the main criticisms of the concept was about its perceived inability to include system-external developments, leading to TIS analysis potentially mis-evaluating the influence of external factors or lacking insight into external, concurrent developments of rivalling innovative technologies (Markard et al., 2015; Bergek et al., 2015). This apparent flaw was sufficient for a number of authors to question the suitability of the TIS approach for studying transition processes (Markard and Truffer, 2008; Smith and Raven, 2012). This risk is partially based on the necessity to delineate system borders at an early stage of a TIS analysis, consequently, the analyst might by virtue of this requirement dismiss actors and developments outside of the system borders (Bergek et al. 2008; Smith and Raven, 2012).

The need to extend the concept of a TIS analysis was recognised by TIS authors (Markard et al., 2015), initially by investigating conceptual similarities and potential co-analytical approaches between TIS and the multi-level approach (Markard and Truffer, 2008), and later by developing a typology for the interaction between a (focal) technological innovation system and system-external context structures influencing the system's development (Bergek et al., 2015). Three generic types of context structures have been recognised (surrounding and related TIS; pre-existing infrastructures and institutions; and context structures related to the provision of specific system-level assets) and interactions of a focal TIS with those structures have been elaborated in depth using four exemplary types of context-related interactions:

1. Interaction between the focal TIS and other TIS
2. Interaction between the focal TIS and relevant sectors
3. TIS development in geographical context
4. Interaction between a focal TIS and the political context

TIS-TIS interaction has been conceptualized earlier (Markard and Truffer, 2008, Sanden and Hillman, 2011) and is seen as consequential to the cross-system and cross-sectoral nature of technological developments, as well as technologies, and the actors supporting their development, interacting repeatedly in different ways. The relationships between technological innovation systems can take place both between vertically and horizontally integrated systems – while vertically integrated relationships are seen as having positive effects on the fulfilment of TIS functions through technological cooperation, knowledge exchange, negative spill over is also a possibility. On the other hand, relationships between horizontally related TIS are likely to be of a more competitive nature, as the systems often draw on the same inputs and share a resource pool, and may be in competition for providing key societal functions (Bergek et al., 2015). However, horizontally related TIS can also be coupled through shared institutional links – for example, broadband policies for renewable technologies can lead to advocates of different, competing TIS to engage in cooperation with the aim of supporting and strengthening the mutually beneficial policies (Jacobsson and Lauber, 2006; Bolton and Foxon, 2015a, 2015b). The nature and level of TIS-TIS interaction can also depend on the development stage of the focal TIS – a system in its pre-development or development stages (Hekkert et al., 2011) will be more dependent on developments in more developed, contextual TIS. On the other hand, if the focal TIS is at a more advanced stage of development compared to the system or systems it is interacting with, developments of and within the system may influence these systems, but the focal system will not be influenced in a significant way (Bergek et al., 2015).

TIS is understood to operate within and in a relationship with the broader sector to which it belongs. In TIS literature the sector is defined in terms of the production, distribution and use of technologies and/or products that serve a certain societal function (ibid.). Parallels of this conceptualization to the regime concept utilized in the multi-level perspective and discussed earlier in this chapter are visible (Geels, 2002, 2004; Smith and Raven, 2012). Systems can operate in one or multiple sectors. At one end there can be a single system – single regime interaction similar to the niche-regime interaction modelled in the MLP approach (Kemp et al., 1998; Geels, 2004; Smith and Raven, 2012), with the system forming a small part of the broader sector. On the other end of the TIS-sector interaction scale a system can be integrated in a particular sector to an extent to which a conceptual separation, and separate observation of system and sector/regime, might be impossible (Bergek et al., 2015), or the TIS might extend across and interact with multiple sectors (Markard and Truffer, 2008). The latter is often the case when the focal technology or technology field provides, or has the capacity to provide more than one societal functions, such as for example combined heat and power generation (Raven and Verbong, 2007, 2009). Here, it can be argued that the system-sector interactions are not only taking place at the interface between system and sector actors and institutions, but are also influenced by the relationship between the sectors; this is a point which will be discussed in more depth, and compared to related concepts from other Transitions approaches later in this work.

A third type of contextual interaction of a TIS is based on the fact that any analysed TIS will be located in a particular spatial location (Bergek et al., 2015). The necessity for spatial delineation of a TIS is put forward as one of the initial analytical steps for prospective analysts (Bergek et al., 2008; Binz et al., 2014). While the challenges of different geographical, cultural, social and political contexts are of little relevance as long as the observed context is located within a single country or comparable political entity, they become relevant once the scope of analysis extends beyond that territory (Truffer and Coenen, 2012; Binz et al., 2014; Bergek et al., 2015). Most recent applications of TIS to empirical cases focused either on a single country (Negro et al., 2007, 2008; Suurs et al., 2009; Hudson et al., 2011; Wirth and Markard, 2011) or on comparative analysis of national TIS (Praetorius et al., 2010; Lovio and Kivimaa, 2012) often without explicitly considering the issue of spatial delineation (Markard et al., 2015). However, the inclusion of the geographical context into broader TIS analysis does imply a number of issues to be considered, two of which have been discussed by Truffer and Coenen (2012):

1. Existence of structural (actors, networks, infrastructure) and institutional couplings embedding a TIS in a specific geographical location
2. Structural (actors, networks) and institutional couplings that connect different spatial locations

The first issue is potentially of key value for a TIS analyst , in many cases specific, spatially limited institutions and the availability of actors, networks, financial and technological resources have led to differences in the development trajectories of innovative, sustainable technologies (Praetorius et al., 2010). Also, considering the role of TIS analysis as a tool for informing policy development and implementation, an additional issue can arise through the limited transferability or reproducibility of specific supportive frameworks. The second issue is related to the initial development of the concept of technological innovation system as a critique of territorially limited innovation systems (Oinas and Malecki, 2002; Bergek et al., 2015). A spatially delineated innovation system carries the analytical challenge of recognising existing interactions in the form of structural couplings across different geographical locations, which are playing an ever-increasing role in supporting the development of TIS in a globalized world (Binz et al., 2014; Markard et al., 2015).

The fourth exemplary type of interaction concerns the relations between the focal TIS and the broader political context; a type of interaction that is recognised to be key to large-scale transformation processes (Lawhon and Murphy, 2012; Geels, 2014;

Markard et al., 2015; Geels et al., 2016). The importance of political processes and political power is also reflected in a number of TIS functions – for example, guidance of the search, market formation, availability of resources, creation of legitimacy/counteracting resistance to change (Hekkert et al., 2007, 2011), legitimation and development of positive externalities (Bergek et al., 2008) are all dependent to some extent on a supportive institutional environment and the creation of supportive policies and clear goals by policy-makers (Negro et al., 2007, 2008; Hudson et al., 2011). Interactions between a focal TIS and the political context also include a spatial dimension, manifested in differences between national socio-political contexts and institutional frameworks (Praetorius et al., 2010; Lovio and Kivimaa, 2012). The influence of the socio-political context on the development prospects and development speed of a technological innovation system can be quite dramatic – an example are the different approaches to renewable energy development in Sweden, with a cost-optimization, technology-neutral political discourse, and Germany where the dominant political discourse is pro-technology, resulting in technology-specific policies and closer and more direct cooperation between technology proponents and policymakers (Bergek et al., 2015). While the role of politics in shaping the environmental discourse, which plays a major role in enabling sustainable transition processes, has been recognised and reviewed for quite some time (Haajer, 1995, Freeman and Louca, 2002), increased attention of transition scholars towards political contexts and political power is a more recent development (Lawhon and Murphy, 2012; Geels, 2014, Bergek et al., 2015; Markard et al., 2015; Geels et al, 2016).

2.6.4 Future challenges for the Technological Innovation Systems approach

For nearly a decade since the start of development of the Technological Innovation System approach and its application as analytical tool (Markard et al., 2012; Markard et al. 2015), it has been subject to frequent criticism related to the conceptualization and applicability of the approach . While the majority of the criticism was related to the initial purpose of TIS as a tool for evaluating the structural and functional performance of innovative technologies, and as a source of recommendations for policymakers (Hekkert et al., 2007; Bergek et al., 2008; Markard et al. 2012) some of the it was also related to the conceptual connections and practical usability of the TIS approach within the broader concept of Sustainability Transitions Research (Markard et al., 2015).

In the following paragraphs, the author will draw on a recent publication concerning key criticisms of the TIS approach (Markard et al., 2015) in order to identify and discuss current and future challenges, and extend the synthesis by insights from related research strands within the field of Transitions Studies (Smith and Raven, 2012) and conceptual proposals on joint models (Markard and Truffer, 2008; Walrave and Raven, 2016). Following is a list of the six areas of criticism as identified by Markard et al. (2015):

1. Relationship between the TIS and context
2. Delineation of a TIS
3. Lack of spatial dimension in the TIS approach
4. Usefulness of TIS approach for studying transition processes
5. Incorporation of politics into TIS research
6. Limits for policy recommendation by TIS analysts

The relationship between a focal TIS and different context structures (Bergek et al., 2015) has been discussed by the author in depth in a previous section, and therefore will be only briefly summarized here. A number of authors have highlighted an “inward-oriented” focus of the TIS approach, criticizing a lack of attentions towards the system’s environment (Markard and Truffer, 2008; Smith and Raven, 2012). Consequently, approaches for extended contextual analyses linking the system with other analytical constructs (sectors, regimes, niches, landscape) and context structures have been proposed (Markard and Truffer, 2008; Wirth and Markard, 2011). This issue has been acknowledged and addressed by TIS scholars, with recent work focusing on the development of a typology of context interactions (Bergek et al., 2015).

Criticism regarding the delineation of a TIS focuses on the analytical choices a TIS analyst must make before implementing a structural and functional analysis (Bergek et al., 2008). The question of system delineation, and the challenges it poses for both the analyst and the subsequent interpretation of the analyst’s work has been discussed previously in a broader innovation system context (Carlsson et al., 2002). Key challenges related to system delineation concern the definition of a technology, or knowledge field (Carlsson et al., 2002; Bergek et al., 2008), the identification of relevant/key actors (Carlsson et al., 2002; Hekkert et al., 2011) and the spatial delineation (i.e. drawing the geographical boundaries) of a focal TIS (Binz et al., 2014; Bergek et al., 2015; Coenen, 2015; Markard et al., 2015). While there are usable and detailed analytical approaches for tackling the above-mentioned delineation challenges (Bergek et al., 2008; Hekkert et al., 2011), the delineation of a focal TIS is finally in the hands of the analyst; as such, it is recognised to be ultimately dependent on the analyst's skills and research aims (Markard et al., 2015).

The relationship between the focal TIS and spatial aspect is discussed both as part of defining the challenges for TIS development (Markard et al., 2015) and within the context of a broader, Transitions-wide discussion on the geography of transitions (Späth and Rohracher, 2010; Coenen and Truffer, 2012; Markard et al., 2012). On the one hand, the spatial dimension of a TIS is defined by the analytical choices made by a researcher (Bergek et al., 2008; Coenen, 2015), while on the other the geographical context of a TIS, to an extent independently of the ultimately chosen borders, can include both location-specific and global institutional and structural couplings which can influence the development and functionality of the observed system (Coenen and Truffer, 2012).The latter issue subsequently creates a risk that the researcher may disregard foreign or global factors which influence the development of the system (Binz et al., 2014), or reduce the comparability of development and transferability of recommendations made for a specific TIS which may be based on location-specific institutional and structural context (Coenen and Truffer, 2012).

Another point of criticism relates to the usability of the TIS approach for studying transition processes – while the approach is considered one of the main research strands within the broader field of Transitions studies (Markard et al., 2012) it was initially designed for the analysis of emerging technologies, focusing on the (sustainable) innovation and the supporting system elements rather on the interaction of the system with other socio-technical systems – niches, regimes or the broader socio-technical landscape utilized in other frameworks, such as the multi-level perspective (Markard and Truffer, 2008; Geels, 2011; Smith and Raven, 2012). Markard et al. (2015) recognize three main aspects of the criticism of the viability of TIS to analyse transition processes: firstly, the approach is criticised for a lack of consideration of the internal structures and dynamics of incumbent, established systems (Geels, 2011) which the emerging technology needs to challenge in order to initiate wider socio-technical system change (Geels, 2004; Raven, 2006; Smith and Raven, 2012). Secondly, TIS is criticized for lack of consideration of external interactions with other socio-technical systems at different stages of development (Markard and Truffer, 2008; Wirth and Markard, 2011; Smith and Raven, 2012), a point which has been reviewed in the broader discussion and typology development for TIS-context interaction undertaken by Bergek et al. (2015), but still requires further consideration and potential conceptual extension of technological innovation systems towards either broader contextual perspectives or the development of joint models including elements from other Transitions frameworks (Markard and Truffer, 2008; Walrave and Raven, 2016). Thirdly, the framework is criticized for lacking a clear theoretical foundation with regards to the role of actors, agency and drivers of change (Kern, 2015).

The next major criticism of the technological innovation systems approach reflects a broader discussion in the Transitions field on the role of politics and political power in enabling, resisting and steering transition processes (Shove and Walker, 2010; Lawhon and Murphy, 2012; Geels, 2014; Markard et al., 2015). This criticism is partially related to the comments on the inward-focused nature of TIS analysis (Markard and Truffer, 2008; Smith and Raven, 2012), which highlight the risk of disregarding external causes for inducement and blocking factors influencing the performance of an observed system (Bergek et al., 2008). While the framework does include political aspects in the form of the legitimation (ibid.) and counteracting resistance to change/legitimacy creation (Hekkert et al., 2007) function, this is not seen as sufficient due to potential political influences manifested as resistance by incumbent system actors (Markard and Truffer, 2008; Geels, 2014) and pervasive influence of politics on other functions, such as market formation (Kern, 2015) or the availability of resources, particularly financial resources. The role of the political context with regard to the development of a TIS is thematised by Bergek et al. (2015), who include the political context in the proposed typology of TIS-context interactions; the need for further advancement in this field is nevertheless suggested by authors (Markard et al., 2015; Kern, 2015).

The final challenge for the TIS framework is based on the second main function of the approach – the provision of policy recommendations related to the support of emerging technologies, and management of identified hindering factors (Bergek et al., 2008), systemic failures (Klein Woolthuis et al., 2005) and barriers to further diffusion and development (Markard et al., 2015). Two main areas of criticism are identified – the focus of TIS-derived policy recommendations on a specific technology or technology field, which is chosen by the analyst as part of the system delineation process (Bergek et al., 2008; Markard et al., 2015). Bening et al. (2015) argue that there needs to be at least some form of justification on the analyst's side regarding the desirability of a particular technological solution. In the broader context, the TIS framework is often applied to sustainable or "green" technologies such as biogas (Negro et al., 2007, 2009); hydrogen and fuel cells (Suurs et al., 2009); microgeneration (Praetorius et al., 2010; Hudson et al., 2011) or biofuels (Lovio and Kivimaa, 2012) the underlying, but not clearly justified assumption being that such technologies are societally desirable. The second criticism relates to the practical applicability of recommendations made by TIS analysts (Bening et al., 2015), with recommendations often seen as being too broad or generic in order to be effective in specific implementation contexts. Markard et al. (2015) posit that while the latter could be potentially counteracted by researchers developing plans of action and concrete, specific policy recommendations, such a course of action would place the academic within a broader political and academic debate, which could influence the outcomes and shape of the proposed programme.

2.7 Research gaps and challenges addressed in this work

In this section, the author will summarize a number of research gaps and challenges proposed by scholars, which will be addressed in the course of this research. After identifying the challenge, the author will outline a potential approach to extending the available knowledge, subsequently, a more detailed discussion on the findings of this work and the proposed theoretical implications will be provided in the discussion chapter.

2.7.1 Reviewing the niche typology

At present, Transitions research strands utilizing the micro-level niche concept recognize and discuss four potential niche types: technological niches (Kemp et al., 1998; Raven et al., 2006), market niches (Levinthal, 1998; Schot and Geels, 2008; Smith, 2008), policy niches (Ieromonachou et al., 2004) and research and development (R&D) niches (Raven, 2006). However, in empirical applications the niche concept is often used to delineate a more general “protective space” (Caniëls and Romijn, 2008a; Adamides and Mouzakitis, 2009; Coenen et al., 2010; Verbong et al., 2010; Verhees et al., 2013; Smith et al., 2014). While this is certainly sufficient for studies on niche-regime dynamics and niche-internal functions, the author is of the opinion that a review of different niche types would benefit research on niche development by investigating connection between niche types and stages of development, following concepts proposed by Raven (2007), Schot and Geels (2008), Raven and Geels (2010) and Smith and Raven (2012). In addition to contributing to existing knowledge on niche-level development, a review of niche typology would add towards theoretical understanding of the conceptual relationships between the different analytical constructs utilized in Transitions Research. Here, the author would focus on the connection between analytical approaches based on the innovation system concept, in particular the technological innovation systems (TIS) approach, and the niche-regime-landscape concept utilized in the multi-level perspective, building on an initial proposal for an integrated framework by Markard and Truffer (2008) .

2.7.2 Investigating transition pathways in multi-regime transitions

Based on the multi-level perspective (MLP), transitions scholars have described the different types of change processes and niche-regime interactions through a typology of transition pathways (Geels and Kemp, 2007; Geels and Schot, 2007) which was further refined and reviewed by Geels et al. (2016). While the described typology presents a good conceptual groundwork for the analysis of transition processes focusing on a single regime interacting with one or multiple niches (ibid.), there is scarce coverage of transition processes in which one or multiple niches interact with more than one regime. A second research strand investigates multi-regime dynamics in transition processes (Raven and Verbong, 2007), but focuses on the dynamics and outcomes of inter-regime interactions (Konrad et al., 2008) and cases of niche technologies crossing regime boundaries in the course of innovation journeys (Raven and Verbong, 2009). The author aims to address the gap between these two strands of research by addressing commonalities between transition pathways and the different types of multi-regime interactions, drawing on insights provided by the chosen empirical case (combined heat and power (CHP) technologies, which interact with both the UK electricity regime and the heating (gas) regime). An attempt will be made to discuss a niche – multi-regime transition utilizing the existing pathway typology, as well as the different proposals put forward for in-transition pathway shifts (Geels et al., 2016). Further on, the author will review the necessity of extensions or additions to the current typology in order to account for potential specific dynamics characteristic for the observed multi-regime type of transition process.

2.7.3 Reviewing approaches for integrated frameworks

The necessity for investigating and developing conceptual connections between the multiple analytical frameworks currently utilized by Transitions scholars with the aim of exploring complementarities has been recognised as one of the major lines for future enquiry in the Transitions Studies field (Markard and Truffer, 2008; Markard et al., 2012). The author will attempt to respond to this call for action by investigating conceptual connections and potentials for further development of an integrated framework combining analytical concepts utilized in the multi-level perspective with the innovation system concept, which was proposed in a study by Markard and Truffer (2008) with related complementarities investigated by Wirth and Markard (2011). In a sequence of analytical steps, the author will first undertake a TIS analysis of the CHP knowledge-field based innovation system in the UK national context, followed by a niche-based analysis drawing on the multi-level perspective (Geels, 2005), insights into multi-regime interactions (Raven and Verbong, 2007, 2009) and niche functions discussed within Strategic Niche Management (SNM) (Kemp et al., 1998; Raven, 2006; Smith and Raven, 2012).

While the above-mentioned proposal for an integrated framework put forward by Markard and Truffer (2008) can be used as the basis for the planned approach, it is still necessary to discuss its potential advantages and disadvantages. One major advantage of the approach, which is also discussed in subsequent chapters, is the ability of the approach to provide multiple points of view on the focal case, varying between a meso-macro perspective for the TIS analysis and a micro-meso perspective for the niche-based analysis. In a sense, instead of choosing one set point of view for the analysis, the author will be able to vary between a top-down and bottom-up observation, in a sense using triangulation methods to verify and extend the gained insights.

The second advantage of the combined approach is to counteract perceived weaknesses of the different approaches and combine their strengths – while the TIS analysis can be quite useful to review a system's internal structure and the fulfilment of internal functions, the requirement to clearly define a system boundary (Bergek et al., 2008) limits the observation of (external) context (Markard et al., 2015) including socio-technical regimes, the landscape (Markard and Truffer, 2008) and/or other TIS influencing the focal TIS (Wirth and Markard, 2011). A niche-regime respectively MLP-based approach, on the other hand, enables the researcher to include a larger number of external analytical constructs (Kemp et al., 1998; Geels and Schot, 2007) and review the dynamics between external constructs (Raven and Verbong, 2009). On the other hand, niche-internal processes, especially nurturing processes are recognised to be well represented in a TIS analysis (Smith and Raven, 2012).

The third discussed advantage is tied in with the first two, and relates to the specific case observed in this thesis, which can be defined as a technology used in a number of application niches that are interacting with two separate regimes. Therefore, in order to broaden the scope of the analysis the analyst needs to make sure to include not only niche-internal and niche-regime dynamics, but also inter-regime relationships that might have indirect positive or negative effects on the technology. While utilizing a TIS approach can help to gain knowledge about the technology observed as an innovation system, incorporating niches as analytical constructs will allow for a more precise review of the barriers faced by technology proponents in specific application fields. Using both types of analysis simultaneously will also allow the researcher to identify relationships between the specific niches, and between the niches and the broader technology system (Markard and Truffer, 2008). Finally, in order to identify and address inter-regime relationships the multi-regime interaction typology will be applied (Raven and Verbong, 2009), which allows to identify the type of interaction between the two observed regimes and then subsequently analyse any side-effects of this interaction on the observed technology. While there is an alternative approach to investigating external context, using the TIS-context conceptualization put forward by Bergek et al. (2015), the multi-regime interaction approach has the advantage of treating the observed regimes as analytical constructs on their own, simplifying the conceptualization and analysis of internal relationships that have no direct effect on the focal technology.

Having discussed the advantages of the approach, the author would like to briefly summarize the expected disadvantages. The primary disadvantage of utilizing a combined approach lies in the use of multiple different analytical constructs, which are observed using two separate analytical approaches. This can result in both conceptual overlaps and discrepancies between findings, in particular where separate analyses of a single real-world factor result in differing outcomes. While the former issue is solved to some satisfaction by Markard and Truffer (2008) who have discussed the possibility of co-existence of TIS, niches and regimes in the same analysis, the latter can create problems regarding the interpretation of information. To circumvent this, a researcher could prioritize certain parts of both approaches in cases of results overlaps, relying on the individual strengths identified above – i.e. the TIS approach could be used to review the internal structure and functions of the observed system, while a niche-regime approach could be utilized to analyse the relationships between the niches and regimes, and between the regimes themselves. In a second step, the results from the other analysis would be used to verify and strengthen the results.

Through discussing and contrasting the findings of both analyses, the author will review the complementarities of the TIS and MLP/SNM approaches, and by extension execute an empirical application of the Markard and Truffer (2008) integrated framework. At the same time, the parallel review of what is essentially an ongoing transition process will provide some empirical insights into the discussion about the applicability of system-based approaches for reviewing transitions, which has been discussed and critically reviewed by multiple authors (Geels, 2011; Smith and Raven, 2012; Markard et al., 2015).

2.8 Chapter summary

In this chapter, the author has provided a brief overview of two analytical approaches utilized in the broader field of transition studies: Strategic Niche Management and the concept of niches as protective spaces, and the Technological Innovation Studies approach. While reviewing the approaches, further concepts from Transitions Studies, particularly from the Multi-Level Perspective were outlined in order to highlight the conceptual similarities and differences forming the basis for discussions on the interchangeability of these approaches (Markard et al., 2012, Smith and Raven, 2012) and the possibility of joint frameworks (Markard and Truffer, 2008; Wirth and Markard, 2011).

Drawing on existing criticism of both approaches and proposed future challenges to their further theoretical development and practical application, the author highlighted three research gaps in the final section of this chapter: the benefits of a review of the niche concept and niche typology used in Transitions Studies; potential issues associated with the application of the current transition pathways typology (Geels et al., 2016) in multi-regime transitions; and a call for using integrated analytical frameworks drawing on several Transitions concept in order to improve the understanding of real-life transition cases. The first two gaps will be developed into research questions in the next chapter, while the call for implementation of integrated framework will be answered in a broad sense through this project in its entirety, by using both SNM and TIS insights in order to analyse and discuss the case of combined heat and power technologies (CHP) in the UK.

3 Research Questions, Research Design and Methodology

This chapter will address the research approach, outline the research instrument and the chosen methods. It will start by defining the research paradigm and discussing the research philosophy behind this work. In further steps, the author will outline the research design, set out the main research question and the supporting sub-questions, and outline the research instrument that will be utilized in chapters 5 and 6 of this thesis. At the end of the chapter, the author will discuss the methods applied, and provide an overview of the data collection undertaken for the purposes of this project.

3.1 Research Paradigm

In any form of research, particularly in the field of qualitative research, the design, implementation and interpretation of research is guided by the philosophical stance taken and represented by the researcher. This stance is referred to as a paradigm, and defined as a basic set of beliefs through which action is informed and guided (Cresswell, 2007). This is especially important in social studies due to the strong need and possibilities for interpretation, which are inherent to studies of human behaviour and social functions. The necessity to rely on, and generate context-dependent, subjective knowledge is further amplified by the caution on the inability of social science to generate general, context-independent theory (Flyvbjerg, 2006),hence the researcher's decision to deviate from a positivist approach and allow for far greater levels of freedom in setting the context, meaning and scope of constructs and (inter)actions with social actors.

In undertaking this research project, the author understands the main concepts of (market, technology or other) niche, socio-technical regime and (technological) innovation system as primarily social constructs closely bound to one or more technological artefacts in a configuration that fulfils a certain function while adhering to technological, societal and cultural requirements. Niches, regimes and systems are to a large extent shaped and defined by sets of beliefs, rules, heuristics and configurations created, developed and reproduced by a group of actors with direct or indirect interests in the technology central to the construct and/or the successful fulfilment of the function for which this particular technology is intended. In the case of sustainable niches, the focal point of interest is related to more sustainable performance, which creates additional complications due to the common good nature of sustainability (Geels, 2010). As the rules and regulations are both enforced and reproduced by the actors involved, they are undergoing a permanent process of negotiation and re-structuring, during which individuals' subjective meanings and understandings play a decisive role (Cresswell, 2007). Change happens over long time periods, and is characterised through repeated variation and selection processes followed by retention of functional constructs and elimination of less successful ones. Due to the actors' internal beliefs, understandings and guiding principles, the variation and selection processes are characterised by local search patterns and satisficing, instead of optimizing search functions, aiming for the cost-effective solution instead of the functionally best one (Nelson and Winter, 1982). While the difference between the regime concept and system concept was discussed in the previous chapter, the author would like to revisit some of the key differences between the two outwardly similar analytical constructs (Markard and Truffer, 2008). The first key difference is in the material dimension of systems. Compared with the (narrower) definition of regimes as sets of shared, embedded rules (Geels, 2004), the technological innovation system definition always includes tangible elements: actors, actor networks, technical infrastructures and the focal technology (Hekkert et al., 2011), the latter being observable as a single product, a group of products or a knowledge field (Bergek et al., 2008). The second key difference relates to the role in the innovation process – the system encompasses both the innovation and production stages (Hekkert et al., 2007), while the regime stabilizes existing structures and enables incremental changes for its incumbents (Geels, 2005; Geels et al., 2016).

Further elaborating on the issue of change, the chosen approach regards all elements of an investigated system as changeable: entities, their attributes and events can change in meaning over time, influenced by changing perceptions and interpretations by actors. Temporal order plays an important role in the observed phenomena, and differences in the sequence in which events are played out can, and does, influence the outcomes (Poole et al., 2000). In general, this research project follows the traditional approach that links transitions research, particularly the Multi-Level

Perspective on social and technical transitions, to evolution theory and social constructivism/interpretivism (Geels, 2005, 2010; Geels and Schot, 2010). This overlap is made possible through structural similarities between the two fundamental assumptions: the presence of agency and (actor) creativity, rules and resources and the shared focus on processes and development over time (Geels, 2005), in particular.

On the chosen empirical case of CHP, the overlapping approaches are reflected in the authors allocation of niche and system/regime actors as the main causal agents driving socio-technical change. The understanding of actors about reality in the context of CHP development and diffusion is informed by their subjective perceptions, and interpreted using an inductive approach (Cresswell, 2007, Bryman and Bell, 2015) drawing on subjective information gained from actor interviews. While observing incumbent regimes, their interrelations and the generated selection environments, the author draws on the evolutionary causal mechanisms of variation, selection and retention (Geels, 2005). Further on, the researcher will observe processes of interaction between CHP actors and their relationships with regime actors, taking into account a number of specific contexts operationalized in form of the CHP application niches. The addition of a system-based approach in the form of the planned TIS analysis does not represent a departure from the chosen paradigm, on the contrary, the researcher will draw on the research subjects' perception of system structures and functions (based on processes), and the actor interaction and normative processes guiding their development and operationalisation.

As a final point, the researcher would like to reflect on the viability of CHP to be considered a coherent technological innovation system in the understanding of TIS literature despite the broad range of technologies applied in CHP schemes, differences in resource use related to the scale of the project, and the heterogeneity of the industry in the UK[4]. While all of these points are certainly valid, CHP is operationalized as a technological innovation system based on a knowledge field rather than a single technology or a group of technologies as the focusing device of the technology, following Bergek et al. (2008). Therefore, CHP is not defined through any specific technology or type of engine (Russell, 2010) but through the principle of

[4] A detailed overview of CHP in the UK, as well as an historical account of the technology's development and diffusion based on previous studies is provided in Chapter 4 of this thesis

co-generation i.e. the simultaneous generation of electric power and (usable) heat in one process (Weber, 2014). By delineating the focal TIS in this way, the author includes all different technological variants of co-generation and schemes of different sizes while at the same time creating a common denominator on which the analytical construct is focused. The second justification for the delineation of CHP in the UK as a TIS is related to its spatial dimension: in this analysis, the geographical borders of the observed system are identical to, and limited by, the political and legal borders of the United Kingdom and the reach of UK policies and regulations. This second distinction is even more important in this context: despite the difference in technology, scale and scope, all cogeneration schemes within this system are understood as CHP schemes in the UK institutional context. While an UK CHP TIS might not exist in reality, this is not required for an analysis to be viable, (Bergek, 2008).

3.2 Research Design

The role of a research design is to provide a framework for the collection and analysis of data, with the choices made by the researcher establishing the order of priority assigned to the different data and conceptual dimensions of the research project (Bryman, 2012). While designing the project, the researcher will make decisions on the methodology used while conducting the research; the timeline within which the project will be implemented as well as the order in which the individual methodological and analytical steps will be addressed; the sample population and the origin of the primary sources; the way in which the required data will be collected and analysed (Wisker, 2008). A good research design will ensure that the project, as well as any findings originating from it, will meet the most prominent criteria in the area of social research: reliability, replication and validity. Reliability is concerned with ensuring that the results of a study are repeatable, which can be ensured through using consistent measures. Replication relates to the ability of other researchers to replicate the findings of a study[5], while the criterion of research validity is concerned with the integrity of research findings and research projects (Bryman, 2012).

This research project is designed as a qualitative-dominant mixed methods study, combining research methods from the qualitative tradition, while using a combination of qualitative and quantitative data. Concerning data weighing and data quantity, the study cannot be considered a full mixed methods approach according to Cresswell's (2006) typology of mixed method designs and is rather meant to be a dominant / less dominant design with qualitative data being the dominant category and quantitative data mainly used to supplement and validate information extracted from qualitative data analysis. Data triangulation techniques will be used throughout the study for validation and cross-referencing (Yin, 2009 and Bryman, 2012). Regarding the replicability of results in this research project it however needs to be highlighted that the underlying theoretical approaches are regarded to be typological theories, used to

[5] The criterion of replication is very common in the natural sciences and in experimental research designs but not used often in the social sciences; nevertheless, there should be a general aim of maintaining replicability especially when conducting case studies due to the quasi-experimental nature (Yin, 2009)

identify patterns developed out of specific and potentially non-replicable economic-societal configurations instead of cause and effect relationships (Geels, 2010).

The researcher intends to use a case study approach as the main research method in this project. A case study is defined by Cresswell (2007) as an in-depth extended exploration of one or more bounded systems (cases) while using multiple sources of information. Yin (2009) describes the case study as an observation of a contemporary phenomenon in a case where the boundaries between phenomenon and context are unclear. Further on, the case study inquiry benefits from guidance and orientation through previously developed theoretical propositions. Within the context of this research project, the case in question is the historical and contemporary development of CHP technologies within the geographical and political boundaries of the United Kingdom, observed through and informed by the theoretical framework of Transition Studies and especially the schools of Strategic Niche Management and Technological Innovation System (TIS) studies. The observed phenomena are the processes, structures and dynamics taking place at the micro-level of the observed system in application niches; on the meso-level within the technological innovation system formed by these niches and associated, supporting institutions and actors; and between the micro- and meso-level by observing the interactions between niche functions and system functions. Finally, the researcher will take into account the wider environment of the observed system, defining additional analytical constructs in the form of interaction of socio-technical regimes with the focal technological innovation system, and with additional interactions taking place between the regime and the system-internal niches. Focusing at the relationship between theory and the research process and the aims of using a certain research method, case studies can be used both in deductive and inductive research (Bryman, 2012) for generating new theory (Eisenhardt, 1989) and testing existing concepts (Flyvbjerg, 2006). In this case, the researcher will use an inductive approach by entering the case studies with a "clean slate", gathering information and using the analytical findings from single cases to support or challenge the theoretical concepts that are used as grounding for the research project.

Both Yin (2009) and Flyvbjerg (2006) note the existing assumption that case studies, especially when using only a single case, lack the scientific rigour needed for formal generalization. The author intends to address and tackle this criticism by using falsification as the main testing method for the theory generated by the researcher and through use of multiple cases within the research design. While the former testing method is recognised as one of the most rigorous tests for a scientific proposition (Flyvbjerg, 2006), the latter ensures an increased level of replicability analogous to conducting multiple experiments in the realm of natural science (Yin, 2009).

Following Yin's (2009) case study design typology, the case will be designed as a multiple-case embedded design following a longitudinal approach (Bryman and Bell, 2007). The objective is to describe and analyse the context of CHP development in the UK by reviewing its historical development and providing an in-depth study of the present situation by examining several cases from different user groups that utilise the technology. A longitudinal analysis will be used to review the history of the technology's application in the UK, while the individual cases will be reviewed over their individual lifetimes, focusing on the period since 2000 if the case's lifetime is longer than 15 years. The longitudinal case design is recognised as a standard approach within Transition Studies (Smith et al., 2014) due to its suitability for describing a historical process and providing multiple, repeated insights into the development of a system through a sequence of events along a timeline (Verhees et al., 2013). In order to provide insights into the present-day situation, several cases will be selected by means of a purposive sampling method so as to ensure the chosen cases are relevant to the research questions and investigated theories (Bryman, 2014). The sampling strategy will follow the maximum variation approach (Flyvbjerg, 2006). The objective of this is to obtain a wide range of information (Cresswell, 2007) across a number of cases of varying sizes (defined through power output) and user groups (defined by varying areas of application and selection environments). The idea of different end-user groups separates CHP users in general into district and communal heating networks (CHP-DH); single site applications in industrial/commercial sites and public buildings; and micro-generation in private households[6]. The concept of maximum variation will be further pursued in the

[6] Industrial/commercial single site CHP schemes are defined by the utilization of cogeneration outputs (heat and usable power) on a single site, and range from large-scale schemes in refineries and paper mills, to small commercial units providing heat, power and sometimes cooling for a single store, such as the Tesco CHP units. Public single site CHP also provides services for a single site, but the site is primarily in public ownership, or provides a public

replication logic arising from multiple cases, where the aim will be to ensure theoretical replication, i.e. prediction of contrasting findings from the individual cases based on reasons expected by the researcher (Yin, 2009).

Each case study will focus on one particular application of CHP technologies within one of the identified application areas, with the case defined through the main actors involved in the application – depending on the project type - this will allow for covering of multiple geographical locations. After obtaining permission from the project manager(s), the case study will start by reviewing available secondary data on the project, which will inform the case outline. In the second step, the researcher will identify potential gaps in the generated knowledge, and will conduct a number of semi-structured interviews with key actors involved in the observed project, all of which will follow a central interview guideline. The number of interviews will depend on the richness of the initially available information, the number of key actors active on the project, and the availability of actors.

The second, parallel, stage, will see the author undertake a series of expert interviews with "elite" actors (Kvale, 2007) representing different positions within the broader field of combined heat and power technologies, defined for the purposes of this stage as a CHP-based technological innovation system. Interview participants will be chosen using a snowballing sampling method (Bryman, 2007), with an initial pool of contacts from different sectors being asked to participate in the study and being asked to propose further contacts who might make significant contributions.

It should be noted at this point that, while the research project is designed as a dual-stage enquiry, both stages will be run concurrently, and data will be collected and analysed simultaneously. In order to ensure replicability and comparability of the observed cases, within the limits allowed by the qualitative tradition (Bryman, 2007; Kvale, 2007), all case studies and interviews will follow a set approach outlined above, regardless of when they will take place.

function (hospitals, leisure centres, universities). Domestic micro-generation concerns the use of CHP units in single households, with the output used in a single housing unit.

The following figure illustrates the above-described research design and highlights the data collection methods and information flows between the different stages of the research project.

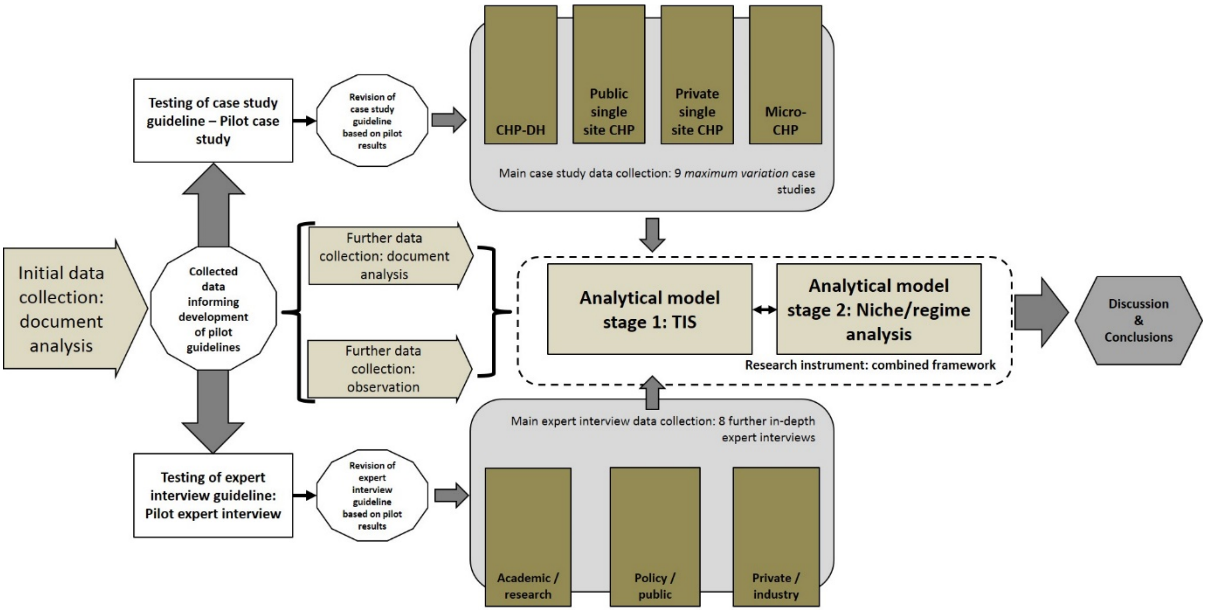

Figure 4: Outline of the research design

The initial data collection, conducted through a document analysis, will be used in order to inform two pilot guidelines for the case studies and expert interviews, which will then be trialled on a pilot case study and one or more pilot interviews. Feedback from the trials related to the practical applicability of the guidelines and the usability of the collected data will then be used to revise the guidelines and respond to any observed errors or inefficiencies. Following the revision, the author will initiate the main data collection phase, consisting of a series of case studies (the first stage outlined above) and a series of expert interviews (the second stage outlined above). At the same time, the document analysis will be continued, supported by data gathered through observation at CHP-related conferences and other events. The collected data will then be used for the two analytical stages of the chosen research instrument, outlined later in this chapter.

3.3 Research Questions

The main research question of this thesis can be summarized as follows: "*Do transition theories focused on innovation system analysis and niche-regime interactions provide useful insights into the development of CHP in the UK as an example of a sustainable technology transition?"* In answering this question, the author is focusing on theoretical insights from Transition Studies in order to develop an analytical framework within the specific case of CHP in the UK can be assessed. This includes the operationalisation of the analytical constructs niche, regime and technological innovation system in order to reflect the real-life development and implementation of cogeneration technologies, and the utilization of system and niche function typologies, transition pathways and inter-regime interactions in order to analyse the interaction between technology supporters, incumbent actors and agency by incumbents that might have unforeseen negative side-effects on the viability of CHP. The author is not testing the theories in a direct way, but rather utilising them as a framing device in order to gain empirical knowledge on the chosen case, some of which can be reflected back onto existing theory with the aim of reviewing and broadening current understanding. In order to facilitate a more structured approach in addressing this question, and sufficiently address the theoretical background as well as the empirical enquiries, the author has further split the research question into several sub-questions. These sub-questions set the main directions of the enquiry, and represent specific areas of interest within the context set by the overarching question; they are described and briefly discussed below:

The first sub-question belongs to the empirical dimension of the project, and attempts to investigate the *socio-technical factors, barriers and developments which have influenced the peculiar development of CHP technologies in the UK*. Compared to other North-West and Central European countries (Raven and Verbong, 2007, 2009; Weber, 2014), diffusion and development of CHP technologies in the UK took place at a significantly lower rate, with CHP taking a far smaller role in the national energy mix. A number of previous studies observed this phenomenon utilizing numerous different perspectives (Russell, 1986, 1993, 2010; Babus'Haq and Probert, 1996; Brown and Minnett, 1996; Toke and Fragaki, 2008; Weber, 2014) and/or observing specific application areas for CHP, such as district heating (Hawkey, 2009, 2012, 2014; Kelly and Pollitt, 2010), domestic micro-generation (Hudson et al., 2011) and single site industrial, commercial and residential applications (Hinnels, 2008). This research project extends upon the findings of these studies by focusing on the present-day situation of CHP, extending the scope of the reviewed studies, where the observed period ended in the 1990s (Russell, Babus'Haq and Probert, Brown and Minnett) or 2000s (other authors). Further on, the author will attempt to review CHP across a broader range of application areas, while the focus of the majority of the above-mentioned studies was on a specific application area, mostly CHP in district heating schemes. Considering the theoretical approach, the author will utilize conceptual models and analytical approaches from Transition Studies research field. While Transitions approaches have been used in previous studies on CHP in the UK (Hudson et al., 2011; Hawkey, 2012) and CHP developments in other localities (Raven and Verbong, 2007, 2009), the two-stage approach applied by the author extends the scope of the data that can be analysed by drawing on niche-regime and inter-regime dynamics, in addition to the system-based perspective used by Hudson et al. and Hawkey. From an empirical point of view, the aim of the author is to identify internal and external barriers, but also fulfilled and blocked system and/or niche functions in order to provide insights to other CHP researchers and CHP developers, and advice on potential „problem areas“ which are currently restricting or blocking the diffusion and development of the technology.

The second sub-question aims to *investigate and discuss the niche typology* utilized in the multi-level perspective (MLP) (Geels, 2002, 2004; Schot and Geels, 2008) and in Strategic Niche Management (SNM) (Kemp et al., 1998; Raven, 2006; Smith and Raven, 2012), discussing the four niche types currently identified by researchers (technology niche, market niche, R&D niche, policy niche). As outlined in the discussion on research gaps in the previous chapter, the author intends to extend the micro-meso-macro level delineation characteristic of both MLP and SNM towards an innovation system perspective, utilizing a conceptual framework combing the MLP with the Technological Innovation Systems (TIS) approach which was proposed by Markard and Truffer (2008). By reviewing the case of CHP in the UK from a (multi-)niche perspective as well as from a system perspective, the author hopes to explore conceptual similarities as well as connections between niches and TIS at different stages of development. Additional line of enquiry is aimed at *exploring the behaviour* *of niches in advanced stages of development*, following proposals on niche development strategies by Raven (2007) and niche development trajectories by Schot and Geels (2008). Drawing from a single, albeit rich, case, this question is based on an inductive approach; the author acknowledges that outcomes including proposed changes to the niche typology will require additional investigation before moving past a conceptual stage. CHP can be conceptualized both as a single niche, interacting with the energy and heating regimes, or as a group of niches defined by specific application areas within an overarching innovation system. The author has opted for the latter approach, while simultaneously taking into account the different development levels of the individual application niches relative to each other and relative to the overarching system, as well as the individual and joint relationships of the niches with one or both regimes.

Finally, the third sub-question focuses back on the specific development of CHP in the United Kingdom, investigating the diffusion and development of the technology from the perspective of transition pathways (Geels and Kemp, 2007; Geels and Schot, 2007; Geels et al., 2016). The author will review the applicability of the current pathways typology (Geels et al., 2016) to the case of CHP in the UK, taking into consideration the multi-regime interactions that cogeneration has with the electricity and heating regimes, and any effects of inter-regime dynamics between the two incumbent regimes. From a theoretical point of view, the latter will draw on research by Raven and Verbong (2007, 2009) and Konrad et al. (2008) who have investigated multi-regime and inter-regime dynamics in the Netherlands and Germany. The main focus of this sub-question will therefore be *whether the pathways typology can be applied in a multi-regime context, and whether the pathway observed for cogeneration in the UK might warrant a proposal for an additional type of transition pathway*. In a broader transition context, the multi-regime case of cogeneration is expected to yield additional insights for this type of transition, adding to the currently dominant single niche – single regime type of review. The empirical relevance of this sub-question is connected to the expected insights into the effects of regime-level developments, particularly policies, on a technology which simultaneously interacts with, and is influenced by the two regimes with partially different institutional frameworks. As both observed regimes are parts of a larger, overarching UK energy system, the author expects the findings to be potentially useful to developers and policymakers in creating strategies for the development of CHP as part of the broader shift towards a low-carbon energy system (DECC, 2009). Further on the recommendations and results may also be applicable for other high-efficiency and/or sustainable technologies interacting with multiple regimes.

All three sub-questions will be discussed in depth in the Discussion and Findings chapter, which will also include a detailed summary of the author's theoretical findings, contributions to the different concepts outlined above, limitations and suggestions for further enquiry. While the empirical findings will form an important point of the Discussion chapter, practice-oriented conclusions and recommendations to policy-makers will be developed in a separate appendix, providing a clearer separation between the theoretical and empirical contributions and allowing for easier reading for industry or public sector readers of this thesis. This type of separation will also align with one of the original purposes of the Technological Innovation Systems approach, which is to provide suggestions for policy developers and industry actors (Bergek et al., 2008; Hekkert et al., 2011; Markard et al., 2015).

3.4 Research Instrument: a combined framework for observation of multi-level sustainable transitions

Following up on the explorative character of this research project, the research instrument will be based on a conceptual framework initially proposed by Markard and Truffer (2008) combining a technological innovation system (TIS) analysis with the socio-technical regime and niche concepts used in the multi-level perspective approach (Geels, 2002, 2004). The utilization of a combined analytical approach allows for the combination of a system-centric perspective (Markard et al., 2015) focusing on the internal structure and fulfilment of internal functions of a meso-level analytical construct (Markard and Truffer, 2008), and a bottom-up perspective focusing on the role of external contexts, materialized in the form of regime-generated selection environments (Smith and Raven, 2012). Further on, the application of the joint approach allows the researcher to combine the advantages of the TIS analysis in describing *system-internal* functions and system structures with the increased role of external, contextual structures and couplings in the MLP/SNM approach, addressing an important point of criticism towards the TIS analysis (Markard and Truffer, 2008; Markard et al., 2015). By including multiple external constructs of the electricity and heating regimes, it will not only be possible to simulate the real-life interactions of CHP with both regimes caused by its dual-output nature, but also to investigate inter-regime relationships and their effects of the diffusion and development of the focal technology, using a typology proposed by Raven and Verbong (2007, 2009).

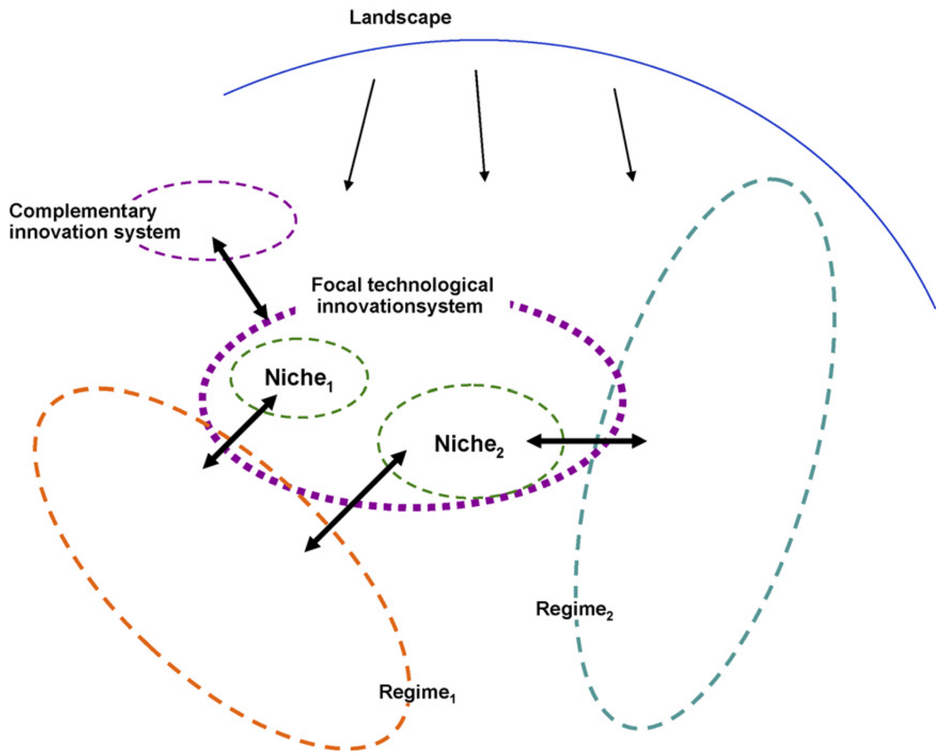

Figure 5: Conceptual model for the interaction of a TIS with the elements of a multi-level framework (Markard and Truffer, 2008)

In order to improve the representation of the observed exemplary case of combined heat and power technologies in the UK, this model in this thesis was further extended by adding additional analytical steps. These focus on developments on micro- and meso-level, as well as on the interaction between micro-level niche actors and meso-level regimes and associated selection environments (Kemp et al., 1998; Raven, 2006; Smith and Raven, 2012; Verhees et al., 2013) which might impede, but potentially also induce niche developments. On the micro-level, the model focuses on niche-internal developments summarized in the concept of *niche empowerment* proposed by Smith and Raven (2012). Further on, the researcher intends to outline and describe the different niches with the goal of observing their position within the focal TIS. On the meso-level, the researcher will attempt to define the selection environments created by the regimes through an analysis of external inducement and blocking mechanisms for the development of the TIS and its niches and, in a secondary step, assess the nature of inter-regime interactions following a typology put forward by Raven (2007a).

While analysing both the functions provided by the TIS and the properties of the individual niches carry a risk of repetitiveness, it is expected that not all functions will be of equal importance for an individual niche. On the other hand the structural and functional analysis of the TIS will return more than a mere sum of the niches it is comprised of, including additional institutions stabilizing the TIS or actors such as industry associations or government agencies who do not engage in the niche context (Markard and Truffer, 2008) as well as the impact those institutions and actors have on the system functions. In addition to this, taking on a bottom-up, niche perspective will provide the researcher with the opportunity of adding a micro-level, practitioner perspective to the TIS analysis by observing the TIS structure and function fulfilment within a practical context.

Below is a visual representation of the extended conceptual model, applied for the case of CHP technologies in the United Kingdom; the individual analytical units and steps of analysis are then described in detail.

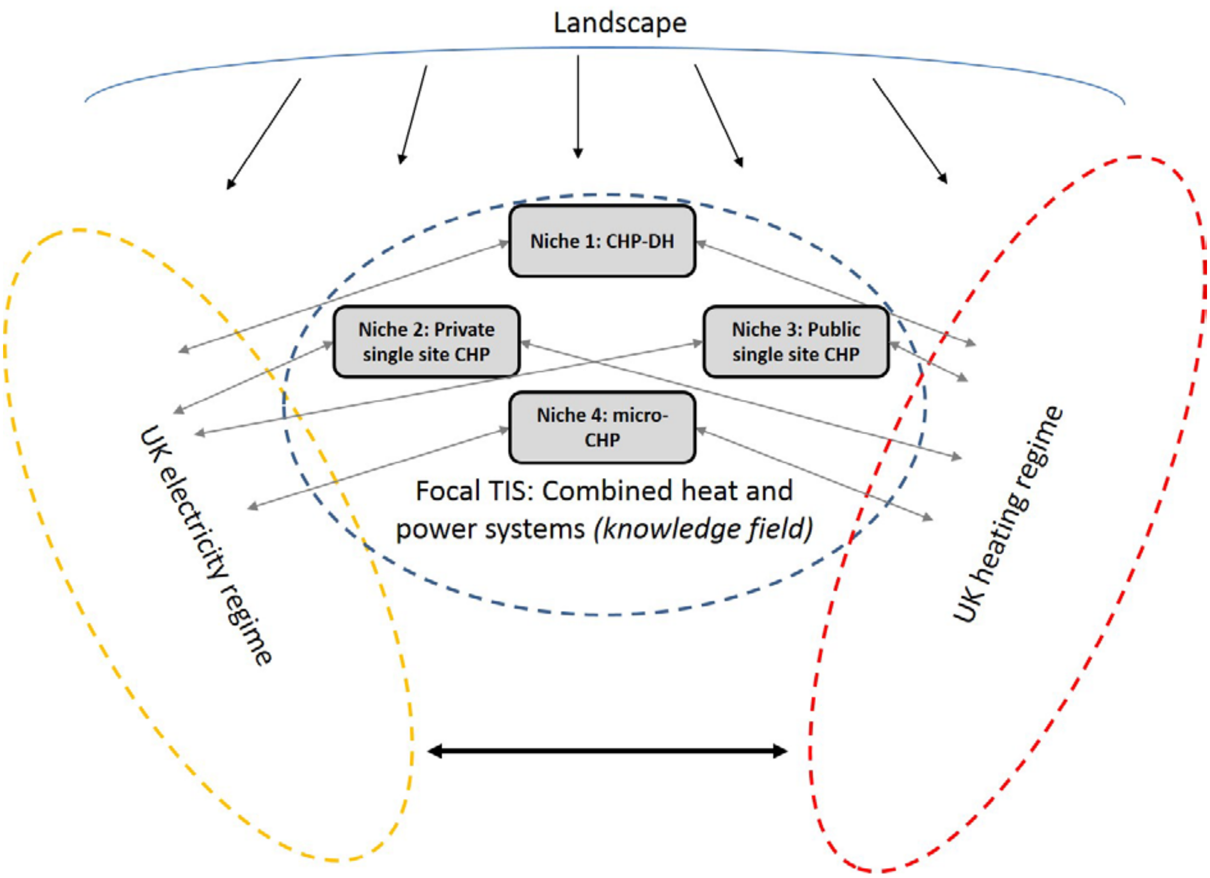

Figure 6: Conceptual analytical model for the analysis of the UK CHP system (Based on interaction model proposed by Markard and Truffer (2008) and further adapted by researcher)

The focus of the research is related to the three sub-questions stemming from the main research question as outlined above, and will therefore focus on the CHP technological innovation system, observing its internal structure and performance through structural and functional analysis (Bergek et al., 2008; Hekkert et al. 2011). The system's interactions with the incumbent regimes are investigated both on a niche level, observing the niche-regime interactions (Raven, 2006; Smith and Raven, 2012; Verhees et al., 2013) and through a review of external barriers to further development of the innovation system (Bergek et al., 2008; Hekkert et al., 2011). Within the context of niche-regime interaction, the researcher will observe the development and protective properties of the niches themselves, centred on shielding, nurturing and particularly empowerment (Smith and Raven, 2012), and the functions of the focal TIS (Hekkert et al., 2011) supportive to niche development. The niches are outlined as distinctive application areas for CHP and will be empirically described further on in this work: CHP in district heating networks (CHP-DH in the above visualization), industrial CHP, smaller commercial CHP, public sector CHP and domestic CHP microgeneration (micro-CHP).

The observed regimes are defined as the heating (gas) regime and the electricity regime and will be examined in the context of creation of supportive or blocking mechanisms (openings) for the development of the observed TIS, its niches and the diffusion of the focal technology as outlined further above. Taking into account the conceptual similarities between the regime concept used in the multi-level framework (Geels, 2002) and the concept of technological innovation systems (Hekkert et al., 2007; Bergek et al., 2008) the researcher expects to observe some of these dynamics through the TIS analysis. However, in order to complete the application of the conceptual framework a separate review of inter-regime interactions will be undertaken.

Below is an overview of the focal and supporting analytical constructs outlining the scope of the constructs, their level of aggregation, the analytical steps involved and the role (focal or supporting/secondary) of the construct within this research project.

Name	**Scope**	**Aggregation level**	**Steps of analysis**	**Role**
CHP Technological Innovation System	Based on the knowledge field *"co-generation of heat and power"* within the geographical borders of the UK, includes several distinct application areas (niches)	Medium	**Structural analysis** *CHP actors* *Networks* *Institutions* *Technological factors* **Functional analysis** *Fulfilment of system functions*	Focal

			Analysis of (system-)internal barriers **Analysis of external blocking mechanisms**	
CHP-DH niche	Applications of CHP technologies within district heating networks	Medium/small	**Functional analysis** *Fulfilment of niche functions*	Focal
Private single site CHP niche	Applications of CHP technologies in privately owned/operated schemes with heat and/or electricity provided to a single site	Medium/small	**Barrier analysis** *General barriers to CHP* *Niche-specific barriers* **Functional analysis** *Fulfilment of niche functions*	Focal
Public single site CHP niche	Applications of CHP technologies in public single site schemes	Small	**Barrier analysis** *General barriers to CHP* *Niche-specific barriers* **Functional analysis**	Focal

			Fulfilment of niche functions	
(Domestic) micro-CHP niche	Application of CHP technologies for domestic micro-generation of heat and power	Small	**Barrier analysis** *General barriers to CHP* *Niche-specific barriers* **Functional analysis** *Fulfilment of niche functions*	Focal
UK electricity regime	Actor networks, rules, knowledge and infrastructures fulfilling the societal function of electrical energy provision in the United Kingdom	Medium	**Analysis of regime-generated barriers** using typology proposed by Kemp et al. (1998) and Smith and Raven (2012) **Observation of inter-regime interactions with heating regime**	Supporting
UK heating regime	Actor networks, rules, knowledge and infrastructures fulfilling the societal function of provision of	Medium	**Analysis of regime-generated barriers** using typology proposed by Kemp et al. (1998) and Smith and Raven (2012)	Supporting

	heating in the United Kingdom		**Observation of inter-regime interactions with electricity regime**	
Landscape	Wider socio-economic, geographical and political national, inter-national and global context	Large	No direct observation, effects of landscape changes taken into account where appropriate	Supporting

Table 9: Overview of analytical constructs used within the model

3.4.1 Technological Innovation System Analysis

In the first analytical step, the researcher will undertake structural and functional analysis of the focal technological innovation system following the analytical approaches put forward by Hekkert et al. (2007, 2011) and Bergek et al. (2008). At the beginning of the analysis, the researcher will delineate the focal TIS, choosing the central focusing device, defining the breadth and *depth* of the observed system and outlining the system's spatial boundaries (Bergek et al., 2008). In doing so, the researcher will set out the boundaries of the analysis, essentially defining the *unit of observation* for this stage (Yin, 2014). Further on, it will allow the analytical distinction between *system* and *system environment*, important for setting the observation limits of the following analytical step (Bergek et al., 2015; Markard et al., 2015)

Having delineated the object of investigation, the researcher will then commence the structural analysis of the focal system, following analytical guidelines set out by Hekkert et al. (2007) and Bergek et al. (2008) and further refined by Hekkert et al. (2011). The structural analysis will consist of four main steps, starting with identification and describing the relevant system actors; followed by the review of the actor networks; relevant institutions and concluded by a discussion of the key underlying technical factors. In the research logic of a TIS analysis, structural delineation is a necessary preparatory step for the core focus of the analysis: a functional review of the focal technological innovation system (Bergek et al., 2008).

In the third step of the analysis, the researcher will run a functional analysis focusing on the seven core functions of TIS as defined by Hekkert et al. (2011), which in itself represents a slightly abridged version of the TIS core functions defined in the analytical approaches proposed by Hekkert et al. (2007), Bergek et al. (2008) and a comparison by Markard and Truffer (2008). While the functions were explored in more depth in the literature review section, the following table serves as a comprehensive overview including a list of indicators which can be used to assess the performance and fulfilment of the individual functions, as well as a list of analytical questions which will be used by the researcher during the planned expert interviews.

Function	**Indicators *(based on Hekkert et al., 2007, Bergek et al., 2008 and Hekkert et al., 2011)***	**Analytical questions *(based on Hekkert et al. 2011)***
F1 Entrepreneurial experimentation and production	- Number of new entrants - Number of diversification activities of incumbent actors - Number of different types of applications - Breadth of technologies used - Number of experiments with new technology	Are the identified actors the most important ones? Are there sufficient industrial actors in the system? Do the industrial actors innovate sufficiently? Do the industrial actors focus sufficiently on large scale production? Do entrepreneurial activities and production form a barrier for the further development of the system?
F2 Knowledge development	- R&D projects - Number of patents - R&D investments	Is the amount and quality of present knowledge sufficient for

		further development of the system? Does the knowledge developed meet the system knowledge needs?
F3 Knowledge exchange	- Number of workshops and conferences - Size and intensity of (research) network - Bibliometrics (citations, volume of publications, orientations)	Is there enough knowledge exchange between science and industry? Is there enough knowledge exchange between users and industry? Is there sufficient knowledge exchange across geographical borders? Are there any issues in the system related to knowledge exchange?
F4 Guidance of the search	- Specific targets set by government or industries - Number of articles in professional journals - Articulation of interest by key customers - Extent of regulatory pressures	Is there a clear vision about how the industry and the market should develop (in terms of growth and technological design)? What are the expectations from this technological field? Are there any clear, reliable policy goals regarding the technology? Are the visions and expectations of actors sufficiently aligned?
F5 Market formation	- Number of niche markets	Is the current and expected market size sufficient?

	- Niche market networks - Specific institutional stimuli for the observed technology (tax, incentives)	Does the size and/or stability of the market form a barrier for the further development of the system?
F6 Resource mobilization	- Physical resources (infrastructure, material) - Human resources (availability of skilled labour) - Financial resources (volume of capital, investments, venture capital, subsidies – *see also F5 Market formation*)	Are there sufficient physical resources in terms of material? Are there sufficient physical resources in terms of available infrastructure? Are there sufficient financial resources in terms of venture and seed capital, investments and available subsidies? Are there sufficient human resources? Does the lack of any of these resources hinder the further development of the system?
F7 Counteract resistance to change/legitimacy creation	- Number of lobby groups - Number of lobby group action - Average duration and success rate of projects from application to full operation	Is there sufficient lobbying activity supporting the technology? What is the average length of a project? Is there a lot of resistance towards the new technology from institutional actors/from the regime?

Table 10: List of TIS functions (Hekkert et al., 2007, 2011)

Throughout its development, a system will go through several phases, starting from a formative phase and progressing towards a growth phase (Bergek et al., 2008). At the same time, the level of aggregation of the system will increase, with developing systems exhibiting medium levels of aggregation, while more mature systems will show high levels of aggregation, the focal technology being used in multiple application contexts (Markard and Truffer, 2008). The development phase of the observed system can be determined by examining key functions typical for a particular phase. Hekkert et al. (2011) have extended the initial development typology through observing system development over four distinct phases: pre-development, development, take-off and acceleration. The importance of system functions varies depending on the development phase of the observed system, and allows observers to indicate the current phase by focusing on the fulfilment of the key functions. The following table provides an overview of the system development phases used in this analysis together with a list of key functions for each development phase.

System development phase	Key functions
Pre-development	F2 Knowledge development F3 Knowledge exchange F4 Guidance of the search
Development	F1 Entrepreneurial experimentation and production F2 Knowledge development F3 Knowledge exchange F4 Guidance of the search
Take-off	F1 Entrepreneurial experimentation and production F6 Resource mobilization F7 Counteracting resistance to change / legitimacy creation
Acceleration	F1 Entrepreneurial experimentation and production F5 Market development F6 Resource mobilisation

Table 11: Overview of system development phases and key functions

After reviewing the fulfilment (or lack thereof) of the system functions, the researcher will investigate the focal system for system failures and the presence of functional barriers and cases of negative fulfilment of system functions which can manifest themselves as “vicious cycles”, where negative fulfilment of a function causes decreased fulfilment of other functions, ultimately slowing down or even stopping development of the focal system (Hekkert et al., 2008). Once the barriers and vicious cycles have been identified, the system structure will be analysed for structural causes, related to actors, networks, institutions or technologies, and the relationship between these causes and the barriers/cycles will be described along with a list of proposals for improvements (Hekkert et al., 2011). The structural causes can be related to unorganised actors or lack of communication, weak or underdeveloped networks (a network analysis investigation of the relationship between network strength and successful transitions has been undertaken by Romijn and Caniels (2008)), lack of institutional support (Bergek et al., 2008) or issues related to the development and performance of key technologies.

In the final part of this analytical step the researcher will extend the focus to the system environment in order to identify and analyse external inducement and blocking mechanisms. To this end, the researcher will review the selection environments created by incumbent regimes (Kemp et al. 1998) interacting with the focal TIS, as well as supportive or hindering factors created by landscape developments (Geels, 2002, 2004). The researcher will use visual mapping to illustrate the relationship between the system functions, internal structural barriers and external inducement and blocking mechanisms (Bergek et al.,2008) with a particular focus on the existing virtuous and vicious cycles. Finally, a list of potential policy measures will be developed with the goal of strengthening and developing positive cycles and inducement mechanisms and breaking up negative fulfilment cycles as well as reducing the strength of blocking mechanisms.

3.4.2 Niche analysis

In the second analytical step, the researcher will focus on the micro-level of the observed system by investigating the five identified distinct application contexts or niches. Following a wider consensus in Transitions studies[7], niches are identified as distinct application areas with selection environments differing from mainstream regime selective pressures (Kemp et al., 1998; Markard and Truffer, 2008). They serve as experimental arenas for nurturing and testing promising, yet immature, technologies, initially at an experimental level in the form of technological niches and later as more mature market niches (Schot and Geels, 2007). The main aim of this step is to observe niches within the focal system through comparing the fulfilment (positive and negative) of niche functions with the results of the functional analysis of

[7] While the concept of a *niche* is reasonably similar throughout Transitions approaches, the main definitions will be drawn from Strategic Niche Management (SNM) and the Multi-Level Perspective (MLP).

system functions undertaken in the previous step. Within the second step, the researcher will also compare the selection environment with the external barriers and inducement mechanisms relevant for the TIS. This approach will add micro-level observations to the meso-level TIS analysis, allowing the researcher to assess the functionality of the focal system by using a bottom-up perspective. It will also allow for testing the theoretical concept of a TIS composed of multiple niches that act as testing and development arenas and as proto-markets and niche markets, with the TIS as a whole offering additional functions beyond the actor-network structures, institutional arrangements and functions offered by the niches (Markard and Truffer, 2008).

The researcher will use data from the Technological Innovation System analysis, as well as data gathered from a series of exemplary case studies across all observed niches in order to first evaluate the development stage of the individual niches and then to analyse the different functions provided by them within the context of them being parts of the focal innovation system and operating within its general functions and performance while interacting with incumbent regimes. Conclusions about the development stage of a niche will be reached on the basis of the fulfilment and quality of the functions it provides, together with its level of alignment with the selection environment provided by the regimes and the system. This can be followed back to the assumption that, in transitions theory, niches are created through and defined by their functions, processes and internal dynamics (Schot, 1998; Kemp et al., 1998; Raven, 2006; Smith and Raven, 2012). Therefore, according to the SNM approach the niche needs to provide for three key functions. Firstly, a certain level of policy-based, societal and/or geographic protective function. Secondly, a series of internal dynamics including the creation and maintaining of social-technical networks, internal and external first and second order learning and knowledge transition processes, shared articulation of expectations, development trajectories and storylines, all of which are aimed at nurturing the niche technology (Geels and Raven, 2006; Raven, 2006). And finally, empowerment processes (Smith and Raven, 2012) aimed at enabling continued survival of the technology after the eventual dismantling of the niche (Kemp et al., 1998).

This typology has been further refined by Smith and Raven (2012) who have subdivided niche functions into the processes of shielding, nurturing and empowering. Shielding can be further subdivided into active and passive shielding (Smith et al.

2014). In theory, empowering processes within niches are separated according to their position towards the incumbent regime and selection environment into fit-and-conform and stretch-and-transform processes (Smith and Raven, 2012). Recently, however, the validity of such a clear distinction is being questioned, with the emergence of evidence of actors in embattled niches who use a rather ecletic mix of both process types and react to changes in the selection environment rather than follow a set strategy (Verhees et al., 2013). This warrants for the inclusion of an additional type of empowerment, which is best characterised as pragmatic. Nurturing processes within a niche are aimed at increasing the niche cohesion through establishment of social networks; supporting articulation and sharing of expectations; and supporting first- and second-order learning processes (Kemp et al., 1998; Smith and Raven, 2012).

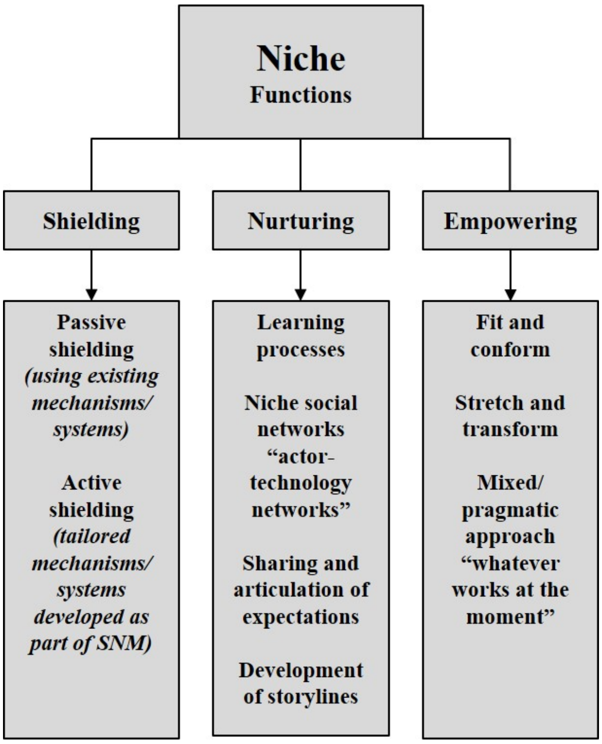

Figure 7: Overview of observed niche functions

The focus of this observation is examination the relationship between the niche functions and the functions provided by the innovation system, specifically in terms of their interchangeability, alignment but also identification of key differences. Following the observation by Markard and Truffer (2008) that TIS is composed of several niches, but that it is also more than the sum of their parts, because of the presence of additional actors, institutions, as well as due to generation of functions on a level above individual niche development, it can be expected that the identified functions of the TIS will, to an extent, differ from the combined functions provided by all niches. Finally, some of the niche markets extend outside the focal TIS, such as domestic micro-CHP which is also a part of the "Domestic micro-generation technologies" system and can interact with other TIS, as well as with regimes which are not in direct contact with the focal TIS (Markard and Truffer, 2008). Those niches can serve as vital knowledge exchange arenas and might open the possibility for alternative development trajectories for the focal TIS (Raven, 2007; Bergek et al. 2008).

The table below presents a theoretical comparison of niche-level functions with TIS functions and indicates areas of potential overlaps:

Niche function (Smith and Raven, 2012)	**TIS function (Hekkert et al., 2008, 2011)**
Shielding *(passive/active)*	F5 Market formation F6 Resource mobilization F7 Counteracting resistance to change / legitimacy creation
Nurturing	
Learning processes	F1 Entrepreneurial experimentation and production F2 Knowledge development F3 Knowledge exchange
Creation of networks	TIS structure – actors and networks F3 Knowledge exchange F5 Market formation
Sharing and articulation of expectations / development of storylines	F1 Entrepreneurial experimentation and production F4 Guidance of the search
Empowering	F4 Guidance of the search F7 Counteracting resistance to change / legitimacy creation

Table 12: Comparison of TIS functions and niche functions

The final step in the niche analysis process will see the analysis of the interaction of the niches with incumbent regimes close to the focal TIS, conducted by observing the relationship of niche and regime stability (Raven, 2006), strategies of niche actors related to the positioning of the niche towards the regime(s) (Schot and Geels, 2007) and different forms of empowerment employed by niche actors in order to either develop a symbiotic relationship with one or more regimes, or to challenge them with the goal of forcing regime change or transformation (Smith and Raven, 2012). Furthermore, the researcher will observe the regime-generated and landscape-generated barriers towards niche development and diffusion, and compare them to the external barriers identified during the TIS analysis. Furthemore, the researcher will compare inducing and supporting mechanisms to the inducing mechanisms identified earlier. In addition to observing the niche-regime interaction, the researcher will also observe inter-regime interactions (Raven and Verbong, 2007, 2009; Konrad et al., 2008) with the goal of investigating the type of these interactions, as well as any effects of the interactions on the selection environments generated by the regimes.

3.5 Methodology

In this section, the author will briefly outline methods of data collection and data analysis used in the course of this research project. In line with the research design, the data collection methods are well-established within the qualitative tradition (Kvale, 2007) and particularly in case studies (Yin, 2014). While there is some utilization of (secondary) quantitative data, qualitative data collection and qualitative analysis are taking a dominant role in this project.

3.5.1 Data collection

The two primary data collection methods employed in this study will be interviews (Kvale, 2007; Yin, 2014) and content analysis of secondary documents (Bryman and Bell, 2015). The use of multiple data collection methods is considered important in the tradition of qualitative enquiry (Cresswell, 2007), particularly in case studies (Yin, 2014), as it allows for data triangulation and cross-validation of collected data (Cresswell, 2007; Yin, 2014; Bryman and Bell, 2015). Considering the research paradigm utilized in this study, the subjective, actor-perspective dependent nature of interviews ties in with the actor-centric causality present in both social constructivism and evolution theory. The author will utilize semi-structured interviews for both expert interviews and case study interviews, with two separate sets of guidelines used depending on the interview setting (expert interview or case study) informed by the two main analytical approaches forming the joint framework, SNM and TIS (Bryman and Bell, 2015). Kvale (2007) defines semi-structured interviews as "…attempt(s) to understand themes of the lived daily world from the subjects' own perspectives. This interview seeks to obtain descriptions of the interviewees' lived world with respect to interpretation of the meaning of the described phenomena." The interviews will be conducted as *elite* interviews (ibid.), with the interview partners being renowned experts in their respective fields (in case of expert interviews), or actors in *elite* positions within their respective organisations or projects (*managers* of the different schemes reviewed in the case studies). The case study interviews will be conducted as single-sitting *shorter case study interviews* (Yin, 2014), taking the form of both factual and narrative interviews (Kvale, 2007), wherein the researcher will attempt to obtain factual information about the observed CHP scheme, as well as to review the interviewees' narrative on the case study history and their perception of different (external and internal) factors and events. In terms of duration, expert interviews will be slightly longer, and will primarily be used to gather both *factual* information (although from the particular experts' perspective) and uncover the expert's own perception of CHP-related structures, functions and mechanics.

For the observed CHP schemes, interview data will be supported by the researcher's direct observations from the site visits. This method is considered as one of the key sources of evidence for case studies (Yin, 2014).

In addition to the primary data collection outlined above, the researcher will also undertake a qualitative content analysis of academic and non-academic documents, including documentation and (where available) archival data on the observed CHP schemes and more general organizational and public documents on combined heat and power technologies; the electricity regime; the heating regime and the broader energy sector. Both public and organisational documents are recognised as primary sources of data for researchers (Yin, 2014; Bryman and Bell, 2015). The secondary data will be used as initial source for informing the development of the case study and expert interview guidelines, as well as throughout the research as a validation reference (Bryman and Bell, 2015).

3.5.2 Data analysis

In the course of this enquiry, the author will apply two main data analysis methods: theory-informed qualitative content analysis of the secondary (document) data and thematic coding of the primary (interview and observation) data.

Qualitative content analysis is considered a prevalent approach to the qualitative analysis of documents (Bryman and Bell, 2015), and focuses on the extraction of underlying themes and patterns from the analysed documents. For purpose of this thesis, the themes and patterns will be informed by the theoretical concepts underlying the joint framework, referring to niche-, regime- and system-level structures and dynamics. The author will particularly look for instances of niche-regime and inter-regime interactions, as well as the fulfilment of niche functions and system-internal functions (as well as the relationship between them).

All interviews will be recorded in the form of notes, with audio recordings made wherever possible and permitted by the interviewee. The audio recordings will be transcribed by the researcher. The transcription process is meant to structure the interview in a form that lends itself to closer analysis, while the process itself is considered to be the initial analysis (Kvale, 2007). The transcripts will then be subjected to a thematic coding process utilizing qualitative analysis software (QSR NVivo). Thematic analysis is defined as a method of identifying, analysing and reporting themes and patterns within data (Braun and Clarke, 2008). However, compared to a “pure” concept of themes and patterns “emerging from the data” (ibid.) the thematic analysis planned for this study will also be informed by the theoretical concepts underlying the utilized joint analytical framework in a manner similar to the content analysis outlined in the previous paragraph. It is worth noting here that the author’s intention is not to not to disrupt the narrative flow of the individual interviews, or prevent the emergence of new themes or patterns, but to use these concepts be primarily as guides in the process of data structuring and categorization.

Finally, both data sets will be cross-referenced and validated using data triangulation methods (Cresswell, 2007), corroborating evidence from different sources connected on an empirical level in order to increase its reliability. Particular attention will be given to patterns emerging in multiple repetitions; while single-occurrence patterns and themes will not be discarded outright, they will not be considered validated information unless the information source, or the circumstances under which the information was obtained, provide sufficient evidence for their validity.

3.6 Data sources

In a final sub-section of this chapter, the author will provide a brief summary of the data sources used in the course of research, reflection on their role in the data collection stages, and the relevance of the gathered data for either stage of the analysis. In total, the author has undertaken 10 case studies on applications of CHP technologies in different schemes, and 10 in-depth expert interviews with interviewees belonging to different sectors of the socio-economic system. These were supported by observations and notes gathered at five research, policy and/or industry conferences visited by the author over the span of 2.5 years. The conferences were chosen based on their relevance to combined heat and power and its applications, as well as based on the agendas and content of the conferences.

Both the data collection through CHP case studies, and the cogeneration expert interviews were preceded by one (case studies) and/or two (expert interviews) pilot studies/interviews which were used for the purposes of testing the interview guide (Kvale, 2007; Yin, 2014), gathering additional information informing further interviews/case studies and broadening the researcher's understanding of the observed field.

The figure below shows graphical presentation of the data gathering process based on the visual representation of the research design provided earlier in this chapter and showcasing the individual case studies and interviews categorized by the CHP application area (for case studies) and/or the expert's area of activity (for the expert interviews). A more detailed explanation of the data sources including a table listing, the individual case studies and interviews is provided below.

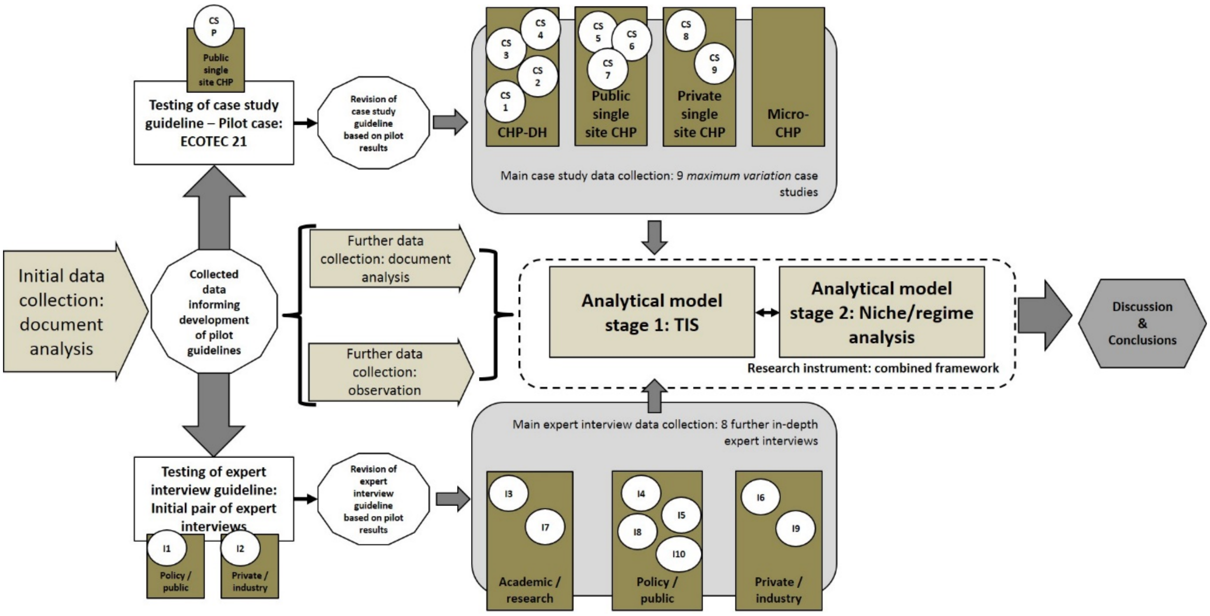

Figure 8: Overview of data sources

The 10 case studies were selected using the snowballing method (Bryman, 2007), with particular consideration given to the geographical location of the reviewed site, the availability of case-related documentation and interview partners. All 10 cases are located in the South-East and South of the United Kingdom, with 8 out of the 10 observed schemes located within the Greater London area. The table below provides a brief overview of the cases, with general information about the scheme, its application area, and the data types and data gathering methods employed for this particular thesis:

Case study #	Short description	Application Area	Data gathered
P (Pilot case)	CHP engine installed on university campus	Public single site	Documentation, Two interviews with actors co-developing the scheme
1	Planned CHP-DH scheme in SE London	CHP-DH	Documentation Interview with two actors leading on scheme planning
2	CHP-DH scheme in private development, Central London	CHP-DH	Documentation Two site visits Two interviews with actors managing the scheme
3	CHP-DH scheme in SE London	CHP-DH	Documentation Site visit Two interviews with actors managing the scheme
4	CHP-DH scheme in N London	CHP-DH	Documentation Interview with lead actor managing the scheme

5	CHP schemes in two hospitals managed by a single NHS Trust	Public single site	Documentation Brief interview with lead actor managing the scheme E-Mail interview with lead actor managing the scheme
6	CHP scheme in public leisure centre	Public single site	Documentation Site visit Two interviews with actors managing the scheme
7	CHP scheme in refinery	Private single site	Documentation Observation of manager presentation at industry conference
8	CHP scheme in plant nursery	Private single site	Documentation Site visit Interview with actor managing the scheme
9	CHP schemes in two office buildings	Private single site	Documentation Site visit Interview with two actors managing the scheme

Table 13: Overview of case studies

It can be seen both from the graph and the list that no case studies were undertaken for the application area of domestic micro-CHP. The main reason for this is scarcity of available actors due low level of diffusion of the technology, as well as logistical and ethical considerations arising from the private nature of these schemes and the necessity to interview non-expert, non-elite subjects in private environments. Ample availability of recent academic studies on micro-CHP (Cockroft and Kelly, 2006; Sauter and Watson, 2007; Allen et al., 2008; Hudson et al., 2011; Wright et al., 2014), government documents (DECC, 2011a, 2011b), as well as abundant information on micro-CHP gathered in the course of the expert interviews led to the researcher's decision to forego further attempts at securing a micro-CHP case study, and rely on the available data instead.

In addition to the case studies, the author has also undertaken a series of 10 in-depth expert interviews with experts from different areas, aiming to develop a broad, multi-viewpoint understanding of the CHP industry using a system-based perspective. The initial two interviews, undertaken in short order, were used as pilot interviews, with the rest of the interviews carried out over the span of one year, depending on interviewees' availability. Throughout the process the author relied on the snowballing sampling method, asking interviewees for further recommendations. The process was partially successful, particularly in the later stages of data collection. The following table provides an overview of the interviews, the experts' areas and the interview type:

Expert interview #	Interviewee	Organisation	Sector	Interview type, data collection method
1 (Pilot)	Policy Director, Interest Association	Interest association for CHP	Industry / Policy	Face-to-face interview, notes
2 (Pilot)	Director, CHP-related consultancy	Energy consultancy	Industry	Face-to-face interview, notes
3	Research Fellow (academia)	UK university	Academic	Skype interview, notes
4	Manager, public sector	Regional government	Public	Face-to-face interview, notes, transcript
5	Manager, public sector	Public sector company using CHP	Public	Face-to-face interview, notes, transcript
6	Manager, CHP consultancy	Consultancy specialised in CHP technologies	Industry	E-Mail interview, notes
7	Professor (academia)	UK university	Academic	Skype interview, notes, transcript
8	Manager, public sector	Local government	Public	Face-to-face interview, notes, transcript
9	Manager, industry	Company specializing in CHP	Industry	Face-to-face interview, notes, transcript
10	Policy officer, Interest Association	Interest association for CHP	Industry / Policy	Face-to-face interview, notes, transcript

Table 14: Overview of expert interviews

It can be seen from the table that while an audio recording and full interview transcript was not possible in all cases; all interviews resulted in the collection of rich, usable data. While the initial intention of the researcher was to extend the sample beyond 10 interviews, logistical consideration, as well as increased data repetition over the course of the final few interviews, led to the conclusion that a workable saturation point was reached.

3.7 Conclusion

In this chapter, the author has presented the reseach paradigm, design and methodology utilized in this study. Further, a research question was formed based on the identified gaps in the (theoretical) literature, as well as the practical questions related to the chosen empirical case. Following the social constructivist and evolution theory paradigms, the author remains within the broader paradigm utilized in Transition Studies (Geels, 2005, 2010). The combination of paradigms allows for simultaneous observation of evolutionary mechanisms (variation, selection, retention and extinction) and development trajectories over long-term cycles, and social interactions, sense-making and construction of rules and meaning at lower levels of aggregation. By choosing a case study approach, the author attempts to encompass the broad nature of the observed empirical case, observing a contemporary set of events over which the researcher has no control (Yin, 2014) and which are related to multiple layers of social interaction and accompanying phenomena. The choice of research design and research method also relates to the notion of conservativism with regard to the broader research field (Transition studies), where case studies and case histories are broadly and repeatedly utilized (Verhees et al., 2013; Smith and Raven, 2014).

Further, the author presents the research instrument, highlighting the planned analytical steps and establishing connections with multiple analytical approaches and theoretical concepts reviewed in the previous chapter. This is followed by a brief review of the chosen methodology, summarizing the author's choice of semi-structured interviews as the main primary data collection method, supported by theory-informed qualitative content analysis of gathered secondary data in the form of academic studies, public reports and documents and industry documentation. The chapter ends with a detailed overview of the data sources used in the course of research, with particular attention on the primary data sources – case studies of CHP schemes and expert interviews.

4 Setting the empirical context – a short history of CHP in the UK

In this chapter, the author will outline the empirical setting of the case observed in this study: the history and current state of combined heat and power (CHP) technologies in the United Kingdom. The chapter will start with a brief description of the CHP concept and the technological artefacts (engines) used for co-generation, followed by a summary of the history of combined heat and power in the UK drawing primarily on previous academic research (Russell, 1986, 1993, 2010; Babus'Haq and Probert, 1996; Hawkey, 2012, 2014), public sector reports (DUKES, 2009, 2014, 2015; Ricardo-AEA, 2013), scenarios (Barton et al., 2015) and industry case studies, and supported by data gathered by the author in the course of his fieldwork. As the main focus of this study is to undertake an evaluation of the current state and future prospects for diffusion and development of the technology in the United Kingdom, the purpose of this chapter is to acquaint the reader with the (technological) concept and set the context for the structures, functions and dynamics analysed in later chapters by providing a synthesized account of the history of CHP development.

In general, CHP technologies can be described as mostly incremental innovations with regard to the technological artefacts and a more radical innovation when observed on a system level due to the need for an at least partially decentralised energy generation system, which is incompatible with the current, centralised UK energy system (Toke and Fragaki, 2008). Looking at the first, incremental part, CHP technologies, oriented on decreasing energy waste (in the form of heat energy) and increasing fuel efficiency seem like a sensible choice of technology, one which wider diffusion was to be expected. However, even though diffusion of CHP happened to a certain degree in some developed European countries such as Germany and the Netherlands (Weber, 2014) and to an even larger degree in others (Toke and Fragaki, 2008), the technology saw, and still sees, fairly limited use in the UK (Russell 1986, 1993, 2010 and Weber 2014). Despite this, the technology never followed the example of other unsuccessful innovations and disappeared from the market, instead remaining present in some form for over a century since the first, experimental applications (Babus'Haq and Probert, 1996), forming relatively stable market niches in several industrial sectors (DECC, 2009) or being upheld and repeatedly promoted by niche actors as well as government initiatives in the case of CHP district heating systems (Hawkey, 2014). Those two developments, and the connections between them, make the story of CHP developments in the UK a remarkable and unique case.

4.1 The combined heat and power technological concept

Combined heat and power generation (CHP) is based on the principle of simultaneous generation (co-generation) of electrical energy and useful forms of heat (mostly in the form of low- or high-temperature steam) in the same exothermic process (Weber, 2014). Regarded as a proven and mature concept, first applications have been recorded around the turn of the 20th century (Russell, 1986., Kelly and Pollitt, 2010), although the technology has undergone multiple changes and improvements to its technological components, including prime movers (engines, turbines, etc.) and supporting technologies such as control systems in the meantime (Weber, 2014). More recent development have extended the principle towards tri-generation, with the system providing a tertiary function in the form of cooling or generation of CO2 in addition to the primary electricity and heating outputs; however, the majority of presently utilized UK CHP technologies are still based on a co-generation principle. The technology can be utilized in multiple settings, ranging from major industrial applications and communal heating schemes with an output of several hundred MWe to domestic micro-generation systems whose electric output can be as low as several or several dozen kWe (Department for Energy and Climate Change, 2015); while the historical main application area for CHP was communal heating (Russell, 2010; Hawkey, 2014) the current application range is much broader.

In the following paragraphs and chapters, the author will refer to CHP primarily as *"CHP schemes"*; this term includes the CHP prime mover or prime movers, supporting control systems and infrastructures such as grid connections and heat piping, as well as localized institutional arrangements regulating the operation of the technological components, and the delivery of the energy outputs to users.

Within the UK CHP sector, multiple types of prime movers and supporting technologies are utilized; the vast majority of them is based either on turbines or reciprocating engines, and is fuelled by non-renewable fossil fuels (90% in 2015), with only 10% of registered schemes utilizing some type of renewable fuel (Department of Energy and Climate Change, 2016). In the annual Digest of United Kingdom Energy Statistics (DUKES), the Department of Energy and Climate Change[8] recognises four principal types of CHP systems:

Steam turbine based systems which can use a number of different fuels, and generate high-pressure steam which is used for electricity generation, with excess steam being utilized as a heat source.

Gas turbine based systems which are often adapted from aerospace engines, where gas or gas-oil fuel is combusted in the gas turbine for power generation, with combustion gases captured and used in a waste heat boiler in order to produce (usable) steam

Combined cycle systems where more than one type of prime mover is utilized within the scheme – this can be any combination of gas turbine, steam turbine and/or combustion engine. This type of system is distinguished by a higher electrical efficiency and a lower heat to power ratio compared to turbine-based systems, but is mainly suited for large sites.

Reciprocating engine systems are based on repurposed automobile or naval engines and mainly use gas or diesel as a fuel source; they are of smaller size compared to the three other main system types, and are used in settings where hot water can be used instead of steam for heating purposes.

The four main, “conventional” types of CHP system are broadly considered to be proven and mature technologies, developed over long time periods and continuously improved through incremental changes (Kelly and Pollitt, 2010). Nevertheless, there is significant uncertainty within the energy sector and among CHP actors and supporters about the long-term prospects of the technology in face of increasingly stringent regulations, especially regarding emissions in urban settings, and a general uncertainty about the future of the UK energy sector (RTP Engine Room, 2015).

[8] The Department of Energy and Climate Change (DECC) was disbanded in July 2016 following the resignation of Prime Minister David Cameron and a re-constitution of a Conservative-led government under Prime Minister Theresa May; presently, the UK energy sector is within the remit of the new Department of Business, Energy and Industrial Strategy (DBEIS)

Ongoing technological development transcends UK borders, with innovative processes taking place in cross-national settings and CHP developers procuring technological artefacts from overseas; as an example, a significant proportion of CHP engines used in small UK schemes is produced in Germany.

While these four main “conventional” types of CHP systems comprise the majority of CHP schemes installed in the United Kingdom, a number of alternative CHP technologies has been proposed and tested. The best known of these are fuel-cell based CHP systems (Brown et al., 2007; Hudson et al., 2011), although alternative suggestions include solar-thermal CHP, Stirling and Rankine cycle engines (Cockroft and Kelly, 2006), bio-liquid engines (Ricardo-AEA, 2013) and nuclear reactors (Carlsson et al., 2012). In addition to these, there are also developments aimed at using alternative, often renewable fuel in existing technological artefacts – two examples reviewed in case studies by the author are the use of algae-derived glycerol in a diesel engine (system type 4) based CHP scheme, and the use of biodiesel derived from used cooking oil in a commercial CHP scheme. Not all of these technologies are considered to be developed and mature (Cockroft and Kelly, 2006), and they are mainly deployed as pilot projects and/or experimental research projects, or small-scale technology demonstration projects. Some of the technologies may be connected to other sectors; for example, fuel cells being utilized in transport applications, and bio-fuels used in CHP schemes can also be used for heating purposes or, in some cases, as vehicle fuel. The future applicability of these renewable or non-conventional CHP technologies is seen as dependant on the future development trajectory of the UK energy system, with particular technological solutions seen as applicable in one or more potential development scenarios:

“Unless we make a full transition of the fuel source away from fossil fuels to renewable sources, and that could be fuel cells, that could be hydrogen, hydrogen-derived from renewable electricity and blocks of biogas that could be injected into the grid and traded over biogas certification arrangements.” (Senior Manager, regional government)

“The fewer fossil fuels will be used, the lower the call for CHP will be; the exception to this is if a hydrogen-based economy will emerge.” (Director, energy consultancy)

“Biodiesel CHP is still problematic, I’ve been involved with some biodiesel project where the engine technology seems to struggle a little bit with the fuel itself, and obviously consistency of the fuel is a bit of an issue as well. Certainly there is no financial case for running a biodiesel CHP which at the moment is kind-of putting development of that technology on the back burner as far as I can tell.” (Sales Manager, specialist CHP company)

The current application areas for CHP systems range from domestic to large-scale industrial and heating applications (Russell, 1993; Hawkey, 2014), and in scheme size from several (dozen) kW to several hundred MW for the largest schemes. While historically the main application areas for cogeneration were district heating schemes (Russell, 1986; 1993; Hawkey 2009, 2012, 2014) and industrial CHP (Brown and Minett, 1996), recent developments have seen cogeneration schemes applied in a broad range of smaller-sized applications in the public and commercial sector. Within the public sector, CHP has been utilized on university campuses, hospitals, leisure centres[9] and wastewater treatment plants; with regards to private developments, hotels, smaller commercial sites with sufficient heat demands and supermarkets have been among the users of CHP schemes[10]. At the same time, industrial use of CHP units has entered a state of stagnation: while the formerly leading sectors such as the chemical and oil industry, the paper industry and the metal industry are still operating some of the largest sites in the UK (DUKES, 2016), their number has been slowly declining reflecting the general downturn in the UK industrial sector; at the same time, the uptake of (mostly smaller) CHP schemes in other sectors has increased by around 20% over the last six years (ibid.).

From a technological point of view, the implementation of CHP schemes follows a general outline: one or multiple prime movers are installed on-site (for most single site schemes) or within a designated energy centre (for district heating and multi-site schemes) and connected to the necessary infrastructure: some form of fuel supply, either through fuel tanks or a direct connection to the gas grid, an on-site or multi-site piping network for the provision of high- and/or low-temperature steam, and either on-site electrical wiring (described as *private wire* in the industry) or the National Grid. If

[9] Both a hospital and a leisure centre were reviewed by the author as case studies
[10] The author has reviewed a nursery site and an office building as case studies

the scheme is run as a tri-generation system, further infrastructure connections are required for the provision of the cooling (via heat exchangers) or an alternative tertiary output[11]. Control systems are either installed locally, or the scheme can be controlled remotely from a centralized control centre (the author was able to visit one such centre belonging to a specialized CHP company, which controlled around 450 individual schemes in the UK, Republic of Ireland and continental Europe). Once installed, a scheme's prime mover units have a useful service life of around 10-15 years, depending on the standard mode of operation (continuous, intermittent) and the specific type of prime mover utilized, although in practice some schemes have been in continuous operation for close to 20 years[12].

The scheme's mode of operation is usually dictated by the initial planning approach, which can be either heat-led (scheme size and operational requirements are set by the user's heat requirements) or electricity-led (scheme size and operational requirements are set by the user's electricity demand). However, in practice this choice often causes a paradox, which is described in the following interview excerpt:

"There is a paradox related to CHP scheme development and performance – the best CHP schemes are heat-led, but power production causes the need for CHP." (Director, energy consultancy)

In practice, this relationship between the on-site heat demand and the on-site electricity demand can cause operational issues for CHP users, particularly in cases where there is little or no possibility to store or sell off excess capacity. If the scheme is primarily electricity-led, a reduction in power demand will usually be managed by reducing the scheme's output, or shutting the scheme down altogether, in which case heat provision will also be interrupted. This can be avoided through the use of heat storage (Toke and Fragaki, 2008), usually in the form of water tanks, although for urban areas there are often operational restrains regarding the size and capacity of heat storage facilities. In the case of a heat-led scheme, the engines can be kept in

[11] One of the CHP schemes observed by the author as a case study utilized the CO2 generated by the (gas turbine) prime movers as a tertiary output; however, this is understood to be a very specific application type which is uncommon in the broader CHP industry

[12] Information provided to the author during a site visit to a CHP control centre operated by a specialized cogeneration company

continuous operation except for periodical maintenance interruptions; with excess electrical power being sold off through the UK capacity market. However, this option is not chosen in all cases due to significant entry barriers for small electricity generators, which can make selling electricity to the grid economically unfeasible. Another factor that needs to be taken into account by developers of heat-led schemes are seasonal differences in heat requirements – while this is not a problem for industrial schemes with constant heat demand or other schemes that require a consistent heat input, such as pools in leisure centres, it can become a relevant constraint for schemes in which the heat output is used primarily for the heating of domestic or public spaces, such as universities or communal heating.

4.1.1 Application areas for CHP technologies

In this section the author will illustrate a number of the most common application settings for CHP schemes in order to illustrate the breadth of applications for the technology, and showcase some of the more common scheme types. The list of application areas is not intended to be comprehensive as the creation of such a database would go beyond the scope of this research project due to the indication of a significant number of unique schemes; its aim is rather to provide the reader with a broad understanding of the multiple application options for CHP technologies, which will be helpful in setting the stage for the more in-depth analysis and discussion taking place in later chapters. It is also important to strictly separate the following account from an analytical typology of application niches proposed by the author later in the work – while the latter are analytical constructs developed by the author as part of a broader structural and functional review, the former list is a part of the empirical context-setting which is the central purpose of this chapter.

4.1.1.1 CHP in district heating networks

CHP technologies used as a power source for communal heating networks are one of the earliest and best-researched application areas for the technology (Russell, 1993, 2010), with CHP-DH applications being one of the two main application areas for the technology for the greater part of its history (Weber, 2014). In general, a mid- to large-sized cogeneration engine is used as the prime mover for a communal heating scheme

(Russell, 2010), with low-temperature steam (<90 degrees Celsius) conveyed to domestic heat control units and radiators through a pipework system (Brown and Minnett, 1996). Electricity is seen as a secondary output, and is mainly exported to the grid, although some CHP-DH schemes do have additional on-site private wire systems. The size of CHP-DH schemes can range from a few dozen buildings for a single development communal heating system, to several hundred or even thousands of homes in a larger municipal heating scheme (Hawkey, 2014). The CHP scheme is mainly operated by local authorities (ibid.) although more recently public actors have increasingly started deploying energy schemes through public/communal, private or public-private energy services companies (ESCo) (Hannon and Bolton, 2015; Bolton and Hannon, 2016).

4.1.1.2 CHP in large industrial single-site applications

The second historic application area for cogeneration technologies are large industrial sites, where constant heat and electricity demand create favourable conditions for the implementation of CHP schemes (Weber, 2014). Initially deployed both before and after the second world war (Brown and Minnett, 1996) industrial CHP is particularly prevalent in a number of industrial sectors where the nature of the core production processes requires constant and significant heat outputs, such as oil refineries, the chemical sector, paper, publishing and printing and food, drink and tobacco (DECC, 2016). Due to the high heat demand, industrial single-site CHP utilizes mid- and large-sized engines, ranging between approximately 4 and 50+ MWe (Green, 1996), which are connected to the industrial site through an on-site pipe network and a private grid system. The heat output is usually utilized on-site[13], while electricity overcapacity can be exported to the National Grid[14]. Operation and maintenance (O&M) of the schemes is often outsourced to specialized CHP companies, while the provision of heat and power is contractually regulated, with multiple types of arrangements possible. These arrangements range from a simple O&M contract in which capital investment is done

[13] A number of industrial sites in the UK have planned potential cooperations with local authorities on developing communal heating network; to date however the author has found little evidence on the operation of such schemes

[14] This was even more prevalent in the 1980s and early 1990s until the introduction of the NETA (New Electricity Trading Arrangement, later renamed into BETTA) in 2011 (Toke and Fragaki, 2008; Pearson and Watson, 2012)

by the industrial company operating the site, to contractual arrangements in which the CHP plant is owned and operated by the subcontracted specialized company, with heat and electricity sold to the site at pre-determined rates.

4.1.1.3 CHP in smaller commercial and public applications

The utilization of CHP in smaller commercial (non-industrial) application has taken up considerably in the last few decades, with the majority of installed schemes being in non-industrial applications (383 registered Good Quality CHP schemes in the industrial sector, 1719 registered Good Quality CHP schemes in other sectors (DECC, 2016)). The energy and heating capacity of the schemes is smaller than industrial or large district heating schemes (ibid.), with most schemes ranging between a few dozen kW and several MW electrical capacity; the upper limit being somewhere between the 4 MWe set as the lower limit for industrial CHP by Green (1996) and 6-7 MWe observed in one of the case studies undertaken in the course of this research project. Similar to CHP applications in the industrial sector, a constant electricity and heat demand is the prerequisite for the development of smaller commercial and public CHP schemes. These conditions are mostly met in the leisure, hospitality, health and education sectors, which account for the majority (1120 out of 1522) of non-commercial registered Good Quality CHP schemes (DECC, 2016). The relevance of these sectors as key users is also recognised by the cogeneration industry:

"So, DH NHS fantastic, as well as universities, very traditional CHP customers, we've been looking after since the 1990s. Leisure centres as well, so again, that's mostly public sector, but again one of the clear, obvious applications of CHP due to the high consistent heat demand. I mean it's always going to be a very good financial case there. Hotels, hotel sector, is again very high heat user, we've had contracts with Hilton and Marriott since the mid-90s, who've obviously (had) fantastic financial and carbon savings from CHP, and continue to do so now." (Sales Manager, specialist CHP company)

Further sectors with notable levels of commercial application of CHP include retail, especially large retail stores such as Tesco (who are a large customer for CHP developers, and have installed CHP units into most newly built retail stores), and office buildings where cogeneration systems are often installed for the purpose of reducing

CO2 emissions and fulfilling environmental/sustainability requirements set by local authorities and other planning authorities. The heat and electricity output of small scale CHP schemes is mainly used on-site, transported through internal piping and private wire systems. Some small commercial sites do export electricity or excess heat, but this is seen as the exception due to the existence of high market entry barriers for small-scale electricity producers (Toke and Fragaki, 2008). Operation and maintenance of the schemes is usually subcontracted to specialized CHP developers/energy consultants utilizing a range of arrangements similar to the arrangements for industrial CHP schemes described in the previous section. There is sporadic evidence of long-term commercial CHP users taking over scheme operation, mainly due to a combination of increased trust in the technology and financial factors:

"[the user] took an ESCO scheme out in the late 90s, and when that towards the end, that came, so that again ran for 5 years beyond its initial term, it's 15 years. But they, because they could see how CHP was performing in terms of their financial savings they decided to go, they bought their next set. So they didn't invest in going with ESCO but because they were now convinced how well CHP did produce financial savings they said, well OK, we have decided to take the risk now because we understand it and we're gonna buy these ones because we can realize better financial savings from purchasing ourselves." (Sales Manager, specialist CHP company)

4.1.1.4 Domestic micro-generation CHP

The final application area for combined heat and power technologies discussed in this work is the use of CHP engines for domestic microgeneration. While there is high potential for the utilization of domestic micro-CHP (Hinnells, 2008), the technology has been emerging rather slowly (Hudson et al., 2011), with slightly more than 600 domestic micro-CHP schemes installed in the entire UK (ADE, 2015). Domestic micro-generation CHP schemes are usually of small size, having a capacity between less than 1 kWe (Hudson et al., 2011) and ca. 4 kWe (Cockroft and Kelly, 2006) with the main output being heat for the building in which they are installed. A number of different engine types is used for micro-CHP units, with the most widely installed being natural gas or diesel fuelled Stirling engines or more conventional internal combustion units (Cockroft and Kelly, 2006; Sauter and Watson, 2007). A potential future type of micro-CHP units is being developed in the form of fuel call based micro-CHP (Hudson et al.,

2011) with some of the key developments taking place in the UK (Hinnells, 2008). While considered a potential future solution by the CHP industry, this type of CHP unit is still in an experimental development phase (Foxon et al., 2005). The heat output of the micro-CHP units is used on-site, while the electrical output is both used on site and exported into a national grid; the latter being regulated through a feed-in-tariff (FiT) (DECC); however, this tariff has been significantly scaled back since its initial introduction (Geels, 2014; Smith et al., 2014). The schemes are usually developed by individual home-owners and can represent a sizeable financial investment, being more expensive than a conventional domestic boiler with a cost of at least £3000 (Sauter and Watson, 2007); maintenance is provided by specialized CHP companies, as standard heating engineers are unable to service the usually more technically complex units.

4.2 A timeline of CHP usage in the United Kingdom

In this section, the author will summarize the development, diffusion and implementation of CHP technologies in the United Kingdom since its earliest experimental applications, through multiple stages of development to the present day state, a review of which will form the central part of this thesis. The author will refer to different application areas for CHP technologies, including CHP in district heating networks (Russell 1986, 1993, 2010; Hawkey, 2009, 2014), single site CHP (Russell 1986, 1993; Brown and Minnett, 1996) and domestic micro-CHP (Cockroft and Kelly, 2006; Allen et al., 2008; Hudson et al., 2011). Following the works of Russell (1986, 1993, 2010) and Hawkey (2009, 2014), the historical development of CHP technologies in the UK can be divided into several major periods, starting with an early stage spanning the first three decades of the 20th century, followed by a post-war regeneration and renationalisation period starting in the second half of the 1940s and ending in the late 1960s (Hawkey, 2014), the oil crises and start of privatisation of the UK energy sector (1970s-80s), the post-privatisation stage (1990s-2000s) characterised by the consolidation and development of the consolidated electricity and gas markets (Toke and Fragaki, 2008, Heather, 2010; Pearson and Watson, 2012) and a current stage of increased sustainability awareness characterised by attempts by multiple actors to devise roadmaps and trajectories for a low-carbon transformation of the UK energy system (HM Government, 2009; DECC, 2011, 2013, 2015; Hawkey, 2014; RTP Engine Room, 2015).

The overview of the earlier stages will primarily be based on existing historical accounts, in particular the work of Stewart Russell (1986, 1993, 2010), David Hawkey (2009, 2012, 2014) and a number of other authors (Babus'Haq and Probert, 1996; Brown and Minnett, 1996; Toke and Fragaki, 2008; Pearson and Watson, 2012; Weber, 2014); while the account of the developments in later stages will be supplanted by information gathered by the author in the course of his fieldwork, mainly in the form of quotes collected through interviews with CHP experts, some of whom have been active in the CHP industry for several decades.

4.2.1 The early stage (ca. 1900 – start of WW2)

The early stage spans the first 40 years of the 20th century, but its beginnings can be traced into the 2nd half of the 19th century when initial experiments on the use of waste heat for industrial and residential purposes took place in the United States, which resonated in contemporary British professional journals and associations (Russell, 1986). Those early experiments were often driven by enterprising engineers-innovators, motivated by the twin goals of waste reduction and efficiency increase. Interestingly, some of those early papers correctly identified technical and planning issues regarding CHP which are still valid today, such as the balancing of heating and electricity production as well as the issues related to economic assessment of proposed schemes. Despite the attention and consideration given to the US initiatives, CHP proponents in Britain were initially hampered by a high degree of decentralisation, resistance by local authorities and individual property-owners and an almost complete lack of heat networks (Russell, 1986). Some scattered references to proposals and actual schemes in the period leading up to the start of World War One can be found in archived documents, however, two of the most thoroughly documented schemes are the Manchester Corporation supplying office blocks and factories with steam from power station boilers, and the cooperation of the St. Marylebone Electricity Department with the local Public Health Committee “disinfecting baths” which was regarded to be financially and organisationally beneficial for both sides (Russell, 1993). Other documented developments include the use of CHP-type engines in the Singer factory in Clydebank in 1898, and the development of district heating schemes in Dundee and Sterling in 1920 and 1922 (Babus’Haq and Probert, 1996). Considering the characteristics of these early schemes, most of them were either industrial single site developments or district heating schemes, with the actual service being externally provided by existing infrastructure. In the 1930s, a number of industry CHP schemes was proposed, however, most of these schemes were never implemented due to wavering professional support and ultimately the start of World War Two. After the end of World War One, a more acute housing shortage coupled with fuel shortages and increasing prices triggered a brief period of increased interest in using CHP to provide heating services to new housing, but technical restrictions combined with wavering public and professional interest led to most proposals and schemes being abandoned shortly thereafter with the notable exception of the Dundee DH scheme, which remained a sole source for industrial and research data on CHP-DH schemes for a long period of time (Russell, 1986). Starting from the 1920s, increasing centralisation of power generators as part of the development of the National Grid acted as a further detrimental factor to the development of commercial and public CHP schemes, which relied on a decentralised market (Hawkey, 2009).

4.2.2 Post-war regeneration (End of WW2 – end-1960s)

The post-war regeneration stage spans the second half of the 1940s and the 1950s, a period that was marked by the rebuilding of urban areas throughout the UK that were heavily damaged during the Second World War. During the initial regeneration push, planning for which started during the war years, public interest in CHP rapidly increased, culminating in the first National Programme for CHP-DH applications. At the start of the programme, many of the initiatives came from the Government, especially the Ministry of Fuel and Power (Russell, 1993), however, by the mid-1950s governmental interest sharply dropped (Hawkey, 2009). Local authorities (LAs) put forward multiple DH schemes, however due to a lack of power on DH and electricity generation they had to promote Local Bills in the Parliament on an individual basis. Even though around 30 councils obtained the necessary powers by 1955, the delay caused government interest, as well as interest from the nationalised electricity industry, to decline, leaving the LAs with very little support. In addition, further restraints on local financing of DH projects, escalating costs and technical problems caused further setbacks. The electricity industry, who at the first showed some interest in CHP-DH, changed its position to oppose electricity generation on a local level. The combined effect of these barriers and the still limited power of LAs ultimately led to the scaling back and abandonment of a majority of the proposed schemes, while some of the schemes that were implemented were treated as trials instead of permanent installations (Russell, 1993). The national coal and gas industry, who at the beginning of the period was almost uniformly opposed to CHP, perceiving it as competition, changed its position in the 1960s, supporting the technology, however this was not sufficient to enable introduction of further schemes or a more stable programme due to increased public scepticism and the government taking on an adversarial position (Russell, 1986). On the industry/commercial side, CHP continued to be used in industry branches with a high and constant heat and power demand, with the take-up and implementation on schemes based on individual economic calculations and fuel savings. While some schemes were implemented, the nationwide number of industrial CHP applications remained low and often unconnected, and entered a period of steady decline in CHP capacity that continued into the 1980s. This decline was connected to a number of factors, the most important being reduced heat-to-power ratios in industry, changes in process operations, and in the later stages (early 1980s) the restructuring of the British Industry (Brown and Minnett, 1996).

4.2.3 Oil crises, start of privatisation (1970s – end 1980s)

This period was primarily marked by the oil crises of the 1970s and the energy security questions arising from them, and the decline of the UKs heavy industry which culminated in the late 1980s. At the same time, the electricity market, nationalised since the Second World War, underwent its second major restructuration in the 20th century, becoming privatised by the end of the 1980s. In the industrial sector, CHP mainly remained limited to the industrial sectors which have run CHP schemes since the early days of the technology (DECC, 2009). Major factors in decision-making still focused on the presence of a sufficiently high, constant heat and power demand, although increased concerns on energy shortages resulted in companies increasingly looking at fuel costs, where CHP technologies could offer a comparative efficiency advantage. The general downturn of UK heavy industry in the 1980s directly influenced the number of CHP schemes as well as their capacity; in line with the developments outlined in the previous section, industrial CHP as well as CHP in general reached its nadir at the end of the decade, with only around 120 registered CHP schemes operating in the country in 1988 with a capacity of 1793 MW, down from around 150 schemes with a capacity of 2254 MW in 1983 and around 240 registered schemes with a capacity of 2793 MW in 1977 (DECC, 2009). In parallel with this development, industry actors started engaging with the privatisation of the energy industry by outsourcing the running of their CHP schemes to private companies. In the group of users-service providers running district heating networks, this period brought the second major national DH initiative, spearheaded by the Lead Cities programme (Hawkey, 2014). However, despite initial government support and a number of proposals brought forward, including some of the “New Cities” built in the post-war years, the government’s position once again quickly changed as the idea of privatisation took hold (Russell, 1993). Paradoxically, CHP-DH was seen as a test case for this new approach, with consciously shrinking public investments leaving any planned schemes to the attention (or lack thereof) of private investors (Hawkey, 2014). Using appreciation models aimed at short-term returns and the generation of transferable assets and infrastructure, private investors were not able to perceive benefits from investments into DH schemes. The situation of the LAs who in a majority of the cases were the drivers behind the scheme proposals was also somewhat constraining; limitations on the development of local power and heat generation were eased, but financial planning still remained centralised to a large degree (Hawkey, 2014). Interestingly, this period also saw the implementation of the Energy Act 1983, which provided some of the first legislative support ever provided to CHP proponents by allowing private generators to buy and sell electricity from Local Electricity Boards (LEBs) and use the national transmission and distribution network (National Grid). Further legislative support was codified in the Electricity Act 1989, which established a series of privileges for generators whose main business is not electricity generation; this particularly benefitted small scale CHP schemes but could also be applied to industrial-scale CHP schemes (Babus'Haq and Probert, 1996).

4.2.4 Post-privatisation (1990s – early 2000s)

The time span here described as the "post-privatisation" period can be seen as a bridging interlude between a rather consistent CHP development (and failures) since the start of the century and the contextual and focal change which happened on a global scale in the most current period. After the number of CHP schemes reached a low point in the late 1980s, CHP use in both industrial and district heating schemes strongly increased at the beginning of this period, rising from around 120 schemes in 120 to 1124 registered schemes in 1994 (DECC, 2009 and 2014). This change was brought about mainly by technological advancements resulting in market availability of more advanced combined cycle engines for the industrial sector (Weber, 2014) as well as small, packaged turn-key generation units (Russell, 2010) as well as some elements of the major restructuring brought about by the privatization of the energy sector, however, the major challenges faced by CHP proponents in the past remained unchanged, with some of them potentially becoming even more challenging due to decreased state agency and private actors putting an even stronger emphasis on short-term based appreciation and transferrable knowledge. On the political stage, the dominant paradigm became minimal interference “Regulatory State Paradigm”, replacing the more interfering centralised government (Hawkey, 2014). While this allowed more freedom of action for LAs, it also increased the necessity for appraisals and audits which historically did not favour CHP technologies (Toke and Fragaki, 2008). Also, reduced state activity caused an acute decrease in government R&D spending towards CHP projects, which forced CHP proponents and researchers to depend on private sector R&D spending. However, private sector actors were rather hesitant in investing in CHP R&D, due to significant initial investments, the incompatibility of the system with large parts of the existing infrastructure and the localised nature of CHP which was in opposition to the industry’s focus on transferrable knowledge (Kelly and Pollitt, 2010).

Industrial schemes continued to be dominated by the same set of sectors expressing high heat and power demand, although the paper sector diminished significantly (DECC, 2009). The first privatization and post-privatization years resulted in strong proliferation of industrial CHP schemes, with widespread developments of very large scale CHP, especially combined cycle (CCGT, Type 3 in the above-presented typology) systems developed as power-optimized, electricity-led schemes and operated through energy service companies (ESCOs); this development was however halted by the introduction of the New Electricity Trading Arrangement (NETA, later BETTA) in 2001 (Pearson and Watson, 2012) which made a large number of the initial economic calculations and pricing algorithms on whom these large schemes were based untenable. Consequently, the attractiveness of large scale industrial CHP was severely diminished, as observed in the following quote:

“I think under that change in the electricity market, where the generator was more exposed to the volatility of the market, that killed industrial CHP off at a stroke.” (Senior Manager, regional government)

A second negative effect of these changes was a reduction of the overall attractiveness of large scale CHP within the efficiency and cost reduction discourse, which effected and to a degree necessitated the reorientation and contextual reframing of combined heat and power benefits towards environmental gains that set the frame for the current period of CHP development.

The reduced interest in large scale cogeneration systems based on high-capacity turbines coincided with increased interest in small- and medium CHP schemes based on small gas and internal combustion engines. Developments of small CHP schemes and turnkey installations by non-industrial commercial users such as universities, hospitals, hotels and leisure facilities increased significantly (DECC, 2009 and 2015) and were supported to an extent by favourable local-level policies and an expanding industry. Some of these schemes were run by the site owners themselves, or operation and management of the schemes was taken over by the owner after a period of cooperation with specialized CHP providers, while other schemes established in hands-off, full-service contracts with the providers, outsourcing both the management and technical maintenance of the schemes.

CHP-DH scheme operators, mainly local authorities, were put at a significant disadvantage by the privatisation of the energy sector – while initially there was increased scheme development activity, private actors did not become sufficiently interested to warrant the necessary large-scale investment (Hawkey, 2014). Although most successful schemes remained in operation, there were few new additions in this period. Towards the end of this period, planned policy changes suggested the possibility of improved conditions for CHP diffusion in the future. This period also saw the introduction of micro-CHP plants in the UK energy market, with first commercially viable micro-CHP units made available to homeowners (Cockroft and Kelly, 2006; Hinnells, 2008) and a rollout of government sponsored demonstration projects (Foxon et al., 2005). However, the high expenses of such an installation, combined with a long break even period and the relative novelty of the technology made CHP microgeneration units less attractive to the majority of homeowners beyond a number of initial proponents and early adopters (Sauter and Watson, 2007; Hinnels, 2008). Further on, the relative novelty of this particular application area caused several different competing designs, characterised by different fuels and engine types, to emerge (Hinnels, 2008), leading to uncertainty among some users who preferred to wait for a final, proven design type to emerge. A further barrier to wider diffusion was the absence of policy support, particularly a feed-in tariff or more extensive loans which would have impacted the personal, economic decision-making processes of the homeowners in a positive, enabling way (Sauter and Watson, 2007).

4.2.5 Current stage (rise of climate concerns) (late 2000s – today)

This, most current stage has been intentionally added by the author compared to the timelines presented in previous research (Russell 1986, 1993 and 2010; Hawkey 2009 and 2014) in order to highlight a shift of CHP expectations from the earlier social-technical goals towards the role of CHP in achieving carbon savings and, through that, a more sustainable configuration of the UK energy system; an aim which is in line with the aims and expectations set by the UK government in successive strategies and White Papers (DECC 2009, 2011, 2013). While some of these discourse and expectation changes originated from within the CHP industry; overall they were essentially a reproduction of macro-developments on a national, continental and global scale – using a concept from Geels' (2004) multi-level perspective model, the landscape for energy systems was changing. The most immediate effects of this landscape change were twofold – on a policy level, governmental institutions started including CHP in white papers and policy drafts detailing potential pathways to a more sustainable UK energy future (DECC, 2013); while on the user level important decision-making variables shifted towards the *environmental benefits* of CHP technologies, a fact that can be illustrated by carbon management plans and carbon savings taking precedence over payoff functions and fuel efficiency. This is not to say that the latter lost any of their importance, however, the rationale for a broader diffusion of combined heat and power technology has undergone a shift. Those changes have influenced diffusion and development both in the industrial/commercial sector and in the DH sector, with the number of CHP schemes strongly increasing since 2008 (DECC, 2014, 2015 and own calculations). However, there is a number of major challenges which still need to be faced – a strong lock-in (Unruh, 2000) of the UK energy and heating sector into centralised generation, high entrance barriers to new entrants into the UK energy market (Toke and Fragaki, 2008) and a general uncertainty about the fact whether CHP technologies in fact have any place in a future zero-carbon energy system (Hawkey, 2014). The later point is reinforced by the current "open competition" stance of public bodies with regard to future developments of the UK heat industry; creating a situation of technological competition between supporters of an all-electric energy system and proponents of a biogas and hydrogen-based energy future. The former potential trajectory is seen as limiting for CHP; while the latter, gas- and hydrogen-based system opens up increased potential for the utilization of CHP technologies as both a "bridging" technology utilizing currently available technologies, and a permanent part of a future energy system in the form of hydrogen-fuelled fuel cell based combined heat and power systems.

On the policy side, an analysis of recent policy and legislative documents influencing CHP diffusion shows that policy support for CHP technologies has markedly increased in the late 2000s (Allen et al., 2008; Ricardo-AEA, 2013; DECC, 2014). In addition to national policies, there has been considerable drive from the European Union level in form of European directives promoting energy efficiency (Directive 2012/27/EU) and also CHP in particular (Directive 2004/08/EC). However, in more recent development supporting policies have been rolled back or reduced in a number of important areas, such as the feed-in-tariff for domestic users (Geels, 2014), the Renewable Heat Incentive (RHI), changes in biogas policies or the abandonment of the proposed zero carbon building standards; the impacts of these changes on the different CHP application areas are discussed later in this chapter. Further on, increased resistance by policymakers and especially capacity market regulators is observed by the industry in certain development settings, as outlined in the below quote:

"I'm seeing more and more across the UK that district network, DNO operators are becoming more and more sort-of anti-CHP, anti-decentralized generation, becoming trickier to deal with, to get project off the ground, fitting larger caps on what's allowed to be generated even if you're not planning to export anything. And certainly, and also preventing exports on a number of projects as well, even if the CHP was capable of producing more electricity that they could export to the grid, a lot of DNOs are just not allowing it." (Sales Manager, specialist CHP company)

Across the different user categories, the number of small- and medium-sized CHP schemes has been continuously increasing, with around three quarters (1719 schemes out of 2102 registered Good Quality CHP schemes) of CHP schemes installed in the non-industrial commercial, public and residential sectors (DECC, 2016); this represents an increase of around 35% compared to the 1151 schemes registered in non-industrial sectors in 2004 (DECC, 2005) and corresponds with observation by industry experts on a continuing stagnation of large-scale industrial CHP and a continuous growth of the small- and medium-size CHP market. This increase in absolute numbers is however not reflected in the electrical capacity of CHP schemes, where the majority of capacity is provided by large-scale industrial schemes in the “traditional” sectors – oil refineries, chemicals, paper, publishing and printing and food, beverages and tobacco – together, CHP schemes installed in these sector account for more than three quarters of installed CHP capacity (77% of total electrical capacity in 2015, compared to 78% in 2004, despite a reduction in the total number of industrial schemes from 401 schemes in 2004 to 383 schemes in 2015), although the share of the oil sector is steadily decreasing reflecting the downturn experienced by the industry (DECC, 2005, 2016). With regards to the mode of operation and business models implemented by CHP users, the majority of large-scale scheme users tend to outsource the operation of their CHP schemes to private contractors, which has enabled a number of small, specialised energy services and infrastructure companies to enter the market in addition to the established major incumbents (“Big 6”), with the latter diversifying their operations through creating units focused on CHP operations, such as Cofely for EDF-Suez, Business Heat CHP for E.ON or Veolia CHP (formerly Cogenco). The increasing focus on environmental issues and carbon management in general mentioned above also leads to some companies taking up an early adopter approach towards CHP technologies in anticipation of more stringent environmental legislation in the future.

For cogeneration systems in district heating schemes, the direction of any future developments is less certain, as despite government support in form of (limited) policies there is a strong barrier in the form of a “lock-in” into a centralised system (Hawkey, 2014). Due to the current structure of the electricity market, there are high barriers for the market entry of small, decentralised power producers (Toke and Fragaki, 2008; Hawkey et al., 2013), a situation which is additionally exacerbated by the lack of a national heat market or a dedicated heat policy (Hinnels, 2008) as well as a general lack of available heating infrastructure in the form of (usable) pipework. Another issue for the diffusion of CHP-DH is the role of LAs, who most often are the main drivers or at least critical partners in the development of new DH networks. Although their powers have steadily increased, building regulations as well as financing structures make their position as DH developers all but certain (Hawkey, 2014). Following a focus on risk distribution and reduction, as well as improvement of the financial situation, development of energy service business models using energy service companies (ESCOs) became a focus of enterprising LAs (Hannon and Bolton, 2015). Looking from the perspective of micro-CHP users, the late 2000s were the time of the first introduction of a feed-in tariff, as well as other forms of financial support. While micro-CHP was also supported by technology maturation, all of these factors did not suffice to markedly increase the number of micro-CHP installations. In March 2015 there were only 643 registered micro-CHP installations in the UK (DECC). Major perceived barriers to micro-CHP diffusion are high upfront costs and long payback periods (Allen et al., 2008), lack of information readily available to average consumers and a disadvantage of micro-CHP and other combustion based microgeneration technologies when compared to zero-carbon technologies such as wind or solar thermal (Sauter and Watson, 2007). A further setback was the reduction of the feed-in tariff for by the current Conservative government (Geels, 2014), with potential future reductions as well as other policy degradation related to sustainable energy generation uncertain but not impossible.

4.3 Chapter Summary

In this chapter, the author introduced the empirical case forming the focus of this study – the long and often disappointing history of the development and diffusion of combined heat and power (CHP) technologies in the United Kingdom. At the beginning of the chapter, the technological concept and the relevant artefacts (engines, infrastructure) were presented, followed by a review of a number of application areas that will be observed in particular detail throughout this study.

In the second part of the chapter, the author attempted to set the historical background of the technology by presenting a timeline of CHP usage in the United Kingdom covering the time span from the initial applications of cogeneration at the beginning of the 20th century to the present day. Drawing on previous studies on the subject, especially the work of Stewart Russell (1986, 1993, 2010) and David Hawkey (2009, 2012, 2013, 2014, 2016) as well as government data and information collected in the course of this project, the author has painted a history of major promises, changing actor coalitions, socio-political and economic change resulting in a “obvious example of a superior technology” (Weber, 2014) being underutilized compared to its recognised potential, and leading a marginal existence at the fringes of the broader UK energy system.

The next chapter will include the first part of the analysis outlined in Chapter 3, using the TIS analytical approach in order to review the internal dynamics and structure of the combined heat and power industry. Keeping in line with the analytical requirements of TIS (Hekkert et al., 2007, 2011; Bergek et al., 2008; Markard et al., 2015) it will primarily be implemented as a present-state analysis, although the historical background will be used in order to inform and set the broader context.

5 A Technological Innovation System (TIS) analysis of the CHP industry in the UK

In this chapter, the author will focus on the internal structure and functions of the combined heat and power industry by conceptualizing it as a technological innovation system (TIS), following the TIS analytical approach developed by Hekkert et al. (2007, 2011) and Bergek et al. (2008). While the analysis will be inward-oriented and focusing on the technology and the structure of its system (Kuhlmann and Arnold, 2001 in Hekkert et al., 2011), the author recognises the need to address both the wider context of the system's environment (Markard and Truffer, 2008; Smith and Raven, 2012) and the influence of politics on system-internal and external developments (Geels, 2014; Markard et al., 2015) by extending the TIS conceptualization to include the concept of socio-technical regimes (Geels, 2002) following the theoretical framework proposed by Markard and Truffer (2008). While recent developments have brought forward an approach for conceptualizing contextual structures and dynamics influencing TIS (Bergek et al., 2015), the author will follow the joint framework approach in order to be able to develop external contextual structures into analytical constructs (regimes and the landscape). Further on, this approach will also enable an analysis of dynamics *between* external constructs (Raven and Verbong, 2007, 2009), some of which may not be reflected on the focal TIS despite their indirect influence on the TIS' development. On the other hand, the TIS analysis outlined in this chapter will enable a more structured insight into the internal structure and dynamics of the CHP system compared to a SNM and MLP-based approach. This is especially true regarding the niche *nurturing* function, and is recognised in recent theoretical developments (Smith and Raven, 2012).

5.1 Defining and delineating the CHP-TIS

As a first step in the analysis, the focal TIS needs to be defined in more detail in order to highlight the unit of analysis and its extent in several dimension relevant to this research. Following Bergek et al. (2008) three main choices need to be made:

1. A choice of the focusing device central to the investigated TIS
2. The choice between breadth and depth related to the range of applications of the focusing device
3. The spatial focus of the research

The choice of the focusing device for the combined heat and power TIS is very much influenced by the aims of this research project, which are to understand the transition dynamics and systemic causes of the present state of combined heat and power (CHP) technologies in the UK energy-technological system, and to a lesser extent the historical reasons that led to the current state of development and the future prospects for CHP technologies in current and future changing contexts of the energy system and the broader economy. While CHP at its core is a relatively simple concept (Weber, 2014), it has been applied in a number of different, but often technologically related artefacts, ranging from steam-powered CHP engines over the current gas and diesel engines to prospective future biofuel-powered or fuel cell based units (Russell, 1986,1993; Hinnells, 2008; Toke and Fragaki, 2008; Hawkey, 2014). Therefore, an inviting choice would be to define the focusing device of the TIS as being combined heat and power generation as a *knowledge field*, encompassing the knowledge developed around the simultaneous generation of electric power and (useful) heat in one process (Weber, 2014).

The knowledge field TIS includes the technical artefacts – engines who generate heat and power using one of multiple types of prime mover, from steam engines to fuel cells, the associated physical infrastructure in the form of control devices, heat and/or electricity storage and cable and piping systems necessary for the management of the generated energy and its transport to the final point of use, and the knowledge developed around the operation of CHP-based systems, the development of business models to regulate the relationship between energy producer and energy user where they are separate entities, and supporting knowledge relevant for the development of new schemes and the development and positioning of the CHP system related to current and future macro-level pressures and meso- and macro-level policies.

However, certain limitations need to be considered when defining the level of aggregation of the study by ensuring that it is focused on *one* specific knowledge field (combined heat and power) observed in a single general context – *combined heat and power* within the UK energy sector. This also allows for a more precise definition of the range of applications of the knowledge field and its technologies (Bergek et al., 2008) by outlining a specific range of applications. For the purposes of this study, this range of applications represents a limited number of general application contexts for CHP technologies, described through their main purpose, scope and scale: CHP used in communal/district heating networks (Russell, 1986, 1993, 2010; Hawkey, 2009, 2012, 2014), CHP in single site industrial and commercial applications (Cockroft and Kelly, 2006; Hinnels, 2008; Hudson et al., 2011), CHP in single-site public applications (Hinnels, 2008) and CHP-based domestic micro-generation (Sauter and Watson, 2007; Allen et al., 2008; Hudson et al., 2011). In further chapters of this work, these application areas are discussed in more detail using concepts from Strategic Niche Management (Smith and Raven, 2012) connected to this analysis using the TIS-MLP cross-conceptual approach by Markard and Truffer (2008). The application areas, whose borders define the extent of the observed TIS in this step, are conceptualized as a group of niches at different levels of diffusion and development existing within the focal TIS (ibid.). Using Strategic Niche Management terms, the TIS can also be understood as a national/global niche (Geels and Raven, 2006).

Finally, the spatial focus of the research is defined through the geographical borders of the United Kingdom and the reach of UK energy and planning policies and other applicable and relevant laws. While the author recognizes a moderate to high level of interconnection between actors across geographical borders and the existence of international technology and knowledge exchange between actors and institutions forming the focal CHP innovation system and external actors either indirectly engaged in the focal TIS or functioning within other, related TIS, as well as the fact that multiple actors, especially multinational companies, are active beyond and across the spatial borders of the focal system, any actions or impacts caused by these actors are considered to be system-external unless their immediate source and impact area are both located within the borders of the system. By doing this, the research is enabled to capture the relevant aspects for the UK TIS system, while at the same time considering international developments and changes in the global context (Bergek et al., 2008).

5.2 Structural analysis

In a second step, the author will outline the structure of the focal innovation system through mapping the system actors, informal and formal networks and relevant institutions (Bergek et al., 2008) and briefly discussing the key technological factors (Hekkert et al., 2011). Due to the breadth of the system, the author will focus on the actors, networks and institutions which have been consistently identified as key in the course of this research, while the technological factors and trajectories will be discussed based on their viability and legitimacy in the UK while considering the fact that, as pointed out above, the majority of these technological trajectories develop across the spatial borders of the observed system.

5.2.1 System actors

A discussion of the key actors of the CHP knowledge field TIS needs to take into account the “between sectors” nature of combined heat and power developments in the UK – based on the two provided types of energy (and, by extension, fulfilled societal functions) CHP actors will be active in both the UK electricity and heating sectors, with a smaller number of actors active in only one of them. While the UK electricity sector is well defined, this is not the case for the UK heating sector, which largely is synonymous with the UK gas sector, except for a smaller section of the market where heating services are provided by electrical technologies (electric heating, ground source heat pumps, etc.). With regards to this dual allocation of actors, the author will discuss the key actors as belonging to both sectors, while highlighting the actors where this is not true. The discussion and mapping will be done using a top-down approach, starting from actors active at the national level across multiple business/industry sectors and breaking down to small actors active in only one sector in limited geographical localities. A more in-depth observation of the interactions between the gas and electricity sectors, operationalized in the form of the electricity and gas/heating regime(s) will take place in the following two chapters, drawing on research by Raven and Verbong (2007, 2009) and Konrad et al. (2008).While reviewing key actors, the author will follow an TIS actor typology developed by Hekkert et al. (2011), who distinguish between five main types of actors: knowledge institutes, educational organizations, industry actors, market actors and government bodies and supportive organisations.

Using this approach, the actor mapping starts at the level of government bodies and supportive organizations; the highest-level government body in the UK responsible for energy being the Department for Business, Energy and Industrial Strategy (DBEIS). Until recently[15] this role was fulfilled by the Department for Energy and Climate Change (DECC)). The second key actor on the national level is the independent national regulatory authority OFGEM, which is responsible for regulating both the gas and the electricity markets through setting and overseeing market rules, guiding market competition and managing licensing and monitoring for electricity and gas market actors. The third key actor on the national level is the private organization National Grid plc, which is tasked with the operation and maintenance of the UK-wide electricity and gas grid. On a sub-national level, the electricity and gas supply is operated by a number of smaller regional gas distribution networks and electricity Distribution Network Operators (DNOs). These actors can also been considered to have a key function, as they are directly responsible for establishing and managing the gas and electricity connections which are necessary for the development and operation of CHP schemes. Also, the DNOs can take a gatekeeper role as they are the actors responsible for setting operational limits for CHP schemes. On a regional level, public CHP actors are local authorities (LAs) and public-private LA-managed organizations who are responsible for the development and running of CHP schemes in the form of district heating (DH) networks and single-site public schemes.

The next group of actors reviewed by the author are knowledge institutes and educational organizations. As the focal knowledge field is rather mature from a technological point of view, there is only a limited amount of technological R&D taking place within the UK in large industry actors and a number of small specialized organizations, some of which (for example, Ceres Power) have developed as offshoots of university projects. There is no centralized academic research programme on CHP although collaborative research projects are regularly taking place, mostly among research-intensive universities such as the Imperial College, the University of

[15] The DECC was disbanded, and the energy portfolio transferred to DBEIS on 14th July 2016 by the new British Government under Theresa May

Sussex and the University of Edinburgh. Most of these research projects however are not focused solely on CHP, but review CHP alongside a different research focus such as for example energy services business models, or heating networks in urban environments. Moving on to the educational side, there is little focus on provision of CHP-specific training on any educational level, which can be tracked back to a lack of public support for CHP-specific education. In summary, the presence of key actors in the academic knowledge and education sectors is rather brief.

Focusing on the CHP industry and market, two main groups of actors can be identified: incumbent energy market companies who operate within the CHP market, mostly through a dedicated subsidy (for example, COGENCO for Veolia) and smaller companies specialized on CHP or a broader application of decentralized energy generation technologies, some of which have been incorporated in larger market actors. Those smaller companies tend to operate on all levels of the CHP value chain, with most of them offering holistic solutions for their clients, ranging from scheme development over implementation to ongoing operation and maintenance. It needs to be pointed out that many of these actors are active beyond the spatial borders of the observed TIS, and engage in ongoing experience, knowledge and technology exchange across system borders. Both categories are seen as key actors in the CHP market due to their almost-monopoly on technology specific knowledge and the capacity to guarantee ongoing operation of CHP schemes, with the majority of CHP users interacting with them at various times during the development and operation of CHP schemes in different settings, often by outsourcing different elements of operations management to these actors through operations & maintenance (O & M) contracts. Industry and market actors also play an important role in R&D activities on CHP technologies, with both large energy incumbents and small "new technology" start-ups engaging in research and experimental applications of next generation CHP technologies, especially regarding different types of renewable CHP engines and CHP micro-generation technologies.

The final reviewed key actor is the umbrella organisation representing CHP technologies in the UK, the Association for Decentralised Energy (ADE)[16], which serves as a major intermediary between CHP industry actors, the research sector and

[16] Formerly the Combined Heat and Power Association (CHPA)

the public sector by maintaining a knowledge database on CHP for private and public sector developers, fostering exchange of information in form of a regular newsletter and annual conferences and taking an active role in public consultations with government bodies with the aim of defending and promoting the interests of CHP proponents. Additional non-profit organizations such as the Carbon Trust and the Energy Saving Trust take an actor role in certain areas of CHP development, however their main activities are usually more general and lack the strong focus of the ADE (this however doesn't mean that they cannot take key roles in particular settings).

5.2.2 Networks within the system

In the next step of this analysis, the author will discuss formal and informal networks within the observed TIS (Bergek et al., 2008). In general, the highly heterogeneous and location-specific nature of CHP technologies does not provide a fertile ground for the existence of structured formal networks, while on the other hand networks focused on particular technological elements of the CHP system tend to operate on an international and even global level. This is for example the case with CHP prime movers, where a large number of UK CHP schemes operate engines produced outside of the spatial borders of the UK, with strong network ties existing between the UK operator of the scheme and the original equipment manufacturer operating in a different location. A formalized network for CHP users is developed through the umbrella organisation ADE, where members are encouraged to exchange information and experience on an ongoing basis. Other temporary formal networks develop through projects and/or public programmes, however these networks tend to last only for the duration of the project/programme as individual actors within these networks seldom take the role of champions. Evidence exists for the existence and successful development of more localized semi-formal networks such as for example in Greater London or in southern Scotland, most often these networks develop from an ongoing effort by a local or regional authority, and are at risk of dissolving should the engagement of the authority end (Hawkey, 2012). On the informal side, however, there is strong evidence for the existence of informal networks, which is a side-effect of the relatively low number of individual actors in the CHP industry, with many developers and operational managers continuously engaged on many different schemes. The lack of a formal network outside of the ADE could also be seen as a supporting factor for the development of informal ties as individual actors tend to cooperate and exchange information on a case-by-case level, often enabled by personal ties and knowledge exchange between key personnel. A negative side-effect of the low number of networks is the lack of concerted efforts and shared visions, which will be discussed later in this chapter.

5.2.3 System institutions

The penultimate step of the structural analysis focuses on institutions of the observed TIS, described as culture, norms, laws and regulations (Bergek et al., 2008). Institutions can be further separated into formal, enforced and codified institutions such as laws or competition rules, and informal, tacit institutions that are continuously shaped and adapted by system actors (Hekkert et al., 2008). In the observed case, the dominant institutional context is shaped by the liberalised UK energy market and a broader policy consensus (or, rather, a lack thereof) on the current and future development pathways for UK energy policy; but also by a lack of institutions related to heat or the heat market – as discussed above, the UK heat market is largely synonymous with the gas sector, with around 85% of UK homes using gas as their primary heating source. Energy market liberalisation developed out of energy privatisation plans draws up by successive Conservative governments in the 1980s, coming to a head with the start of the electricity market privatisation in 1990 – a process that was largely completed by 1998 (Toke and Fragaki, 2008). Electricity trading rules are enforced by the independent market regulator OFGEM, which has been discussed in the actor review, in the form of the British Electricity Trade and Transmission Arrangements (BETTA). On the gas side, the privatisation process was largely completed by 1996 (Heather, 2010), with gas trading regulations codified in the form of the 1995 Gas Act and the 2005 Unified Network Code, and enforced by OFGEM and National Grid Gas, who acts as the main transmission system operator (TSO) (Working Group report to the All Party Parliamentary Group on Energy Costs, 2015). On a supranational level, both the electricity and gas sectors are further regulated through the EU Regulation on wholesale energy market integrity and transparency (EU) 1227/2011 (REMIT), with OFGEM and its subsidiaries ensuring and monitoring continuous enforcement on a national level, and the EU Directive 2012/17

EU on energy efficiency, which promotes and sets a broader frame for the application of co-generation technologies and other high efficiency energy generation processes.

Regarding a broader institutional consensus on UK energy policy the outlook is rather muddled, with successive governments taking multiple and in some cases contradictory positions on current UK energy strategy and its future development trajectory (Geels, 2014; own observations). On a broader level, the institutional frame behind current UK energy policy is embedded within the context of a general transition to a low-carbon economy. The laws and regulations influencing UK energy policy development are codified in several documents, the most important being the 2008 UK Climate Change Act, the 2009 UK Low Carbon Transition Plan, the 2011 Energy White Paper and the 2016 UK Energy Act. Institutional context, both formal and informal, is also generated by the existence of strategic targets informed by these documents, such as the 2020 or 2050 emissions targets. Despite the existence of this formal institutional framework there remains a significant amount of uncertainty among CHP actors about future prospects for the technology's development. At present, the institutional framework is perceived as mainly neutral with a number of positive components, however, previous changes such as the reduction of an existing Feed-In-Tariff (FiT) or reviews to the RHI and embedded benefits create a sense of uncertainty.

On the micro-level, this uncertainty is reflected in a rather piecemeal approach taken by CHP actors, with public actors using institutional support on a case-by-case basis, and a number of private actors preferring to develop CHP schemes outside of institutional provisions, merely complying with existing regulations to a satisfactory level. For some application types, local institutions such as planning regulations (Section 106 and similar), connection permissions to the national grid (provided by regional DNOs) and, particularly in urban areas, emissions and noise regulations play an important role. This role is however very context-specific, with local institutional contexts varying depending on the geographical location and influenced by the agency of both system-internal and system-external actors at different levels. The former is especially the case when public actors such as local authorities take an active role in the planning and implementation of CHP schemes as they can, to a certain extent, set the micro-level institutional framework (this was observed in a number of public sector case studies where local councils put out specific regulations which influenced the uptake of CHP). However, there are limitations to the extent of their influence as they may lack the authority and/or the ability to change or override elements of macro-level institutions (this is discussed at more length by Russell (1994, 2010) and Hawkey (2012, 2014)).

5.2.4 Key CHP technological factors

In the final step of the structural analysis, the author will briefly discuss key technological factors within the CHP system and try to map out currently existing technological trajectories (Hekkert et al., 2014). Overall CHP technologies can be considered to be technologically mature, with engines, supporting technologies and infrastructures having being developed to the current standard over a period of almost 100 years (Russell, 1986). There seems to be an informal separation between "mainstream" CHP where the prime movers are gas turbines or reciprocating engines using fossil fuels, and "renewable" CHP which covers a range of different concepts ranging from incremental improvements to existing CHP technologies such as biofuel-capable engines and biogas turbines to more radical developments such as fuel cell based CHP or solar CHP. While "mainstream" CHP technologies constitute the majority of all UK CHP schemes, renewable fuels are used in around 10% of registered UK CHP installations (Digest of United Kingdom Energy Statistics, 2016). However, observations at industry and research conferences as well as a number of interviews have indicated the existence of an informal institutional frame among CHP actors regarding the long-term viability of "mainstream" CHP technologies within the broader decarbonisation context, as they do not constitute a viable solution for a theoretical very low carbon or zero carbon economy. As part of this frame, actors are likely to agree that "renewable" CHP technologies are a more likely future solution, however, there are multiple different expectations about the preferred development trajectory, with some actors inclined to dispute the long-term suitability of CHP as a concept altogether. Reasons for this can be traced back to the overall fragmentation of the CHP system and a rather weak presence of networks, the lack of public sector guidance and shifting institutional frameworks and availability of financial resources for R&D activities.

A more positive influence on CHP development is shaped through cross-border cooperation and international/global developments, where technological solutions are developed by actors working in different countries and therefore different institutional settings, with results shared across borders of the observed UK TIS system. Large multinational firms active in multiple national markets often engage in this type of R&D behaviour, while some development trajectories where important breakthroughs have been achieved in the UK, but which very ultimately unsuccessful from a diffusion point of view, have been taken up by actors in different localities (for example, UK research on microgeneration fuel cell CHP and Stirling engines has been implemented with more success in Scandinavia and continental Europe (Praetorius et al., 2010; Hudson et al., 2011).

5.3 System function analysis

Following the structural analysis of the focal TIS, the author will assess the fulfilment of the system's functions using the TIS function typology proposed by Hekkert et al. (2007, 2011). While both Hekkert et al. (2007) and Bergek et al. (2008) utilize a functional analysis as one of the key elements of a TIS analysis, they propose slightly different sets of seven system functions, with the difference between the two approaches being discussed as part of the literature review. The observed functions therefore are (adapted from Hekkert et al., 2011; Hudson et al., 2011):

System function	Performance criteria
F1: Entrepreneurial experimentation and production	Amount of entrepreneurial activity, number of experimental applications, technological diversification of the field
F2: Knowledge development	Evolution of the knowledge base, performed research and testing, development of patents and R&D pilot projects
F3: Knowledge exchange	Accessibility of knowledge to TIS actors, ease of exchanging knowledge, number of seminars/network events, availability of databases/publications
F4: Guidance of the search	Actor expectations and visions; incentives for development along certain trajectories, existence of specific targets or objectives by governance actors, articulated user demand
F5: Market formation	Phase of the market, number and development stage of niche markets, existence of market rules and

	regulations, policy market support, ease of access to markets
F6: Resource mobilization	Availability of financial resources for R&D and commercial development; availability and accessibility of technological components and supporting infrastructure; availability of trained personnel at different functional levels
F7: Counteract resistance to change/legitimacy creation	Level of lobbying activities, presence of powerful supporting actors ("champions"), public legitimacy of focal technology, resistance by incumbents/public actors, consumer and institutional expectations

Table 15: Overview of system functions and associated performance criteria

5.3.1 F1: Entrepreneurial Experimentation and Production

There is an existing but limited market for CHP technologies in the UK, with entrepreneurial activities mainly limited to local settings (Hawkey, 2012) or to individual sites (in case of commercial/domestic single-site applications). Most CHP developments take place within their own spatial and institutional micro-context, with system-wide resources and knowledge drawn on as necessary and shaped to fit localized requirements. There is a number of actors focused on the provision of technological artefacts such as CHP engines and supporting technologies, with some of them offering more holistic approaches including scheme development, implementation and ongoing operations management and maintenance. CHP entrepreneurial activities most often create short-lived actor coalitions consisting of end users, technology providers and project developers/consultants, with the consultants taking an intermediary role between the customer/end user and technology provider. In some cases, additional actors will be drawn into the coalition – an example being a CHP scheme where the technology was provided and installed by one company, while another company was contracted for operations and maintenance at a later level. CHP technologies are applied in multiple sectors, but there is still a strong focus on communal heating networks (Hawkey 2012, 2014) and public sector schemes, in particular hospitals, universities and leisure centres. While a number of industry sectors (oil, chemical, paper, metal, sewage treatment) utilize CHP to a large degree (Digest of United Kingdom Energy Statistics, 2016), overall applications in industrial settings are stagnating, especially regarding large schemes. Smaller scale commercial CHP increased significantly since the broader contextual change towards the utilization of CHP for carbon benefits, however, private sector CHP schemes are still predominantly implemented based on case-by-case viability of cogeneration for specific electricity and heating demands. This makes entrepreneurial activity in private CHP schemes directly dependant on energy market developments, especially the so-called "spark gap", which is the difference, at any given moment, between the wholesale price for electricity and the wholesale price for gas. In general, a wide "spark gap" where gas is significantly cheaper then wholesale electricity is seen as positive for CHP entrepreneurial activities, as it improves the economic case for the use of CHP technologies. On the other hand, a persistently narrow "spark gap" decreases the interest of cost-led actors in cogeneration as the financial case for cost reduction through self-generation of electrical power is weakened. In the cases of actors developing CHP schemes in unsupportive "spark gap" conditions the use of CHP technologies is most often necessitated due to additional institutional regulations, such as emission limits, obligations to use renewable technologies, or available funding for the use of CHP technologies such as subventions received through the Renewable Heat Incentive (RHI).

Entrepreneurial activities in the CHP industry are also influenced by the highly project-specific nature of CHP schemes – while engines, supporting technologies and infrastructure components are all available, either on the national market or through importing from other (mainly continental European) markets, most CHP schemes need to be tailored to the requirements of a particular application setting. This also has a direct effect on the above discussed role of consultancies and project developers as intermediaries and knowledge brokers who facilitate communication and cooperation between a more national/global technology provider level and a locality-specific user level.

There is limited interest among large market actors for CHP technologies; while some of the major incumbent utilities companies maintain CHP-focused subsidiaries (Cogenco Ltd., RWE npower Cogen, E.ON UK CHP), a significant amount of entrepreneurial activity is undertaken by a number of smaller specialized actors such as for example ENER-G Combined Power Limited, Edina UK Ltd or Vital Energi Utilities Ltd. While large actors benefit from more available resources and better connections with the broader energy sector, smaller, more specialized actors can in certain cases have knowledge advantages due to a stronger focus on CHP technologies. However, limited interest of large market actors together with a general uncertainty regarding the government position also results in a lack of strong CHP champions who can shape the aims and expectations of CHP, and improve the flow of information on the technology towards the general public – the latter being identified as one of the possible problems influencing the diffusion potential of CHP.

There is probably not enough large-scale production in the CHP system at the moment as most new CHP developments are small or medium-sized (Digest of United Kingdom Energy Statistics, 2016), this coincides with the majority of active CHP entrepreneurs being small or medium enterprises. Considering small and medium schemes there seems to be an acceptable level of experimentation, however there is little evidence of joint efforts going beyond the linking of several schemes (such as for example the Thameswey project in Woking, Surrey being extended to Milton Keynes, Buckinghamshire). This together with a lack of large-scale experimentation and production can have a negative effect on public visibility and collective public learning, but also on the willingness of new entrepreneurs to enter the sector as it might not be perceived as "profitable". Finally, start-ups and new entrants working with "mainstream", fossil-fuel based CHP can be dissuaded by the uncertainty regarding the future potential of these technologies due to the above-discussed uncertainty regarding the development direction of the UK energy system, and policy changes related to electricity and gas market access, charging regulations and emissions barriers.

5.3.2 F2: Knowledge development

As with virtually all TIS, sufficient and guided knowledge development is key to the ongoing development and diffusion of the CHP system (Hekkert et al., 2011; Praetorius et al., 2010). In the case of CHP, knowledge development takes place at multiple interacting levels, influenced both by the localised nature of practical applications of the technology, and the ongoing development of CHP technologies on an international level, fostered by the activities of multinational companies and international R&D cooperation and knowledge exchange. As an example, the planning of a local CHP-based district heating network draws on national or even global knowledge in the form of CHP engines, supporting technologies and infrastructural elements and shapes that information to fit into a local context, which is created and informed by local spatial, temporal and governance characteristics such as heat and electricity demand, local-level formal and informal institutions such as preferences regarding the applied business model, financing and the ownership and management structure, or planning and emissions regulations, and key actor expectations. Once developed, this knowledge is fed back to the global knowledge level through consultancies and other intermediaries participating in project development, and exchanged with other actors and CHP users either through the existing networks within the CHP industry or through company-internal communication networks developed by large market actors active in multiple localities.

National-level knowledge development is supported by public sector actors, who have repeatedly developed methodologies and commissioned studies on the viability and future prospects for CHP (DECC 2013, 2014a, 2014b; Ricardo-AEA 2013, 2016) as well as supported research projects in cooperation with universities and other public and private research institutions (RTP Engine Room, 2015; Hannon and Bolton, 2015). Localized knowledge development is in certain cases supported by regional governments or local authorities (Hawkey, 2012, 2014), or it can take place through collaborative research projects (ECOTEC21, 2014; Hawkey et al, 2016). While the developed knowledge is generally valuable and very usable in its particular context, and most individual knowledge development processes are perceived as successes, it is possible to perceive a lack of direction on the system level caused by the lack of clear government directions and an unwillingness to engage in countrywide development programmes. Finally, while technical knowledge development is consistent and undergoes continuous development, the development of context—specific but also policy-level institutional and operational knowledge is far less consistent and suffers of the lack of clear development trajectories mentioned above. This imbalance is in part caused by the simplified transferability of technical knowledge across system barriers (in the discussed case, the national borders of the UK), while context-specific institutional and operational knowledge remains confined to a specific setting and requires a higher level of commitment by participating actors for developing the knowledge in that particular setting.

5.3.3 F3: Knowledge exchange

Similar to knowledge development in the CHP system discussed in the previous section, the exchange of existing knowledge is influenced by the dichotomous nature of CHP specific knowledge, split into a more general, *global* knowledge level and a context-shaped *local* knowledge level defined by spatial, social and institutional characteristics of the locality in which a particular CHP application scheme is being developed. In order to gauge the fulfilment of the knowledge exchange function for the CHP TIS (Hekkert et al., 2007), the author needs to review the nature of that relationship as well as the roles taken by key actors (and actor categories) of the cogeneration system.

In general, knowledge exchange seems to be functioning adequately in the case of established actors and existing schemes, with flows of information between public sector actors, research and academia actors, CHP industry actors and scheme end users. While the overall strength of networks in the CHP system is rather low, existing networks such as the network generated by the Association for Decentralized Energy (ADE) or regional/local level network seem to be fulfilling the knowledge exchange role, with both general and specific knowledge available to network members and actors directly connected to network members. The flow of knowledge appears to be consistent irrespective of the actor’s sector, although public sector projects and research projects are often utilized as initial knowledge sources due to their higher potential for new knowledge development and experimental application of existing knowledge. These demonstration projects can play a key role in testing and demonstrating the viability of innovative developments related to the focal technology as they can be developed outside of the constraints of market user/government actor expectations.

The fulfilment of this function is rather weak, however, in the case of new system entrants such as local authorities interested in developing a CHP scheme or private actors considering using CHP engines within their business. Due to a low visibility of the CHP industry in the general public, these actors at times express a high level of interest in utilizing cogeneration but lack the necessary knowledge to undertake the first steps towards project development. This high initial barrier preventing access to knowledge can and usually is surmounted either through utilizing connections to established CHP actors, or through employing specialized consultancy companies who both have the necessary knowledge and are able to act as intermediaries towards other established CHP actors who can support the new entrant in developing the scheme. The existence of these intermediaries is considered by the author to be critical for knowledge diffusion, but it also creates potential information “bottlenecks” and enables the intermediaries to, at times unwittingly, take on the role of gatekeepers for participation in the CHP system in a broader sense. This is especially the case for specific technological knowledge, where particular skillsets (for example, engineering training) and extensive working experience are especially important. While in general the performance of intermediaries is considered satisfactory by new market entrants, some of the schemes observed in detail by the author have indicated a certain level of dissatisfaction by the end users caused by a perceived lack of communication.

The dichotomous nature of CHP knowledge presents a further challenge to the fulfilment of the knowledge exchange function because it necessitates transmitted knowledge to undergo multiple translation processes while moving between the *global* and *local* levels, with translation errors potentially carrying the risk of actor disappointment or, in the worst case, technological failure. Also, it requires actors participating in the knowledge exchange to understand whether a translation is possible at all or what types of knowledge can be successfully translated – this is particularly the case with actors attempting to exchange knowledge across system borders (an example given to the author would be knowledge exchange between a large utility provider’s UK CHP subsidiary and it Polish CHP subsidiary, where vastly different availability of technical/infrastructure resources as well as a different institutional context have made direct cross-border utilization of experience and insights all but impossible).

5.3.4 F4: Guidance of the Search

Within the CHP system, there is little general clarity about the expected development trajectories, specific user wants and demands (Hekkert et al., 2007; Bergek et al., 2008) and other incentives for development due to multiple system-internal but also external reasons. While individual actors within the TIS demonstrate a higher level of clarity about development goals and technology- or governance-related challenges (with most interviewed actors and reviewed case studies clearly outlining the expectations and aims representative for their own position) this clarity is missing at a system level. There the development of effective guidance mechanisms is hindered by the influence of large internal and external actors, some of whom deploy competing visions or have a stake in technologies competing in the wider UK energy system context, and by a high level of uncertainty about government goals caused by a long history of policy shifts (Russell, 2010; Hawkey, 2014). These difficulties are further compounded by a sense of uncertainty about the future prospects of CHP in the face of ongoing decarbonisation efforts in the UK energy system; even though there seems to be a consensus among actors that there is sufficient time left to utilize current short- and medium-term developments.

This lack of a clear vision is seen as an issue by most actors as it prevents any system-level advances within the CHP technological field – while it remains perfectly viable to develop and implement individual schemes based on localized, case-by-case requirements, there is a lack of both resources and agency for developing a broader vision for a CHP future. While there are efforts undertaken by key actors such as the market association ADE (Association for Decentralized Energy) and periodically the DBEIS these efforts are perceived by the actors as worthwhile but lacking the necessary momentum.

A number of actors within the industry are developing next-generation CHP technologies based on low- and zero-carbon concepts such as biofuel-CHP (including biogas, biodiesel but also more exotic fuels such as bio-glycerol), fuel cell CHP or solar CHP, however, these efforts are fragmented and contained to individual companies or

R&D cooperation. While there is a number of experimental and early-market schemes utilizing these technologies operating at the moment, none of them have yet managed to influence development visions and expectations in a significant way.

The general state of uncertainty and fragmentation related to future expectations and development visions for CHP technologies is influenced by a general uncertainty about future development in the UK electricity and heating regimes. This uncertainty generates significant conflict potential between established actors in the heating regime, who tend to support one of two main trajectories: the electrification trajectory which would result in the full electrification of the UK heating sector, or the green gas/hydrogen trajectory which aims to utilize the existing gas grid, which is currently being upgraded, to deliver more renewable forms of gas fuels. There seems to be no current consensus among governmental institutions about the preferred trajectory at the moment, which further increases uncertainty but remains in line with a overall open market/competition approach preferred by the UK public sector.

It is uncertain how this inter-regime conflict will influence future developments of CHP technologies although there currently seems to be a consensus that incumbent CHP based on gas turbines and reciprocating engines would remain viable only in the case of a future green gas or hydrogen based regime, while full electrification of the energy system would have a major detrimental impact as competing technologies, such as ground-source heat pumps, would become far more viable.

5.3.5 F5: Market Formation

There is an existing market for CHP technologies comprised of a number of application niches with differing requirements, motivations, and user group, with the main ones being district/communal heating networks (usually run by public bodies such as boroughs, or public-derived and controlled special purpose companies), single site industrial and other commercial schemes, ranging in size from refineries, over nurseries and hotels to privately run leisure centres and supermarkets, public sector applications (primarily universities, hospitals and wastewater purification centres) and domestic micro-generation. Regarding its size and state of development the market cannot be considered a mass market, but would fit the “bridging market” definition (Bergek et al., 2008) – in a number of very specific contexts such as water purification centres, oil refineries and paper mills virtually all actors are using CHP technologies, but overall there is still significant growth potential. The scope of the market however often transcends the defined boundaries of the observed TIS, as key technological artefacts such as prime movers are sourced from a global CHP market, and then fitted by national/regional actors to meet local performance criteria. In a majority of the application niches the end users do not interact with the market directly due to a lack of specific knowledge, using intermediaries in the form of energy consultancies and developers instead.

While there seems to be a constant market growth, primarily caused by increased communal heating and industrial/commercial CHP developments the existing policy uncertainty and ever-changing policy aims have a negative effect on the overall market growth rate. Further on, the CHP market can also be observed as a part of the wider efficient/sustainable energy technology market, in which case the technology directly competes with other low consumption/emission technologies such as heat pumps, solar panels and others in certain application areas, at times being at a disadvantage due to a objectively lower sustainability performance compared to orthodox zero-carbon technologies. This is particularly visible in the domestic micro-generation sector (Allen et al., 2008; Hudson et al., 2011). In larger schemes and especially in communal networks, the focus of market actors has also shifted to the development of viable business models, with the physical technology only applied if a suitable business and operation model can be developed (Hannon and Bolton, 2015).

5.3.6 F6: Resource Mobilization

The provision of human, financial and physical/infrastructural resources (Hekkert et al., 2011) varies for the CHP TIS, with the availability of resources dependent to a certain degree on the specific application context. Regarding financial resources there seems to be an overall consensus that funds are available to both new entrants and existing actors, although availability and simplicity of access usually depends on the specific context – while at present there are significant funds available for the development of local heat networks (a fund of £320m was confirmed by Government in 2015), private schemes might be subject to more stringent requirements depending on the chosen funding source. There are significant differences regarding the sourcing of financial resources depending on the application area. Public-sector CHP including both district heating networks and single-site applications such as for example hospitals, universities and leisure centres are usually funded and developed as part of broader public programmes, while private sector CHP schemes tend to be financed by the private actor based on their financial viability, with public resources (both for the development and for the ongoing operation of these schemes) being utilized when available but not seen as critical for the development of the scheme.

Considering the availability and mobilization of human resources the author has identified a second consensus among the interviewed actors from all backgrounds on a relative scarcity of trained, experienced personnel, ranging from scheme developers and managers to on-site engineers. The former are perceived as critical actors for the development of CHP schemes, especially in the public DH sector where local authorities usually do not possess the technical, policy-related and technical knowledge necessary for the successful planning, implementation and operation of CHP-DH schemes. This scarcity has a direct negative effect on the development of public CHP-DH schemes, with local authorities who have expressed interest in CHP use being unwilling to take concrete steps towards CHP implementation due to concerns about a lack of knowledge. The scarcity of trained engineers can create issues for both the successful installation and continuous operation and maintenance of CHP schemes. Due to the individual nature of CHP installations and the high reliance of CHP models on the continuous, full capacity operation of CHP engines lack of professional installation and maintenance can lead to performance issues and unexpected downtime, which in turn create losses for CHP scheme operators and have a direct negative effect on their willingness to support and further utilize the technology.

Physical resources in the form of CHP engines and supporting installations are usually readily available, although they at times need to be adapted to meet site-specific requirements due to the highly heterogeneous and localized nature of CHP scheme developments – this availability might be connected to the fact that CHP technologies are procured from the global market when necessary, reducing the dependence on regional/national production. There is no perceived barrier regarding the availability of “mainstream” CHP engines or supporting technologies, with multiple technological options readily available for different application types and sizes. The procurement of renewable CHP technologies, on the other hand, can be more problematic, with a number of projects utilizing biogas- or biofuel-powered engines needing to develop their own, tailor-made solutions.

However, there is a major lack of available infrastructure, especially on the heat side of CHP, as well as increasing barriers for CHP actors attempting to utilize the existing electricity infrastructure. With little tradition in developing heat infrastructure in the form of piping in UK urban areas, present developers are faced with the high costs and significant logistical challenges of retrofitting previously inexistent infrastructure. In new-build developments, this factor is less significant but problems can be created from increased costs and a general lack of statutory powers for heat developers, which may complicate the development of pipelines especially in the case of district heating schemes serving multiple localities. Despite a good overall level of development of the UK National Grid, access to the existing electricity infrastructure can be limited by local network capacities and at times by regional Distribution Network Operators (DNOs), who are perceived to be increasingly negative towards new CHP developments by a number of CHP actors – a development that is likely influenced by the overarching conflict between the centralized and decentralized electricity generation paradigms, and exacerbated by prevailing institutional uncertainty.

5.3.7 F7: Counteract resistance to change / legitimacy creation

Within the borders of the observed system, CHP is considered a potentially useful technology in a broader context, but significant resistance can be created by actors or groups of actors on specific legal, governance and technical issues. Combined with a low level of awareness among the general public and prevalent political apathy, this resistance might not be able to stop or even reverse the development of the CHP industry as a whole, but can create major issues for actors in specific contexts, with negative knock-on effects spreading to wider patches of the industry.

While there seems to be a satisfactory level of public legitimacy for the further development of CHP, this positive development is in parts countermanded by a lack of public knowledge, necessitating resources to be used for information exchange. This lack of public knowledge is also connected to the lack of major “CHP champions” who could engage in an ambassadorial role towards the public and potential future users, and engage in lobbying activities supporting further development of the CHP system. Lobbying activities in general are constrained to the activities of the umbrella organization ADE, who are actively engaged in policy consultations and public discussions, and individual actions by different actors, usually following successful implementation of projects, or the drafting of development plans and strategies on a sub-national level. In the current sustainability and decarbonisation context, lobbying activities supporting CHP development tend to be combined with wider approaches lobbying for a more sustainable energy system rather than being specific to the focal technology.

Further on, CHP actors prefer to shape their activities towards fitting into the existing institutional context rather than attempting to shape the context towards meeting their own aims, with some actors, especially in the private sector, abandoning “fitting into the context” as far as possible, focusing onto necessary compliance and site-specific subjective benefits. This reactive approach has been observed by the author during the review of historical studies on CHP, and its effect on the overall persistence of CHP as a technology despite its low diffusion rate will be discussed in more detail later in this work.

Due to the decentralized nature of combined heat and power, there is also resistance by major regime incumbents, some of whom paradoxically are also actors in the CHP industry through company departments and smaller, purpose-founded firms. This factor is directly connected to a broader debate on the general configuration of a future UK energy sector, with two possible options being a continuation of the current centralized, homogeneous energy generation system or a transition towards a heterogeneous, decentralized energy generation system.[17] Another major source of resistance are the legal and policy arrangements of the existing energy market, and the organisations tasked with overseeing and managing the market – small CHP

[17] While this particular debate is mainly taking place in the electricity sector of the broader UK energy generation system, a similar debate can be observed in discussions about the future of the UK heating sector, where the two potential trajectories are electrification (which would enable decentralized generation of heat and by extension power) or a “greening” of the existing gas network towards utilization of green gas (biogas) or hydrogen, in which case the heating system would retain a centralized nature due to an ongoing reliance on the existing infrastructure which is operated by a number of major gas suppliers.

schemes often face major barriers for entering the energy market due to the current trading system or due to a lack of local capacity, while regional energy network operators are increasingly more demanding in approving new CHP projects. Most of this resistance can be described as *passive* rather than *active* resistance, although more recently cases of active resistance to further CHP development have been observed by market actors.

The resistance encountered by CHP proponents can be compared to the broader resistance to low-carbon transitions in the UK energy sector discussed by Geels (2014), as well as to instances of regime resistance to sustainable technologies discussed in studies on the Netherlands (Verhees et al., 2013), and the UK (Smith et al., 2014). Due to the fact that, on a technological level, CHP represented a less radical change than “true” zero-carbon technologies, cogeneration proponents did not encounter the direct resistance and overt adversarial action encountered by, for example, solar farms (Smith et al., 2014) and wind farms. some of the policies developed or affected by regime actors had a direct negative effect on the development of the CHP TIS – a prime example being the negative effect that the reduction of the UK feed-in-tariff (FiT) had on the diffusion of domestic micro-CHP.

5.4 Barriers and blocking mechanisms

In the following section, the author will review the internal barriers and functional failures that are hindering the development of the observed technological innovation system. Drawing on the analytical steps proposed by Bergek et al. (2008) the author will attempt to identify relevant inducement and blocking mechanisms influencing the development of the observed TIS. In order to evaluate the system-external and internal components of an identified barrier, the author will draw on the system failure typology developed by Klein Woolthuuis et al. (2005) and the analytical approach proposed by Hekkert et al. (2011) for identifying structural causes for functional barriers.

5.4.1 Barrier 1 – Lack of a shared vision

The first identified internal obstacle to the development of the CHP TIS is a lack of a strong, shared vision on the future performance and development trajectory among the system actors. The main system function generating the obstacle is F4 – Guidance of the Search, although it has negative effects on F2 – Knowledge generation, F6 – Resource mobilization and F7 – Counteract resistance to change / legitimacy creation. Different actors supporting a number of different visions cause a fragmentation of development trajectories, with entrepreneurial activities, production, experimenting and research happening in multiple separate localized micro-contexts, reducing the positive effect on a system level and creating uncertainty among new entrants and external observers. This fragmentation has an additional negative effect on resource mobilization, as necessary resources are allocated within the system on a local or, at best, regional level, while the perceived heterogeneity of the system reduces the ability of system actors to engage in meaningful lobbying activities or designate major actors as “champions” or “ambassadors”. From a structural perspective, the lack of a shared vision can be related to the relative weakness of networks within the system and to varying institutional contexts within the different application areas, as well as a general sense of uncertainty regarding the overarching national energy system development trajectory. Taking a system failure perspective, this barrier can be described as a case of institutional failure, with “hard” institutional failure in the form of government policy uncertainty and the lack/reduction of targeted support compounding a system-internal “soft” institutional failure manifested in the lack of vision alignment (Klein Woolthuis et al., 2005).

“There are different visions and expectations – there is no single vision shared by a lot of actors, partly that’s because CHP is quite unusual in the UK – there are different ways of analysing its impact on the energy system now and in the future; different assumptions could be made…(…)…Different actors therefore think about CHP in different ways, and draw different conclusions.” (Head of Policy, interest association)

The general lack of a shared vision is also manifested through the system-internal uncertainty about the future viability of the cogeneration concept in a low- or zero-carbon energy system, with a general consensus about the potential for “renewable” CHP without a general specific agreement on the preferred trajectory (at this point, it needs to be pointed out that this lack of agreement is in no way caused solely by CHP actors, as there are parallel discussions throughout the UK energy sector, with multiple positions put forward as possible solutions).

5.4.2 Barrier 2 – Lack of available resources

This obstacle is directly connected to the fulfilment of F6 – Resource mobilization and mainly relates to the lack of human and infrastructural resources, which present a serious barrier for the development and satisfactory operation of CHP schemes, particularly within the district heating network application area. One set of blocking mechanisms contributing to this barrier is related to the lack of available infrastructure in form of piping for heat networks, which is further exacerbated by the lack of institutional support for heat developers in the form of statutory rights, which greatly complicates the practical development of heating networks, especially in the case of retrofitting or extensions of existing networks. A second set of blocking mechanisms is related to a general lack of trained personnel, both on the project developer/manager level and on the engineering level. While the former mainly slows down the development of existing projects and increases the dependence of new entrants on existing actors or consultancies/intermediaries, the latter increases the risk of improper technical installation resulting in unsatisfactory performance or breakdowns of existing schemes, which in turn creates frustration and feelings of disillusionment with CHP technologies among end users. The structural cause for a lack of infrastructure, as well as the lack of necessary institutional support for heating infrastructure development is mainly system-external and can be tracked to the broader societal construct and informal institutions related to the provision of heating in the UK. On the other hand, the cause for a lack of human resources is both system-internal and system-external – while a lack of trained technical staff can be related to an overall lack of government support for training and education, a low number of experienced system developers and managers can also be related to the relatively weak state of the network as well as a low general interest and high entrance barriers to engaging with CHP schemes.

5.4.3 Barrier 3 – Blocking mechanisms created by embeddedness in electricity and heating sectors

The particular position of the UK CHP system in the UK institutional framework, where it is positioned in between and connected to both the electricity and heating (gas) sectors creates a particularly complicated blocking mechanism as it requires CHP to simultaneously fit in two institutional contexts which are not always aligned and who in both cases are designed using a centralized basic design diametrically opposite to the underlying decentralized technical and institutional design of CHP applications. This opposition creates major entrance barriers in form of licensing, production models and caps, and pricing models for electricity producers regulated by Distribution Network Operators and the central regulator OFGEM, and through the lack of formal institutions for a heating market. Together, these barriers make market participation by small CHP schemes very complicated or even outright impossible (Toke and Fragaki, 2008), while even large CHP operators are inclined to use the majority of the generated energy on site. While there are some attempts by government actors to alleviate some of the entrance barriers through simplified market participation and licensing models (for example, License Light in the Greater London Area), overall the access of CHP to the heating and electricity sector is more strictly regulated than in comparable continental European countries.

Further on, the general uncertainty related to the future development of the UK energy sector does not reduce the impact of these blocking mechanisms – while there is an underlying regulatory framework and development strategy, changes are frequent, depending on the current political climate and there is little regulatory constancy, causing actors to focus on short payback periods and short-term developments, which is at odds with the mid- to long-term return on investment inherent to the majority of CHP schemes. Besides the frequency of the changes, their scope is also perceived as a barrier by CHP actors, with an interviewed expert stating that:

“The only thing I would really wish from policymakers would be to make changes a bit more gradual, a bit more. Because businesses can adapt, but not overnight.” (Sales Manager, specialist CHP company)

5.4.4 Barrier 4 – Localized nature of CHP schemes

The final identified obstacle relates to the context-specific, localized nature of CHP applications and the resulting barriers to cooperation and transfer of usable knowledge between the local, national and global levels. As a rule, CHP schemes are tailored based on site specific use patterns, electricity and heat demand, which necessitates a comparatively high level of locality-unique project development, creating localized knowledge and reducing the necessity for communication beyond the project scope once the project has entered a sufficiently advanced stage of development. This localized knowledge is then subjected to potential translation losses when exchanged with other actors as context-specific elements related to micro-level institutions, social and spatial characteristics are often not translatable to more generic contexts.

Also, the dependence of CHP on specific energy sector institutions reduces the usability of non-technical knowledge imported from actors belonging to other TIS across system borders despite the presence of a supranational institutional context in the form of EU directives and regulations. This was in particular observed by the author in the case of actors working within multinational companies utilizing company-internal networks to engage in cross-border knowledge transfers; while CHP-specific knowledge was certainly available, the usability of the available knowledge was relatively low due to differences in institutional frameworks, available infrastructure and user expectations and usage patterns:

“I mean, the issue that we do find is that it’s very different country to country, so, for example, our networks in Poland are very different because they don’t… so within London, our issue is digging up the roads and they’re very congested, there’s lots of services they’re all in there, there’s bus lanes and all that kind of things. Whereas in

Poland, they often, they don't have those problems because it's simply a different setup there. And so, you know, they don't even have the pipes below ground but have them mounted against things." (Contract Manager – District Heating, utility company)

5.5 Chapter summary

This chapter formed the first of the two analytical stages planned for this research project, and focused on the internal structure and fulfilment of internal structures of the CHP industry, conceptualized as a knowledge field-based technological innovation system (TIS). At the beginning of the chapter, the author defined and delineated the system following a number of delineation steps proposed by Bergek et al. (2008, 2015) and Markard et al. (2015). Having defined the system's *breadth* and *depth* as well as having outlined the system's spatial borders, the next step was an in-depth structural analysis of the CHP TIS, reviewing key system actors, existing actor networks, relevant system institutions and key technological factors in the form of artefacts, infrastructures and dominant technical trajectories.

Following the structural analysis, the author reviewed the system internal dynamics through a functional analysis of seven core TIS functions: entrepreneurial experimentation and production, knowledge development, knowledge exchange, guidance of the search, market formation and counteracting resistance to change/legitimacy creation (Hekkert et al., 2011). The findings of this review can be also considered relevant for the second analytical stage, with the internal TIS functions broadly equivalent to the fulfilment of niche functions, in particular the nurturing function (Smith and Raven, 2012).

In the final section, the TIS analysis was concluded by identifying a number of *internal* barriers and blocking mechanisms negatively influencing the fulfilment of the system's function, and therefore the development of the system and diffusion of the focal technology. While existing literature allows, and to a certain degree calls for a broader barrier/blocking mechanisms analysis (Hekkert et al., 2007, 2011; Bergek et al., 2008) and the inclusion of broader contextual structures and interaction dynamics (Bergek et al., 2015), this was not followed up in this analysis due to the existence of the second, SNM-based analytical stage which focused on external barriers and contextual influence, using existing analytical constructs – regime(s) and the landscape. This second stage will be the focus of the following chapter, with the analysts' perspective changing to a bottom-up, externally oriented focus, exploring the interactions of system-internal elements (niches) with external, contextual factors (regimes, landscape) and potential influences of interactions between external actors and institutions (Raven and Verbong, 2007, 2009).

6 Extending the focus – a review of combined heat and power application niches and their interaction with incumbent regimes

Following the CHP system-centric analysis undertaken in the previous chapter by following the technological innovation systems (TIS) analytical approach, in this chapter the author will follow the theoretical proposal of Markard and Truffer (2008) on MLP-TIS conceptual similarities by extending the scope of the analysis outwards and investigating the interactions between CHP technologies and the UK electricity and heating regimes, the dynamics and development processes within the different CHP application areas (Smith and Raven, 2012) and the interactions between the regimes themselves which are deemed as relevant for the development of co-generation technologies (based on the multi-regime interaction work by Raven and Verbong (2007). In doing so, the author will attempt to both shine more light on micro-level dynamics and the role of individual micro-level developments, and to extend the scope of the observation beyond the system borders, taking into account external context as suggested by Jacobsson and Bergek (2011) and further discussed by Markard et al. (2015) and Bergek et al. (2015). With regard to the latter, however, it needs to be pointed out that the aim is not to remain within the analytical scope of a technological innovation system analysis, something that can certainly be attempted utilizing recent conceptual developments, but to try and utilize the theoretical connection to the niche-regime-landscape system of constructs utilized in the multi-level perspective approach (Geels, 2002). By doing that, the author hopes to contribute towards the broader theoretical goal of this work, which is to explore the conceptual connections and especially the possibility for empirical utilisation of these connections, with the *ultima ratio* being a streamlining of the currently quite heterogeneous field of transitions research (Markard et al., 2012).

In the following sections, the theoretical model used in this part of the empirical analysis will be outlined together with its connections to the TIS model utilized in the previous chapter, followed by a discussion of regime barriers based on Kemp et al. (1998) as well as more recent work by Smith and Raven (2012). Following that, the internal dynamics and the niche-regime relationship will be outlined and discussed. At the end of the chapter, the author will also refer to potential regime-regime relationships, the role of the broader UK socio-economic landscape and the influence of regime and landscape changes on different types of context (Bergek et al., 2015) within which CHP is developing. Compared to the previous section, which was intended to primarily be a current-state analysis, this section will extend more towards previous developments and their influence on CHP, and utilize information about ongoing developments gained from historical academic and public sector data and primary data collection in the form of case studies, keeping in line with the tradition of transitions researchers (Verhees et al., 2013).

At this point, the question may be put forward about a possible extension of this enquiry towards the development of future scenarios; while this is certainly an interesting line of thought and development of scenarios has been utilized in, or the outcome of multiple research projects in the UK energy sector (Foxon et al., 2010; Foxon, 2013; Ricardo-AEA, 2013; RTP Engine Room, 2015) there have been far fewer future-oriented enquiries in Transition Studies, with existing research falling in the area of quantitative modelling rather than qualitative enquiry (Walrave and Raven, 2016). While TIS-based reviews do result in the generation of suggestions to policymakers (Bergek et al., 2008), these suggestions can be subject to limitations, with the actual usability being discussed (Markard et al., 2015). Therefore, we can conclude that *neither* of the two approaches can be used for true future-oriented work if executed as a qualitative study – certain recommendations and bits of knowledge can be extracted, but cannot be considered true future scenarios in the tradition of scenario building (Bradfield et al., 2005; Amer et al., 2013).

6.1 The analytical constructs

The two key analytical constructs utilized in this chapter are the concepts of *niche* and *regime*[18], representing distinct application areas for CHP technologies and the two incumbent socio-technical regimes fulfilling the societal functions of electricity provision and heating. Following the conceptual framework put forward by Markard

[18] A far more detailed discussion on the niche and regime concepts, the relationship between the MLP and the TIS and Transitions Studies in general is provided in the Literature Review chapter

and Truffer (2008) the author will further on place these constructs in relation to the TIS observed in the previous chapter, with a detailed comparison and analysis of the theoretical connections and implications on the empirical case taking place in the following chapter.

In order to conceptualize the analytical construct in a sufficiently rigorous way, the initial consideration needs to be on the nature of the observed niche(s), its internal structures and its border. Within the field of Strategic Niche Management, niches are generally defined as protected spaces (Kemp et al., 1998; Smith and Raven, 2012) where specific user needs and availability of resources (Levinthal, 1998) create favourable conditions for the utilization of a technology which, at the moment of observation, may not be competitive in the broader market. Further on, a distinction needs to be made between "market niches" and "technological niches", with the former potentially operating as functional anomalies within an existing regime (Markard and Truffer, 2008), while the latter represent initial, actor-created and actor-maintained protective spaces with a more unstable set of rules (Schot and Geels, 2008). Finally, a niche perspective needs also to consider the relationship between local-level applications subject to localized contexts which apply knowledge extracted from, but also feed knowledge back to a global innovation level (alternatively, this can be imagined as a "global niche") (ibid.). Keeping these definitions in mind, the key challenge posed to the author is the operationalization of the empirical case, combined heat and power generation in the UK, utilizing the niche concept. In order to do so, the author proposes to consider the CHP knowledge field as a "global", developed niche, with the different UK application areas for CHP technologies representing a number of market niches, some of which might have a high degree of mutual similarity with regards to the main actors, the networks and both formal and informal institutions. The market niches constantly interact with the broader "global" niche and are influenced by incumbent regimes, both on an individual and a collective level. They are considered to be a more developed version of the initial technological niche discussed in the majority of the SNM literature (Raven, 2006), having developed proto-market and/or niche markets, as well as users belonging either to the "innovators" or "early adopters" group (Rogers, 2003) whose specific needs and willingness to utilize CHP technologies outweigh possible negative effects caused by technological inefficiencies or barriers (Levinthal, 1998), or the lack of significant economies of scale. Further, on, the market niche exhibits a high level of conceptual similarity with the “application niche” concept utilized by Markard and Truffer (2008), while the market niche-global niche interaction shares similarities with the niche – TIS interaction. This point will be discussed in more depth in the following discussion chapter. For the purposes of this research project, the author is proposing the following typology, which was developed based on the results of previous research work on combined heat and power and related technologies and concepts, and the author’s own insights gained from primary data collection in form of a series of expert interviews and multiple case studies covering different application contexts (both the interviews and concepts are described in more detail earlier in this thesis):

1) CHP in communal/district heating networks (CHP-DH)
2) CHP in other public single-site applications (Public single site CHP)
3) CHP in industrial/commercial single-site applications (Private single site CHP)
4) CHP utilized for domestic micro-generation (Microgeneration CHP)

While there is a significant overlap between these niches with regards to the utilized technologies, networks, actors and to a certain level expectations and visions, there are also a number of significant differences in the institutional context – while the entire broader CHP niche operates within the context of UK energy legislation and a liberalised energy market, on a localized level the different niches can be subject to different contexts related to the main actors (for example, a local authority implementing a district heating network operates within a different context compared to a tomato nursery utilizing an on-site CHP engine). In the following paragraphs, the author will attempt to provide a short outline of each of the four application niches.

6.1.1 CHP in communal/district heating networks (CHP-DH)

This application niche covers the utilization of CHP prime movers as an energy source in communal/district heating networks (Hawkey 2012, 2014; Hawkey et al. 2013; Russell, 2010). Within this application context, local authorities take on a key role as lead actors within schemes, either running the schemes directly or through a purposely developed vehicle (most often, an “arm’s length” energy services company (ESCo) or a public-private partnership (PPP) (Hannon and Bolton, 2015)); in certain cases, the operation of parts of the scheme can also be subcontracted to a third party, usually a

CHP company or the CHP subsidiary of a major utilities provider. One important facet influencing the development of CHP schemes within this application niches is the importance of business models regulating the operation of the scheme, the roles and stakes of the main actors and the relationship with the end users, who are usually private households in council-run housing (Hannon and Bolton, 2015, Hawkey and Webb, 2016). A second important factor are power dynamics and political relationships between local, regional and national-level governance bodies – while this factor might have lost some of its historical importance (Russell 1986, 1993, 2010; Hawkey 2014; Weber 2014) questions of energy governance and particularly of access to finances still can develop into „make-or-break" decisions when developing public schemes. Due to the physical characteristics of the infrastructure required for the successful operation of a DH network, the institutional background of the UK heating regime also plays an important role; such as, for example, the presence or absence of statutory rights for heat developers. Finally, the wider development context of DH networks can be slightly different to the one utilized by private, single-site CHP developers – while factors such as sustainability and cost efficiency undoubtedly play an important role, social issues such as the provision of affordable heating and energy to disadvantaged social groups also play an important role.

6.1.2 CHP in other public single site applications (Public single site CHP)

This application niche describes the utilization of CHP engines for the provision of energy and heating in public sector single site applications such as hospitals, universities, leisure centres, wastewater treatment plants and other public buildings[19]. Besides the application of CHP in communal heating networks, and in a number of energy-intensive industry sectors, public single site CHP includes some of the „traditional" and well-developed user groups for CHP technologies. Quoting an interviewed expert working for the CHP subsidiary of a large utilities company:

"So, DH NHS fantastic, as well as universities, very traditional CHP customers, we've been looking after since the 1990s. Leisure centres as well, so again, that's mostly

[19] Interestingly enough, a number of public buildings in Westminster, London, were supplied by heating generated by a CHP engine for a long period in the second half of the 20th century (Russell, 1986), however, the author has found that this scheme has since been replaced by all-electric heating

public sector, but again one of the clear, obvious applications of CHP due to the high consistent heat demand." (Sales Manager, specialist CHP company)

Compared to the CHP-DH application niche, the main difference is that the energy and heating output of the cogeneration engine is utilized within a single geographical location, excluding the necessity of installing and operating heating infrastructure or business models required to coordinate the actions of and relationships between a number of users. Nevertheless, public single site CHP actors operate within the broader contextual framework of public sector operations, and may be limited in operating and developing CHP schemes by regional and national public policy. Public single site actors also often lack the necessary knowledge and skills for successful development of CHP schemes, instead utilizing consultancies acting as intermediaries between the scheme developer and actors operating within the global CHP niche, and often sub-contracting ongoing operations and maintenance of CHP schemes to specialized firms (which can, but do not have to be the same actors who developed a scheme in the first place). This outsourcing of CHP development and operation is a characteristic which is also present in the private single site CHP niche, the main difference being that public single site schemes are financed through public funds, which can range from nation-wide programmes such as the Renewable Heating Initiative (RHI) to local regeneration funds and are subject to public procurement and tendering rules. The dominating development context in public single site CHP schemes is cost savings and emissions reductions, which tie into the current landscape trajectories towards a low carbon economy, and towards maintained public sector austerity.

6.1.3 CHP in industrial/commercial single site applications (Private single site CHP)

This application niche has a rather broad scope, covering all private sector CHP schemes in industrial and other commercial applications, independent of the scheme size or the industrial sector (for example, CHP schemes are utilized in the chemical sector, the oil industry, but also in the hospitality sector and in retail). In general, all of these schemes are designed to utilize their electricity and heat output within the limits of the site, again making additional infrastructure unnecessary[20] The main contextual difference to the public sector application niches lies in the fact that commercial CHP developments are based on the case-specific suitability of CHP technologies for a particular actor, related to cost savings, environmental impact reduction or a combination of both. Further on, operative decisions are usually made by a single actor (the company which has comissioned the scheme) and while the broader institutional context provides a general frame for the development of the scheme, it has less direct influence on CHP development than in the public sector. A characteristic shared with single site public sector development (and to a certain extent, CHP-DH) is a reliance on intermediaries for scheme development and subcontracting of operations and maintenance to specialized actors; in some cases, the private sector actor doesn't even have direct influence on choosing CHP as a technology but only provides a general brief related to cost savings and/or emissions reduction targets:

“So, (the) reasons for CHP was not just given by the end customer, they just wanted cheaper costs with what I just explained. So, we introduced CHP because it had the benefit of having the CO2 as a by-product as well.“ (Scheme Manager, specialist CHP consultancy)

In some cases, CHP technologies are utilized primarily because of the necessity of compliance with local rules and regulations, with energy and cost savings considered to be a positive add-on effect:

“*At the time, I guess, there was a previous iteration of the London Plan and that’s what inspired the CHP. So we used gas-fired CHP and that’s part of UC so complying to our Section 106, complying to the London Plan and to our planning permission. We have also some other elements we need to comply to like a fuel cell, so on-site we will have to install a fuel cell, that’s our section 106 obligation and we need also to do studies about biomass instead of using gas-fired CHP.“ (Project Director, property development company)*

[20] There do exist a number of large industry CHP schemes where excess heat and/or power are exported to other company sites or to neighbouring communities, however, they were not included as a separate category as there are no indications that there are significant institutional or contextual differences to general private sector CHP applications

Actors in the private single site CHP niche are likely to act in a very pragmatic way, with CHP schemes utilized based on proven economic and/or regulatory benefits – the existence of a convincing business/financial case for CHP is a necessity for the development of the technology. This business/financial case can be and has been historically influenced by institutional changes, however, overall the private single site application niche is less susceptible to them, with recent entrants opting to remove themselves from participation in public sector programmes, and from dependence on public sector funding as far as possible.

6.1.4 Microgeneration CHP

The final identified application niche covers the utilization of CHP technologies for domestic micro-generation of electricity and heating, with a variety of technologies in development including Stirling engines, Organic Rankine Cycle engines and fuel-cell based designs (Hudson et al., 2011). Compared to the other three application niches this niche is far younger, with the first experimental applications taking place in the 1990s and a fledgling industry developing in the late 1990s and early 2000s (Allen et al., 2008). Niche actors in this niche also operate within a markedly different development context: while they are still subject to the broad institutional framework of the UK energy market, their main customers are private households and they are in direct competition with a number of other prospective micro-generation technologies such as solar PV, ground source heat pumps or micro wind turbines (ibid.). Compared to the other three application areas, where a somewhat stabilized (niche) market has developed, the microgeneration CHP niche is at an earlier stage of development, with even CHP actors expressing uncertainty about its future trajectory and its development prospects:

"I don't think domestic consumers will accept the level of… they won't accept high levels of maintenance, that's not what they want. (...) Until there's a technology out there that can do the same for domestic CHP consistently and deliver the reliability, maintenance-free benefits of what the current boiler will, it will never ever trump the boiler." (Sales Manager, specialist CHP company)

With the primary users in this application niche being individual households, there is an even greater reliance on intermediaries which is further compounded by severely limited resources (a private household is very unlikely to task a specialized CHP company with the development of a CHP scheme for a single residential building), as well as a reliance on CHP companies providing ongoing technical support and required maintenance in order to ensure a reliable, fault-free operation of the CHP engine. Due to weak agency of the primary users, reliance on public funding and stable regulations is high, with institutional changes having significant impact on the viability of micro-generation technologies in general and CHP in particular (Hudson et al., 2011; Geels, 2014). An additional issue encountered by developers of micro-CHP technologies is the lower sustainability performance of (non-fuel cell) micro-CHP compared to „true" zero-carbon technologies, while fuel cell-based micro-CHP units are not sufficiently mature from a technological point of view (Hudson et al., 2011). This issue will also be discussed, in more detail, in the barrier analysis later in this chapter.

Having listed and described the application niches utilized in this part of the analysis, the author will move to the meso-level by outlining the two regimes influencing the development of CHP in the UK – the UK electricity regime and the UK heating regime. A socio-technical regime is defined as a „set of rules embedded (...) in the knowledge base, engineering practices, corporate governance structures, manufacturing processes and product characteristics" (Geels, 2002, p. 1260). For the purposes of this analysis, the author will extend the notion of „regime as a rule set" to encompass the regime infrastructure (Raven, 2007) and will further on take note of the actors who uphold and reinforce the regime rules with the aim of exploring how agency and expression of various forms of power by these actors influence the regime and the barriers impacting CHP development (Geels, 2014). Within the scope of the following description, the author will highlight the institutional and infrastructural characteristics of the two regimes, as they have a key impact on the development of renewable and decentralized technologies in general and CHP technologies in particular. Both regimes share a lot of commonalities, being part of the broader UK energy sector and having much of their formal institutional framework within the liberalized UK energy market (Toke and Fragaki, 2008), however, there is a number of differences between the regimes, as well as inter-regime dynamics, especially related to the future development trajectory. All CHP application niches as well as the CHP global niche are interacting with elements of both incumbent regimes even though elements of one of the regimes might have increased relevance for a particular application niche or an individual scheme, this multi-regime interaction was already observed and analyzed by Raven and Verbong (2007) in a study on the development of combined heat and power technologies in the Netherlands.

6.1.5 The UK electricity regime

The first of the two regimes outlined and observed in this work is the UK electricity regime, delineated as encompassing the institutional framework regulating the UK electricity market, and the infrastructure that enables the functionality of that market and actor interactions within the market. The roots of the current liberalized energy market have developed in the 1980s under successive Conservative governments, with the privatisation process implemented in 1990 and largely completed by 1998 (Pearson and Watson, 2012). The liberalization and privatisation can also be conceptualized as part of a broader, landscape-level political and economic development towards denationalisation and privatisation which dominated (and arguably still dominates) the UK econo-political landscape since the late 1970s/early 1980s. Formalized rules and regulations for the operation of the energy market are codified in form of the British Electricity Trade and Transmission Arrangements (BETTA), enforced on a national level by the market regulator OFGEM and on a regional level by a number of distribution network operators (DNOs). Further institutional context is provided by the UK Energy Act, the 2011 Energy White Paper and a number of applicable transnational EU regulations[21], with the key regulation on energy trading being the EU Regulation on wholesale energy market integrity and transparency EU 1227/2011 (REMIT). The regime is further on strongly defined by its infrastructure components – the National Grid, a highly developed, UK-wide network of electricity transmission infrastructure. Drawing back to the late 1920s, the National Grid has undergone several context changes, but as a whole is suited to support a centralized system of energy generation, where a low number of major market competitors operates a comparatively low number of large-scale generation plants. The codified regime rules are rather hostile towards small, decentralized generators,

[21] This represents the current state of the system, but might not be the case in the near future dependent on the progress of the British departure from the European Union

with major obstacles for small scheme development in the form of predictive capacity trading, electricity price dynamics and the role of DNOs as gatekeepers regulating generation licencing and network access. At present, the development of the UK electricity regime is influenced by landscape developments towards a low carbon economy, and the necessity to utilize new energy sources in the face of ever-decreasing deposits of fossil fuels.

6.1.6 The UK heating regime

The second observed regime, the UK heating regime is defined by the author as the rule-sets, formal and informal codes and regulations and the supporting infrastructure necessary for the provision of the societal function of heating. In observing the fulfilment of this function, it becomes clear that the notion of a “heating regime” is a rather diffuse one, with a large majority of UK households and other users (85% of UK households according to Glover, 2016) utilizing gas for heating purposes. This together with a general lack of codified rules for non-gas heating leads towards the conclusion that the role of the UK heating regime is largely taken over by the UK gas regime, with heat generators outside of the gas regime operating in a rather unsupportive environment, lacking supportive regulations. The gas regime is regulated on a national level by the 1995 Gas Act and the 2005 Unified Network Code, which are enforced by OFGEM and National Grid Gas, the latter acting as the main transmission system operator (TSO). As the national grid is shared with the electricity regime (though two different types of technical infrastructures are used) the gas regime is also regulated on a supra-national level by the EU REMIT regulation. Informally, the gas regime is dominated by a number of major gas providers, who supply gas as a fuel rather than directly supplying usable heat – while there are internal regulations on heat trading, primary data collected by the author indicates that the provision of usable heat is, from a regulatory point of view, not well known to individual employees. The weakness of the UK heating regime is further influenced by three major factors – the absence of statutory powers for heating developers, technical challenges related to the transmission of usable heat and a lack of existing heat transmission infrastructure, and user preference towards on-site heat generation in the form of gas boilers. The absence of statutory powers regulating infrastructure development is a major barrier to regime actors developing new schemes and/or installing additional infrastructure because compared to electricity and telecommunications developers, heating developers are subject to the cooperation of landowners, being unable to request the requisition of plots of land. Technical challenges related to the transmission of usable heat limit the extent of heat network development and the provision of heat in sparsely populated rural areas, while a lack of existing infrastructure in the form of heat networks creates a need for costly infrastructural developments (which in certain cases can be made even more expensive, or downright impossible due to the lack of statutory powers outlined above) as part of any larger-scale heat network implementation. Finally, UK heat users exhibit an increased level of conservativism and resistance to change, preferring established localized heat generation methods in the form of boilers to shared heat provision – some of the reasons found for that preference are initial installation and ongoing maintenance costs, familiarity with established technologies and a perceived lack of control over the heating system in the case of non-localized generation. Regarding its future prospects, the landscape developments towards a low carbon economy and, as part of it, a low carbon energy system which are influencing the electricity regime have an even greater impact on the heating regime (and its substitute, the gas regime), with an imminent regime-internal conflict between two major prospective trajectories (author's notes from the 2016 Heat Summit). One potential trajectory is the ongoing utilization of gas as the main heating source, with carbon reductions and increased sustainability achieved through the use of biogas and potentially hydrogen instead of the currently used natural gas. This trajectory is preferred by established gas regime actors, who have made major investments into the existing gas infrastructure with the objective of upgrading it to biogas-capable standards. The second, competing trajectory aims to solve the emissions and costs challenges through full electrification of the UK heating regime, resulting in integration of the heating regime into the existing electricity regime (Raven, 2007). This trajectory is supported by multiple actors operating within the existing skeleton heating regime, but outside of the dominant gas regime, as well as by established actors from the electricity regime who see opportunities for market growth. There seems to be no current governmental consensus on the preferred trajectory, with the responsible ministry (the Department for Business, Energy and Industrial Strategy (DBEIS)) preferring to allow competing actors and technologies to compete under open market conditions, with institutional support for one or the other trajectory being largely withdrawn (author's notes from the 2016 Heat Summit).

As a conclusion to this section, the author has developed a graphical outline of the utilized constructs, showcasing the analytical units and the perceived connections and interactions between them. The graphic is partially based on work by Geels (2002), Schot and Geels (2008) and Markard and Truffer (2008) although it is adapted by the author to fit the empirical case analysed in this work.

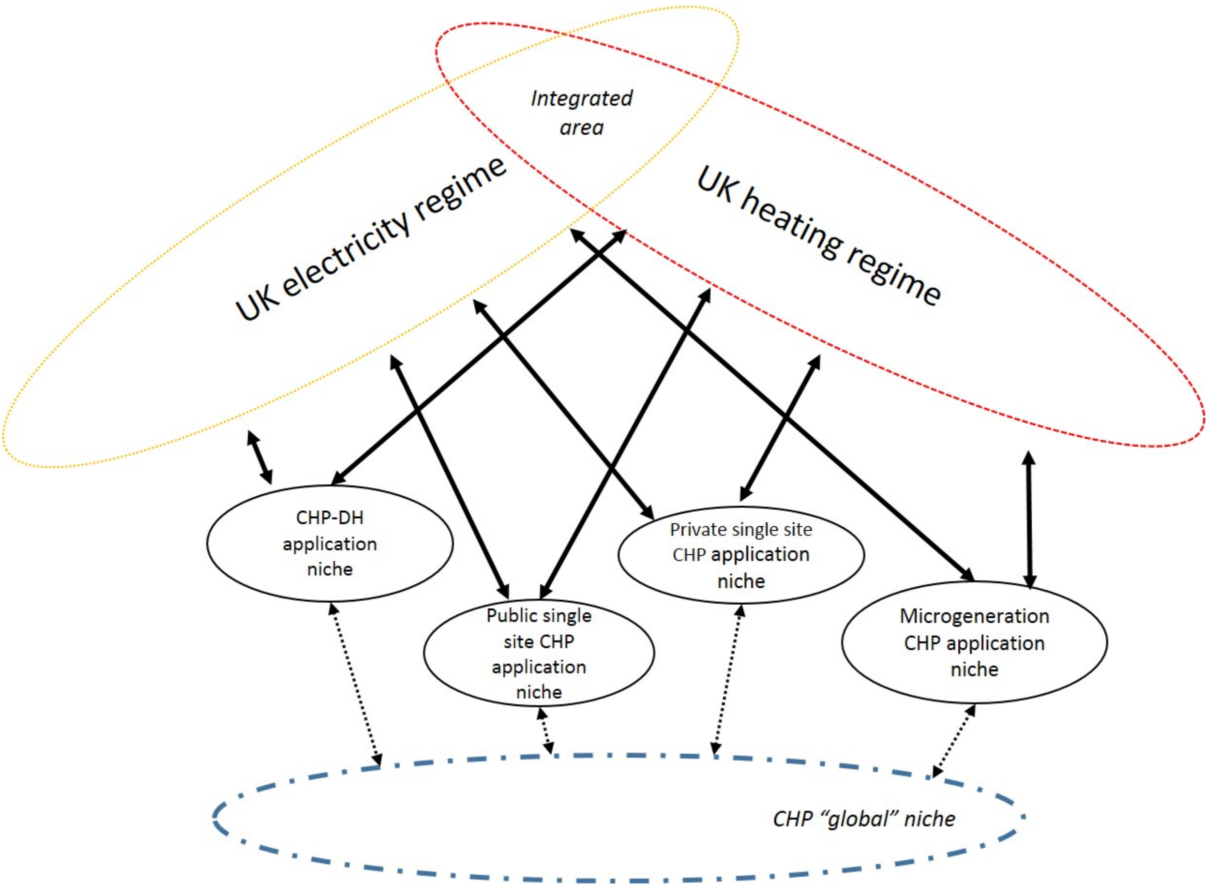

Figure 9: Visualization of the analytical constructs and their relationships

It needs to be noted that the constructs are not sorted according to their level of aggregation, where the individual application niches represent the lowest level of aggregation, followed by the more extensive "global" niche and the electricity and heating regimes. The "integrated area" shared by the electricity and heating regimes represents the institutional overlap in the form of shared rules and regulations (the UK

Energy Act, the 2011 Energy White Paper, the EU REMIT directive and the EU Energy Efficiency directive (2012/17)). Further on, there are certainly structural overlaps as well as significant technological overlaps between the application niches – these will be discussed in more detail in the following sections, but could not have been included in the visualization due to the limitations of this medium. The relationship between the application niches, the CHP "global" niche and the electricity and heating regimes is similar to the (global) niche-TIS-regime-landscape relationship illustrated by Markard and Truffer (2008, p.612) – this similarity is based on the author drawing on that model with the intention of applying it to an empirical case, and evaluating it where possible.

6.2 Barrier analysis

In the following section the author will discuss the external barriers for CHP development, conceptualized as a set of selection sub-environments belonging to the material (in particular infrastructural), institutional and socio-cultural dimension following a typology created by Smith (2007) and further refined by Smith and Raven (2012). These barriers include the *established industry structures*, *dominant technologies and infrastructures*, guiding principles and established heuristics in the incumbent *knowledge base*, *existing markets and dominant user practices*, the *cultural significance* attached to specific regimes and the selection environment created by *public policies and especially political power*. In the following table, the author will list the different selection environments and the processes and institutional settings through whose barriers to niche developments are created.

Selection environment	**Processes and institutional settings creating barriers**
Established industry structures	Network relations, industry platforms, strong ties between users and producers, shared routines and heuristics among industry actors, existing technical and non-technical capabilities, resource allocation procedures
Dominant technologies and infrastructures	Established and codified technical standards, infrastructural arrangements, technology alignment (or lack thereof) with existing infrastructures
Knowledge base	Guidance of search processes and knowledge development geared towards incremental changes to incumbent regime, insufficient resource

	allocation to new knowledge development, lack of incentive for research actors to engage new technology development
Existing markets and dominant user practices	Established market institutions, supply and demand mechanisms, price mechanisms, user preferences and user routines
Public policies and political power	Regulations supporting incumbent regime, policy networks and regime actor influence on policy development, lobbying activities by regime actors, lack of interest by government actors
Cultural significance attached to a specific regime	Symbolic value of existing regime for general public / user base, innovative technologies perceived as challenges to established user constructs

Table 16: External barriers to niche development (adapted from Smith and Raven, 2012)

The barriers will be discussed in across all four application areas, with individual selection sub-environments particular to one or more specific application niches highlighted as such and also discussed in a table summary at the end of this section.

6.2.1 Established industry structures

The UK energy industry consists of a number of large utility providers (colloquially referred to as the “Big Six”) operating in a centralized system based on well-developed infrastructure in the form of the National Grid and regulated through two sets of regulations, the British Electricity Transmission and Trading Arrangements (BETTA) and the 2005 Unified Network Code, which are enforced by an independent market regulator on the national level and by a number of distribution network operators

(DNOs) and/or transmission network operators (TNOs) on a regional level. The institutional context for electricity and gas trading favours large market actors over small, decentralized providers, with small providers unable to directly sell electricity to the grid (Toke and Fragaki, 2008). While there is a level of interest in CHP technologies among the existing large market actors, with some of the “Big Six” maintaining subsidiaries specializing in cogeneration technologies, these actors do not exhibit any significant agency towards supporting further development of CHP.

6.2.2 Dominant technologies and infrastructures

The majority of currently utilized CHP technologies is based on existing power and heat generators and can be considered to be incremental improvements, enabling CHP engines to be used interchangeably with generators and boilers without cogeneration capacities. “Renewable” CHP technologies such as biofuel or fuel cell based engines, on the other hand, require the development of new supporting technologies and/or the establishment of supply chains, which can prove to be a major challenge in certain settings. While the existing electricity transmission and distribution infrastructure does not represent a direct technical barrier to any type of CHP, access to this infrastructure is regulated and may be blocked by network actors, primarily the distribution network operators (DNOs). On the other hand, the lack of dedicated heating infrastructure in the form of heat pipes represents a major barrier for all CHP applications in which the generated heat is not used on-site.

6.2.3 Knowledge base

While previous research indicates that the creation, availability and distribution of knowledge is not a significant barrier due to the CHP being more of an incremental than a radical improvement (Weber, 2014), existing knowledge still tends to be generated in site-specific settings, with knowledge transfer and utilization in more generic context complicated due to the strongly site-specific nature of individual CHP schemes. Knowledge development and search heuristics in energy-related R&D activities are generally open to different technological approaches and solutions, including CHP; however, the lack of dedicated resources or direct public sector support reduces research activities to single projects in specific settings or R&D

activities initiated by large market actors, again for utilization in specific sectors. While the broadband approach to energy research can be seen as generally positive as it stimulates the development of heterogeneous ideas, it also lowers the amount of targeted support for specific technologies, leading to longer development processes. This lack of targeted knowledge development and diffusion support is also reflected on CHP skills development, with a lack of both trained CHP project developers and managers, and engineers familiar with CHP technologies.

6.2.4 Market and dominant user practices

This selection mechanism represents a significant barrier for the development of CHP technologies in general, primarily due to high market entry barriers in the form of restrictive licensing by distribution network operators and predictive production modelling, and disadvantageous pricing policies having a negative effect on the economic side of CHP schemes that usually are operating as small electricity producers. While there has been a number of improvements over time, for example through the introduction of a simplified licensing system for small generators, pricing discrepancies compared to major producers are still creating a disadvantageous situation for CHP operators, motivating them to use as much of the generated energy as they can on-site (compared to, for example, France, where the optimal economic case for a small producer reviewed in the course of this research was to sell all of the generated electricity to the national network, then buy power back at discounted prices). Dominant practices among private users can form a barrier for the heat provision function of CHP; with private users in the UK exhibiting a strong preference for conventional gas boiler based on-site heat generation. Further barriers for domestic applications are created through decreased viability of CHP at low power outputs and a growing consensus among a number of CHP actors about the unsuitability of CHP for domestic settings. While CHP microgeneration units have lower initial procurement costs compared to other micro-generation technologies (Allen et al., 2008), domestic users tend to compare CHP units to technically similar conventional boilers without an energy generation capacity, whose initial purchase cost as well as ongoing maintenance costs are even lower. Commercial users are generally neutral towards CHP, with decisions for CHP use based on cost reductions and/or emissions gains obtained using the technology rather than on any particular preference for the technology itself. An example would be the following statement by an energy consultant obtained in the course of an industry case study implemented by the author:

“So, (the) reasons for CHP was not just given by the end customer, they just wanted cheaper costs with what I just explained. So, we introduced CHP because it had the benefit of having the CO2 as a by-product as well.” (Scheme Manager, specialist CHP consultancy)

Once a commercial user has made an initial decision for the implementation of a CHP scheme, both the implementation and ongoing operation and maintenance are often outsources to specialized companies. While most often this is done by the same company, changes in project ownership and development responsibilities can lead to installed CHP schemes being “inherited” by different market actors, who can face operations issues due to lack of compatibility or adequate documentation.

6.2.5 Public policies and political power

Overall, energy-related public policies create a neutral to slightly supportive environment for the development of CHP technologies in general, with current development plans and international regulations supporting high efficiency and/or low emissions generation technologies. However, there is also little direct support for CHP, with Government being perceived as overlooking CHP and its potential benefits:

“CHP is not front of mind with most current government politicians and there are no current government policy initiatives.” (Director, energy consultancy)

“And you know, Government is supportive of CHP but it should be, for the benefit it brings we would expect it to be more supportive and what we’re really trying to push is for Government to explore how all the benefits that CHP can bring to the system are appropriately valued.” (Policy Officer, interest association)

However, a significant barrier is created by abrupt policy changes (implementation of BETTA trading arrangements, changes to the feed-in-tariff (Geels, 2014), changes to available subsidies (RHI) and changes to gas policies) which have a significant impact on the long-term viability of CHP schemes and through that on the strategies of CHP actors as well as the willingness of additional actors to enter the market. While some of these changes may not be perceived as hindering *per se* by the technology’s proponents, the abrupt nature of their implementation, changes or dissolution creates a general atmosphere of uncertainty. The lack of direct support for CHP is partially caused by its low public visibility, with large parts of the public having no knowledge about the technology or about possible benefits from utilizing CHP. This is caused in part by the highly technical nature of CHP and the fact that its larger applications tend to be in specific industrial sectors, but also by the above-mentioned lack of direct government support, with the latter condition creating a self-reinforcing negative feedback loop (Lack of direct government support -> Low public visibility -> Lack of visibility leading to low level of knowledge/awareness among political actors).

While there is no direct, overt political opposition to the development of CHP, a lack of large, powerful "champions" supporting the development of the technology reduces the capability of the technology's proponents to use lobbying to influence the government's stance of CHP or to protect the technology from policy changes which might cause unintended negative consequences to the cogeneration industry – the latter being recognised as a potential problem by a number of interviewed experts:

"It needs to be noted that the current government developments against CHP are not deliberate – they are rather unintended/side consequences." (Director, energy consultancy)

6.2.6 Cultural significance attached to a specific regime

Both the electricity and the heating (gas) regime and the electrical power and useable heat provided by them are considered key elements of the UK as a modern post-industrial economy by government actors and the public. However, despite the key positions of both regimes, there is a high level of user pragmatism regarding the technical solutions utilized to fulfil the societal function – provision of electrical power and usable heat to commercial units and private households. This user position can be observed in the following quote regarding domestic customer requirements for heating solutions:

"They won't accept high levels of maintenance, that's not what they want. They expect to get their boiler a quick once-over once a year and they have to run perfectly the rest of the time." (Sales Manager, specialist CHP company)

However, this pragmatism also can create barriers for relatively immature technologies, as there is little patience even for promising technologies that don't fulfil present user requirements, which can be aggravated by knowledge on previous negative experiences by other users (Sauter and Watson, 2007). This can be further exacerbated by prevalent user conservativism in the form of adherence to a tried-and-true construct of an in-house heat generator operated directly by the user. While this conservative stance can be successfully engaged through public information and ongoing communication, user distrust based on potential loss of control as a consequence of joining communal heating scheme can form a potential barrier in certain settings. Public information and communication campaigns can themselves be subject to barriers due to the technical nature of CHP, which makes benefits of CHP use hard to explain:

"And all the benefits that CHP brings are quite technical benefits and quite complicated benefits so it's hard to tell that story in an engaging way without people getting confused."

Another cultural barrier is manifested in the form of user thinking of heat services as use of a particular fuel (mainly gas); due to this, there is a distinct lack of perception of heat itself as a service. To illustrate this point, private users will often equate heating use and the associated costs with the use of gas rather than thinking of heating as a service in itself; this complicates both the introduction and acceptance of business models linked to selling heat services.

In summary, barriers created through cultural significance of existing regimes, while present in certain settings, do not have a major negative impact on the development of cogeneration technologies, especially not if compared with the far more formidable cultural barriers present in, for example, transition processes towards more sustainable transport options (Kemp et al., 1998).

As a conclusion to this overview of general barriers to CHP development, all barriers are summarized in table form together with a qualitative assessment of their strength, expressed through the ability of a particular barrier to hinder or prevent development of the technology, while also considering the ability of niche actors to engage and dismantle or circumvent these barriers (these actions will be discussed later in more detail using the *niche empowerment* typology proposed by Smith and Raven (2012)).

Selection environment	**Identified general barriers**	**Strength/significance of barrier(s)**
Established industry structures	Institutional context of both regimes favours centralized system with few large actors	**Strong**
Dominant technologies and infrastructures	Lack of heating infrastructure	**Medium**
Knowledge base	Little centralized guidance caused by lack of shared vision	**Medium**
Existing markets and dominant user practices	High barriers for small capacity generators joining the capacity market	**Strong**
Public policies and political power	Abrupt policy changes can create negative conditions for industry	**Medium**
Cultural significance attached to a specific regime	Little cultural significance assigned to regime technologies, user preferences can cause weak barrier	**Weak**

Table 17: Summary of general barriers to CHP development

Following the above general barrier analysis, the author will next investigate the presence of regime-generated barriers specific to one or more of the identified application niches. This will be done for each of the niches, with the particular barriers highlighted and their connection to regime and/or government actors highlighted where applicable. At the end of the section, all specific barriers will be summarized in table form.

6.2.7 Barriers specific for CHP-DH

While CHP-DH development is affected by a majority of the general barriers discussed in the previous section, additional barriers for the development of communal heating networks are manifested in the form of lack of political power at a local governance level (Russell, 2010), as well as a lack of decision-making ability on the energy sector for devolved regional governments; for example, DH network developments in Scotland are subject to a conflicting separation of responsibilities – while electricity and gas are regarded as reserved, and are regulated by the central UK government, heat has been devolved to the Scottish government. While the centralization of energy policies is not as prevalent as in the early days of district heating development (Russel, 1986; Hawkey, 2014), local authorities can still face significant difficulties in obtaining the necessary financial resources for developing extensive communal heating networks, reducing the economic case for co-generation technologies. This financial barrier is further exacerbated by the high cost of large CHP-DH schemes, partly due to a general lack of available heat infrastructure, whose development is both costly and difficult from a planning point of view due to non-existent heating regulations and especially a lack of statutory powers for heat developers. The latter complicates the planning process for infrastructure development, as individual stakeholders can block or complicate technical planning due to a variety of reasons, an example for which can be seen in the following quote from a DH scheme manager describing the development of a DH network in Southeast London:

"But the pipe routes, nearly all of them do involve interacting with Network Rail. And so I think it's, I think it would be… and also, the other thing as well, is that, um, so if you're putting in a gas main, a water pipe or electricity, um, they have, they're statutory providers whereas district heating isn't at the moment. So again, it's just another thing

where it's not quite a level playing field and even with council support it's not quite as easy as putting in other services. We're sort of a lower priority." (Contract Manager – District Heating, utility company)

Potential barriers related to the availability of financial resources can also impact the planning process for CHP-DH schemes, where some form of cooperation with private actors can become necessary, requiring the development of business models which can fulfil financial requirements, customer relationship demands and control interests of all participating actors (Hannon and Bolton, 2015; Hawkey and Webb, 2016).

6.2.8 Barriers specific for public single site CHP

The barriers for public single site CHP applications are relatively similar to the barriers faced by actors in the CHP-DH application niche, with the main difference being a lower relevance of the non-existence of statutory powers, as well as lower barriers related to financial resources, both due to the relatively smaller size of single site CHP schemes compared to communal heating networks. Most public single site CHP applications are in settings with a natural high heating demand (hospitals, leisure centres, wastewater processing, universities), which tends to create a positive financial case, however, a general lack of public finances in the current context of public sector austerity can create issues for some schemes (for example, NHS trusts running hospitals). The following quote from a former CHP development manager at a major public hospital illustrates this, as well as offering potential solutions for circumventing this particular barrier:

"Capital funding is a stumbling block, but there are interest free loans such as Salix that healthcare can benefit from. I feel there should be leadership at Department of Health and NHS England level, and perhaps also from NHS Improvement, to challenge Trusts that have not yet considered this technology." (Case Study 5, E-mail interview)

A second set of barriers, which also applies to private single site CHP and CHP-DH, is connected to the availability of specialized knowledge on CHP, especially related to the development and operation of CHP schemes. Within the public sector, professionals with that type of knowledge are both rare and in high demand, leading public bodies developing single-site CHP to rely on consultancies and specialized technical developers from the CHP industry, outsourcing the development and operation of CHP schemes to them. While in the majority of cases this causes no significant negative impacts apart from increased development costs, it also creates a situation of dependence, where lack of action and/or effective communication by any of the actors can hinder the development and/or operation of the scheme, and even decrease the willingness of public actors to utilize CHP technologies in the future. A good example for this type of barrier can be seen in the following quote from a regional manager describing the development of a public leisure centre in South London and the attitude to CHP technologies in the leisure sector:

"However in practice the [company] doesn't always find out that something has happened – this is another type of communication issues – and it creates frustration...

...[company] wasn't involved at the design stage – it inherited the unit and the niggles, which soured the taste of CHP a bit...Some people (in the industry) like CHP but some people in management have slightly lost trust in it" (Regional Technical Manager, leisure management company)

6.2.9 Barriers specific for private single site CHP

In addition to the knowledge-related issue discussed in the previous section, which can result in communication and coordination issues, private single site CHP niche development is constrained by a number of specific barriers, some of which are particularly relevant to CHP schemes of a specific size.

The main barrier for industrial single site CHP development are regulatory restrictions related to available benefits, access to the energy capacity market and energy pricing. These barriers are generated both by the existing UK capacity market and its institutional framework, and by public policies developed to support a centralized energy generation system. Current developments related to the removal of embedded benefits are likely to further strengthen this barrier as the financial case for large industrial CHP plants would be significantly worsened, as illustrated in the following quote:

"Things such as threats, the embedded benefit removal, which is the avoided cost of not using the transmission network, so by on-site generation or; and that removal is

sort of valued at £45/kW. That's a huge amount of money for a lot of manufacturing sites that have CHP and chase triads and avoid the winter peak." (Policy Officer, interest association)

While mid- and small-size private CHP schemes are diffusing at a fast rate, they can also face barriers related to market access and energy pricing, even though not all schemes engage with electricity sales. There is indication of barriers being created by market institutions and policymakers, with local distribution network operators (DNOs) increasingly resisting the development of new schemes:

"Personally, probably the bigger concern is network applications, with the DNO. I'm seeing more and more across the UK that district network, DNO operators are becoming more and more sort-of anti-CHP, anti-decentralized generation, becoming trickier to deal with, to get project off the ground, fitting larger caps on what's allowed to be generated even if you're not planning to export anything." (Sales Manager, specialist CHP company)

6.2.10 Barriers specific for microgeneration CHP

Specific barriers for the development of microgeneration CHP are mainly related to existing markets and dominant user practices, and to a lesser degree to public policies and the cultural construct attached to the provision of heating in the United Kingdom.

Compared to other application areas for CHP technologies, microgeneration cogeneration in the form of domestic-sized CHP-capable boiler units competes with a number of alternative microgeneration technologies, such as solar thermal, photovoltaics or ground source heat pumps (Allen et al., 2008). Users likely to take up microgeneration might see CHP as not being „sufficiently sustainable" due to its reliance on combustion processes compared to other zero-carbon options, while users for whom the sustainability performance of the technology is less relevant may prefer conventional boilers due to their lower costs and complexity:

"The maintenance aspects of CHP sub-100 kW electric in my opinion makes all CHP under a 100 kW at this moment in time financially tricky. The smaller you go, the less financially viable it becomes. I don't think domestic consumers will accept the level of… they won't accept high levels of maintenance, that's not what they want. They

expect to get their boiler a quick once-over once a year and they have to run perfectly the rest of the time. Until there's a technology out there that can do the same for domestic CHP consistently and deliver the reliability, maintenance-free benefits of what the current boiler will, it will never ever trump the boiler.“ (Sales Manager, specialist CHP company)

This also indicates the presence of a financial barrier for microgeneration CHP which is influenced by energy market rules as well as established user practices in providing heating at a household level – within the scope of the technology itself microgeneration CHP suffers from negative economies of scale related to its power output, which contributes to making it financially unviable compared to established heating generation technologies.

Another significant barrier for the developmetn of microgeneration CHP is the lack of adequate policy support; while there is a number of public policies supporting the development of microgeneration capabilities (Allen et al., 2008; Hudson et al., 2011), abrupt changes in these policies following changes in the overall political direction such as the lowering of the Feed-In Tariff (Geels, 2014) and changes to the Renewable Heating Incentive (RHI) have reduced the financial viability of domestic microgeneration to private households.

Following is an overview of the barriers specific to one or more CHP applicaiton niches, structured following the barrier typology developed by Kemp et al. (1998) and Smith and Raven (2012):

Selection environment	**CHP-DH**	**Public single site CHP**	**Private single site CHP**	**Microgeneration CHP**
Established industry structures	**-**	**-**	**Barriers created by incumbents**	**Microgeneration not supported by incumbents**
Dominant technologies and infrastructures	**Heat infrastructure unsuited for decentralized developments**	**-**	**High capital cost of required tech for large schemes**	**Increased maintenance costs**
Knowledge base	**-**	**Lack of available knowledge**	**Lack of available knowledge**	**Lack of available knowledge**
Existing markets and dominant user practices	**-**	**-**	**Regulation of capacity market**	**Users preferring either conventional or zero-carbon**
Public policies and political power	**Lack of political power for LA actors**	**Lack of political power, finances**	**Uncertain public policies**	**Uncertain public policies**
Cultural significance attached to a specific regime	**-**	**-**	**-**	**-**

Table 18: Overview of barriers specific for one or more application niches

6.3 CHP niche processes

In this section the author will analyse the inward- and outward-oriented niche processes which protect niche actors and the focal technology from the external selection environments and support internal niche development (Kemp et al., 1998). Following the niche function typology outlined by Smith and Raven (2012), the author will investigate:

1) Shielding processes
    a. *Passive* shielding where generic spaces are operationalised by niche actors
    b. *Active* shielding where protective spaces are created through strategic, delibarate action
2) Nurturing processes, further separated by Schot and Geels (2008) into
    a. Development of shared *expectations and visions*
    b. Creation and maintenance of *social networks*
    c. Learning processes, especially deep, second-order learning (Schot and Rip, 1996)
3) Empowerment processes
    a. Empowering to *fit and conform*, where the niche innovation is developed to be competitive within an unchanged selection environment
    b. Empowering to *stretch and transform*, where the aim of niche actors is to change existing regimes and their selection environments in favour of the niche technology

Utilizing the analytical structures defined and outlined at the beginning of this chapter, the author will review the existence and state of fulfilment of niche processes for the four identified application niches. Due to overlaps between the different application niches, as well as the partially shared overlapping institutional framework of the UK energy sector and the capacity market, a number of processes will be highly similar across multiple niches – this will be pointed out in each relevant case. Finally, at the end of the section the author will provide a summary of the observed niche processes in table form.

In general, there is little evidence of *active shielding* across all observed application niches – while niche actors are willing to swiftly appropriate existing and newly created genertic protective spaces and utilize them to support the development and diffusion of cogeneration technologies (for example, the Renewable Heat Incentive (RHI) was never developed with the intention to solely support cogeneration technologies, but it was nevertheless quickly appropriated by CHP actors as a financial resource, particularly in the public and private single site niches), they in general lacked the political power and agency to deliberately create and maintain protective spaces. Examples for *active shielding* include the Good Quality CHP (CHPQA) certification developed by the former Department for Energy and Climate Change (DECC), currently operated by the Department for Business, Energy and Industrial Strategy (DBEIS), and CHP-specific funding available through specialized organisations such as Salix Finance.

Nurturing processes can be observed to certain extent in all application niches, as well as between niches, but are limited in their scope and intensity by restrictions to learning caused by the influence of localized contexts on larger CHP schemes, making experimental learning only partially transferable to different spatial localities. Further limitations to nurturing processes are a consequence of a lack of shared visions caused by a lack of dominant actors, or „champions", leading to multiple actors developing different, and at times contrasting sets of expectations towards the technology, as can be illustrated in the following quote:

"There are different visions and expectations – there is no single vision shared by a lot of actors, partly that's because CHP is quite unusual in the UK – there are different ways of analysing its impact on the energy system now and in the future; different assumptions could be made." (Research Fellow, UK university)

While there is a certain level of network activity, most of it is concentrated in a single, umbrella network maintained by the key interest association for CHP in the UK, the Association for Decentralized Energy. The effectiveness of this single network in facilitating information exchange and actor communication is not clear – while some actors report successful utilization of the network's resources in the development of their schemes, a similar number of actors notes a lack of available information forcing them to either rely on intermediaries – consultancies or to develop their own projects, the latter very often being the case if elements of a planned scheme are particularly innovative. Examples for this could be the development of a small, experimental CHP scheme at one of the University of Greenwich's campuses, or the development of two CHP schemes in office buildings belonging to a major business consultancy company, where biodiesel refined from used cooking oil was used as the main fuel. While the former scheme was able to draw on CHP knowledge collected by other actors through local networks and specialized companies participating in the project, developers of the latter scheme were unable to draw on any knowledge, forcing them to develop the project completely on their own:

"No, exactly for that reason, there's nobody to try (…), so it's pretty much learning by experience." (Scheme Manager, engineering company)

The main network recognizes this weakness and the potential negative impacts on actors considering entering the market and actively attempts to address them by encouraging knowledge exchange in the form of regular events and practitioner forums, however, it is recognized that these processes and the associated activities need further improvement:

"And so it's important to have a place for somebody without much knowledge to have a guidance document or something. We're trying to get the information out as much as possible but it is not as good as we would like it. Having more events where you have LAs or universities or public sector being able to… talking to experts about what they need to provide and what they need to look for when they're doing a project is really important." (Policy Officer, interest association)

While there is a fair amount of reflexive learning across all CHP application niches, knowledge transfer can be limited due to multiple factors: the location-specific characteristics of large CHP schemes and especially district heating networks, which reduce the local-global exchange of knowledge between local projects and the national level (Geels and Raven, 2006) as context-specific variety is primarily defined by local contexts, and therefore only partially translatable to a broader national context. Further on, the relative weakness of existing niche networks limits the access to knowledge for new entrants and actors engaged in non-conventional projects; this is particularly true for public sector actors where specific technical knowledge is not usually available in-house:

“And it’s… so we are actively looking now how we can develop a heat master plan for the borough, what kind of support is out there, both financially and expertise, but it’s a struggle when you don’t quite know what you’re looking for, to know where to find the programme support, so that’s I think the stage we’re at, at the moment.“ (Manager, local government)

Finally, the efficiency of learning processes is somewhat limited for systemic learning due to uncertainty on the desired future trajectory for cogeneration technologies caused both by multiple parallel visions about the future of CHP, and a lack of either powerful actors or targeted support for a particular vision by the UK government. This leads to a situation where learning effects remain limited to particular application areas and specific scheme characteristics, with knowledge exchange and transfer often happening on an actor-to-actor basis once a direct contact between actors has been established:

“We’ll be talking to experts in other boroughs who, some of them used to work here and were very interested in this back in the day, we haven’t involved any, um… I should know, Housing, I haven’t seen the report but they did employ consultants to look at what the best financial options were, in terms of installing individual boilers or use CHP or just maintenance of the existing system.” (Energy and Carbon Reduction Manager, local government)

In addition to learning processes happening within the spatial borders of the United Kingdom, there is evidence for a certain level of cross-border learning drawing on CHP knowledge from other European countries, however, this learning is often constrained to technical learning focusing on the engines, supporting technologies and technical infrastructure due to significant differences in the national institutional frameworks in the energy sectors, as well as the availability of different resources (for example, in countries with a long tradition of district heating such as Germany or Sweden, CHP actors face far weaker barriers related to the availability of infrastructural resources such as heat piping). Cross-border learning has been observed both in the public sector, where LA actors have sought out knowledge from LA actors in other European countries, and with private actors where individual experts working in major multinational utilities have utilized company-internal communication networks to exchange knowledge with colleagues active in other localities. Following is an example for local authority CHP developers drawing on knowledge from other locations:

“(The) ailings of many heat networks in the UK is that they built to British standards, um, which mean, well they’re basically unfortunately not good enough if you’re going to give a fair price to the consumer. So, we’ve ensured that ours are going to be built to gold level Scandinavian standards and we’ve also spent an awful lot of time trying to win the hearts and minds of our consumers.” (Head of Sustainability, local government)

Finally, with regards to niche empowerment processes, most developments observed in a review of historic CHP utilization in the UK, as well as the current state of the technology indicate that niche actors mostly engage in *fit and conform* empowerment, attempting to enable the technology to compete within the existing selection environment. While *stretch and transform* empowerment was also observed, those processes mostly take place either in limited experimental locales in the course of supported development projects, or by alignment of CHP actor visions and expectations to broader change trajectories such as the decarbonisation of the UK energy sector. The latter developments could also be considered a form of *fit and conform* empowerment within the context of an intended broader system change, as CHP actors are attempting to forecast and fit the technology into a prospective future regime configuration, taking little attempt to actively influence the change trajectory.

With regards to a conception of empowerment processes as deliberate, strategic action by niche actors, the author would certainly consider the *fit and conform* empowerment processes to be the result of deliberate agency, however, it is questionable as to what extent these activities can be considered strategic, as often they seem to be *reactive processes* to broader regime- or landscape level developments, with niche actors attempting different fits in order to match the functions of the technology to opportunities in the incumbent regime configuration. An empirical example could be the shift of CHP-DH focus from a primarily social (affordable energy) aim during the first two national DH programmes to a primarily environmental (emissions and resource use reduction) focus within the sustainability/decarbonisation discussion of the early 2000s (Hawkey, 2014). These findings together with the author’s own insights are in line with earlier findings on niche empowerment by

Verhees et al. (2013) who have reported on parallel occurrences of both *fit and conform* and *stretch and transform* empowerment, resembling a piecemeal strategy at times. Niche empowerment processes are further on influenced by the preference of UK public bodies for open market competition, which somewhat limits the ability of niche actors to actively influence existing selection environments as the public focus is on the requirement for the niche technology to successfully compete within the existing regime.

"Whereas the UK, its regulations are all about consumer protection, competition, may the best technology win. So, you know, when we compare ourselves with other European countries, it's pointless looking at technologies, it's everything to do with the regulatory and market environment that they've being deployed in." (Senior Manager, regional government)

Having discussed CHP niche processes in a more general context, the author will now proceed to do the same for processes specific to a particular application niche.

6.3.1 CHP-DH niche processes

Shielding processes in the district heating application niches are mostly realized in the form of *passive shielding*, with niche actors utilizing existing programmes such as localized regeneration programmes, local or regional funding such as the London Energy Efficiency Fund (LEEF) or broader support such as the current government funding for development of heat networks, with £320 million being made available. None of these programmes are however developed solely for CHP, creating competition with other prospective technologies as well as uncertainty about future development directions. When *active shielding* processes take place, they are implemented mainly in localized environments, with devolved governments (such as, for example, the Scottish government) or local authorities creating favourable environments for the development of district heating schemes. Due to the strong connection of communal heating developers, who are often local authorities, on policy-based support and fulfilment of broader political aims, the operationalization of effective shielding is often different due to the fact that CHP technologies fall between the electricity regime and the heating (gas) regime, while most shielding measures, and in particular policy- or public programme-based shielding are aimed at only one of the regimes.

Nurturing processes in the CHP-DH niche are broadly similar to the general CHP nurturing processes discussed above, although user networks are often formed through general interaction between local authorities, with individual developers using general communication channels to share experiences and transfer knowledge between different projects. In some localities, additional smaller-scale networks are set up by regional authorities, such as for example the Greater London Authority's (GLA) Decentralised Energy Programme Delivery Unit (DEPDU), however, with most of these networks being created and maintained through specific projects and/or programmes, their lifespan is often limited upon ending or termination of the initial project/programme (Hawkey, 2014). Regarding the development of expectations and visions, most actors active in this application scheme tie the visions of CHP-DH development to the ideas of affordable energy, therefore continuing some of the initial drivers behind CHP development (Russell 1986, 1993; Hawkey, 2014) while also developing expectations of lowered emissions and efficiency increases resulting in lower resource costs (which is indeed an attractive prospect in the current age of ongoing public austerity). *Learning* processes take place mostly on an individual, project-specific level, with some of the relatively few available experts working on multiple subsequent developments, taking their accumulating knowledge from project to project – a development that is mirrored on company level by specialized CHP developers and consultancies. An example for project-specific learning and exchange of knowledge can be seen in the following quote, which illustrates some of the actions prospective CHP actors can take in order to acquire the necessary knowledge:

"We've recruited a team of experts in the industry to make this happen. It's a very small number of people that actually know how to do this, so we've recruited a few of those, um, I think, a very, very experienced team that have done this in Europe and in the UK. We've also, at board level we've bought in industry experience, so Tim Rotheray who's, runs the ADE, he's on our board, um, we've also got a guy called Michael King who's got experience of heat networks in Aberdeen with Aberdeen Heat and Power so they bring that industry expertise at the board level. The operational team itself has been there, done it and learned the lessons." (Head of Sustainability, local government)

Additional learning can take place through the above-mentioned localized actor networks in case such a network is present, or if there are resources available for its development, however, the knowledge accumulated in such networks is at risk of fragmenting back to individual actors upon the dissolution of the network. Local-national-global learning and knowledge transfer is especially complicated for CHP-DH developers due to the highly site-specific nature of district heating networks and the influence of local institutional context, together with varying availability of technical resources and/or means to develop the necessary technical infrastructure; while there is no question that learning does take place and knowledge can be transferred between actors, this can be done to a lesser extent than for single site CHP applications.

Niche empowerment processes in the CHP-DH niche mainly take the form of *fit and conform* empowerment, with niche actors lacking the (political) power and the agency to directly influence regime incumbents. Communal heating networks are designed to operate within the institutional framework of both regimes (electricity and heating/gas), with *empowerment processes* often oriented at improving the financial case for district heating – one prospective development trajectory being the implementation of business models connecting LA developers with private actors or community owned schemes (Hannon and Bolton, 2015). From the different heating networks observed by the author, virtually all operate as either LA-owned ESCOs or public-private partnerships (an example for the latter would be the district heating scheme operated by Southwark Council, where heating is provided by the SELCHP plant which is run by the private utility company Veolia).

6.3.2 Public single site CHP niche processes

In public single site operations, most of the niche processes taking place are broadly similar to the niche processes in the CHP-DH application niche, which is a consequence of similar key actors, who have to operate in broadly similar local, regional and national institutional frameworks. However, there is a number of important differences, which are mainly caused by the difference in scheme size, utilization of the provided services (electricity and heat) and different expectations from the technologies.

Due to the smaller scheme size compared to district heating networks, actors developing public single site CHP are more able to implement *active shielding* measures by allocating funding at local level and/or implementing planning requirements for the development of public buildings. Further on, some of the actors implementing CHP schemes in public buildings are able to utilize *passive shielding* in the form of sector-specific support programmes (for example, universities or hospitals).

This is directly connected to the development of expectations and visions for CHP technologies used in single site public applications, where the key expectations are invariably increased energy efficiency, cost reduction and improved environmental performance in the form of reduced emissions – example for this can be seen in the following quotes from public sector case studies reviewed by the author:

"The Trust was keen to use CHP for its efficiency credentials and, due to our 24 hour heat demand, the technology fit our purposes very closely. We were also keen to reduce our environmental impact, and through the installation of the two 3MW engines, the Trust avoids over 11,000 tonnes of CO2 annually." (Manager, public sector organisation)

"The [council] set planning requirements to contractors which included a requirement for the building to achieve a "very good" BREEAM rating, which is unusual for leisure centres. The BREEAM rating and other planning requirements related to sustainability and energy efficiency were also part of the broader planning permission for the site." (Leisure Contract Officer, local government)

The latter quote also indicates the ability of councils to provide indirect *active shielding* through supporting high-efficiency technologies – even though there is no direct mention of CHP technologies being the sole or preferred solution, the broader context of this case and similar cases reveals that the required performance can only be satisfactorily provided by co-generation engines. Network development for single site public CHP largely mirrors the networks utilized by CHP-DH actors, with the addition of sector-specific networks such as NHS internal networks, higher education sector alliances and/or leisure sector associations such as Sport England. While these networks are not solely focused on CHP, they can nevertheless be utilized to share knowledge and provide information on CHP to interested prospective actors:

“…points out that Sport England had developed a fund a few years ago which was intended for investing in sustainability in leisure centres – more information should be available on the Sport England website, including advice to local authorities and leisure clubs.” (Regional Technical Manager, leisure management company)

Due to the size of public single site schemes, knowledge necessary for scheme development and operation is usually acquired through sub-contracting the planning, implementation and operation and maintenance to specialized external providers – these can be both energy consultants specializing in CHP and the engineering companies providing the technical equipment. In some cases, CHP is not specified by the public actors themselves, rather, a number of targets is set and the technical details left to the developer-intermediary:

“Subsequently the council left the detailed planning to the contractor; the contractor made a list of recommendations on certain energy products to be used in the new centre and CHP was one of them.” (Leisure Contract Officer, local government)

It can be argued that in this case the developer takes on the role of lead actor, with learning processes taking place at their level, as well as along their connections to the wider CHP industry. While this presents a somewhat effective (if potentially costly) solution for public actors, it also poses the risk of excluding them from benefitting from learning processes and knowledge exchange.

Empowerment processes are broadly similar to the *fit and conform* empowerment implemented by actors in the CHP-DH niche, with the technology developed towards fitting into the existing selection environment. While there is evidence of regime transformations in the broader field of energy efficiency and environmental performance, there is little evidence that these transformations are a result of agency by CHP niche actors.

6.3.3 Private single site CHP niche processes

In the private single site CHP application niche, shielding is implemented in a similar fashion to the broader CHP context discussed above: most processes can be classified as *passive shielding*, with actors utilizing different general policies and measures in order to improve the business case for CHP technologies. Examples for these policies are the Renewable Heat Incentive (RHI), carbon tax benefits (CCR/CCL rebates and exemption) based on the increased efficiency of CHP technologies, or benefits in kind for on-site generators and TRIAD payments. However, there is increased uncertainty about the ongoing availability of these schemes due to previous abrupt policy changes such as the reduction of Feed-In-Tariffs (FiT) (Geels, 2014), current policy developments towards a re-evaluation of some of these schemes and a general uncertainty about the future development direction of the UK energy sector, which leads some CHP developers to forego available shielding mechanisms altogether and attempt to implement CHP schemes which are competitive in the current state of the energy and hearing regimes, leading to, at times, unconventional solutions (one such solution was observed by the author in the case of a CHP plant operated by an energy consultancy at a tomato nursery in Kent, where heat and CO2 was used on site, supported by thermal storage, while the prime movers were run based on capacity market peak prices, with almost the entire energy output being sold into the capacity market). In line with the niche empowerment typology, this type of development can be seen as an end-stage result of *fit and conform* empowerment, however, this approach would also severely limit the number of sectors in whom CHP is viable, slowing or altogether stopping further diffusion of the technology.

There is little evidence of *active shielding* – while actors active in this application niche can certainly benefit from general shielding such as the CHPQA certification or CHP-specific capital funds, actors who would potentially be able to engage in lobbying such as large utility companies with CHP subsidiaries have so far shown little interest in engaging in such behaviour. This also relates to the prevalence of *fit and conform* empowerment over *stretch and transform* empowerment, with the majority of actors attempting to optimize the performance of CHP within the existing selection environment. This was done rather successfully for small and medium-sized CHP, where a strong and expanding market niche exists, while the diffusion of large, industrial CHP schemes is currently stagnating despite potential for further market expansion, with actors preferring to protect existing investments over developing new ones.

Development of *expectations and visions* is closely tied to the corporate nature of most actors in the private single site CHP sector – the companies implementing CHP schemes and the different specialized consultancies, engineering companies and subsidiaries of large energy sector companies – with CHP technologies expected to provide increased operational efficiency with regard to electricity and heat generation, resulting in reduced energy costs, and improved environmental performance through emissions reduction, or improvements towards the fulfilment of planning regulations or building standards. An example for the latter would be biofuel CHP engines playing a relevant role in the achievement of a BREEAM outstanding rating for a London office building:

"Well, it gave us 6 additional points, along with innovation, it gave us 2 innovation points, which are hard to come by, for the biodiesel, um, progression. So, yeah, an additional 8 points which is, it's quite a lot in the BREEAM marking." (Scheme Manager, engineering company)

However, it needs to be noted that there is also some uncertainty present about the long-term viability of CHP in a decarbonizing energy sector, in particular in urban environments, with actors expressing reservations about the long-term viability of conventional, gas and diesel-fuelled CHP prime movers:

"And there are some people in the industry at the moment saying that we should not use any more gas fired CHP because if we keep on doing that we won't meet our carbon targets. (…) So I think, in a way, the legislation in terms of carbon performance and, you know, registering (the) carbon footprint may get in the way of gas-fired CHP in the future. I can't say if it's in the near future, but, pretty soon…" (Project Director, property development company)

This uncertainty does not exist for renewable CHP technologies, who are broadly perceived as fitting within a potential future zero or low-carbon energy system, however, the majority of current CHP schemes are using non-renewable fuels, with only 11.7% of registered Good Quality CHP capacity being generated using renewable fuels (DUKES, 2016).

Network development in the private single site CHP niche is mainly constrained to the ADE network, with actors utilizing the ADE knowledge database and ADE events for contact establishment and knowledge exchange. Specialized CHP developers and energy consultancies can make use of secondary network connections in the form of engineering associations, institutes and other sector-specific institutions, while CHP users at times utilize existing channels within their own business sector. In general, network development in the private single site niche is rather limited and favourable to established actors, while new entrants may face barriers in accessing basic knowledge, often resorting to subcontracting CHP development in order to benefit from the knowledge available to specialized developers and consultancies, who take on the role of brokers and intermediaries between the project principal and the broader cogeneration industry. In this type of relationship*, learning* is mainly concentrated with the intermediaries, who can utilize knowledge gained from a particular project in further engagements, and also share it with other established network members. However, there is anecdotal evidence of learning extending to the project principals, who can be motivated by potential cost savings to end their relationship with intermediaries and take on CHP scheme development and operation themselves, as can be seen from the following example:

"Marriott Hotels took an ESCO scheme out in the late 90s, and when that towards the end, that came, so that again ran for 5 years beyond its initial term, it's 15 years. But they, because they could see how CHP was performing in terms of their financial savings they decided to go, they bought their next set. So they didn't invest in going with ESCO but because they were now convinced how well CHP did produce financial savings they said, well OK, we have decided to take the risk now because we understand it and we're gonna buy these ones because we can realize better financial savings from purchasing ourselves." (Sales Manager, specialist CHP company)

6.3.4 Microgeneration CHP niche processes

Internal niche processes in the microgeneration CHP application niche are significantly different to the processes in the three niches outlined above, a consequence of a different institutional framework (multiple regulations relevant for larger CHP operators have little to no relevance for private, domestic actors), reduced support by government and industry actors compared to the other application areas and a different main market.

Due to the low number of active actors in the sector, and their relative weakness in terms of political power and lobbying capacity, most shielding processes in the niche take the form of *passive shielding*, with a small degree of *active shielding* provided by supportive regime actors through the 2011 UK Microgeneration Strategy (although the two main supportive instruments, the Renewable Heat Incentive for the provision of heating, and the Feed-In Tariff for the provision of electricity, are not specific to CHP but extend to other forms of energy generation as well). The availability of passive shielding is somewhat hampered by the circumstance that multiple public policy initiatives apply solely to “renewable” microgeneration, with currently available technological solutions for microgeneration CHP utilizing non-renewable fuel sources – primarily gas and oil-based fuels (Hudson et al., 2011). In summary, there is little targeted protection for microgeneration CHP in particular, with technology proponents being in competition with alternative microgeneration technologies in the available generic protected spaces (Allen et al., 2008).

In addition to the umbrella CHP network, the ADE, microgeneration CHP users also utilize two further networks, which however are not cogeneration-specific networks but rather associations representing micro-generation in general (the Micropower Council (MC)) and the broader heating industry (Heating and Hot water industry council (HHIC)) (Hudson et al., 2011). This is somewhat similar with network availability for CHP actors in other niche markets – due to the lack of specific, focused networks beyond the ADE, actors utilize related, available network connections instead. *Learning activities* are taking place with technology developers and through localized trials (Hudson et al, 2011), but are limited due to a generally low interest in this particular application niche, as well as the relative newness of the technology, especially compared to the other observed niches. Due to the domestic nature of microgeneration schemes, transfer of information, especially back from the user towards the broader niche, can be difficult. Finally, there is little clarity about shared *expectations and visions* – while there seems to be a public-side expectation about the potential role of micro-CHP in a more decentralized energy system (2011 Energy White Paper, 2011 UK Microgeneration Strategy), those expectations are not specifically focused on microgeneration CHP, but on all potential microgeneration solutions, reinforcing the market competition approach often taken by UK public authorities and possibly best illustrated in the following quote by a regional DH manager:

“Whereas the UK, its regulations are all about consumer protection, competition, may the best technology win.” (Research Fellow, UK university)

Development of further expectations and visions is also generally hampered by a sector-wide sense of disenchantment regarding the future prospects of microgeneration CHP – while some of the interviewed experts expressed a hope for a potential resurgence of microgeneration CHP through technological innovation in the form of micro-scale fuel cell based engines, the majority regarded microgeneration CHP as a static, “failed niche”:

“The domestic micro-CHP sector is, there is very little happening, if anything. Our members are really, a couple are involved in it at a very minor level. I think that it’s an expensive thing and the scheme that Government put in place just wasn’t appropriate to bring forward micro-CHP.” (Policy Officer, interest association)

With regard to niche *empowerment*, the majority of the actions taken by niche actors were of the *fit and conform* type, caused both by the low power of microgeneration proponents and by the necessity to fit microgeneration CHP within the framework of the available general supporting measures implemented by the UK government. Some of these processes were also aimed at the restoration of government trust in CHP as a microgeneration solution, which was at least partially eroded as a consequence of below-expectations performance by the micro-CHP sector in the early 2000s (Hudson et al., 2011).

In order to provide a brief summary of the discussed niche functions across all four observed niches the author has outlined them in short terms in the following table:

Niche function		CHP-DH	Public single site CHP	Private single site CHP	Micro-generation CHP
	Active	Only in localized environments, spaces created by local public actors	Can be provided by local actors through planning regulations/ requirements	Little evidence	Generalized shielding for micro-generation
	Passive	Utilization of existing spaces (efficiency, low carbon)	Utilization of existing spaces (efficiency, low carbon)	Utilization of existing spaces across regimes	Utilization of existing spaces where possible
	Expectations and visions	Cost reduction, increased efficiency	Shared visions of efficiency, cost reduction and lower emissions	Cost reduction, increased efficiency – improved business case	Little clarity about expectation or visions
	Social networks	Created by ADE, additional localized actor networks	ADE, additional localized or sector specific networks	ADE, engineering associations, sector specific networks	ADE, MC, HHIC – latter two not CHP-specific
	Learning	Locality-specific, translation to other localities difficult at times	Key role of intermediaries, transfer of knowledge through them	Key role of intermediaries, transfer of knowledge through them	Experimental learning, knowledge transfer through (specialized) intermediaries
	Fit and conform	Mainly fit and conform empowerment	Mainly fit and conform empowerment	Mainly fit and conform empowerment	Mainly fit and conform empowerment
	Stretch and transform	Little due to lack of agency/power	/	/	/

Table 19: Summary of niche functions

6.4 Inter-regime interactions

As a final section of this chapter, the author will discuss inter-regime interactions between the electricity and the heating (gas) regime, utilizing the multi-regime interaction typology developed by Raven and Verbong (2007) and further refined in their 2009 paper. Drawing on empirical studies on bioenergy and combined heat and power in the Netherlands, Raven and Verbong (2009) propose the following four types of interaction, noting that the typology represents ideal types of interaction, with simultaneous different types of interaction as well as a sequential set of interactions being possible:

1) **Competition** – regimes fulfilling similar functions; regime actors start competing for resources and/or institutional arrangements
2) **Symbiosis** – regimes reaping mutual benefits from cooperation: access to resources, improved performance; mutual interdependence takes place
3) **Integration** – separated regimes combine to form a joint, singular regime, integration can happen at the actor level, but also at the technology and institutional level
4) **Spill-over** – institutional arrangements are transferred between regimes, this can happen directly but also through actors replicating behavioural patterns

Starting the observation from the societal functions provided by the two regimes, it can be observed that while, in broad terms, they provide two different societal functions – electrical energy (electricity regime) and fuel for heating (gas regime) there is a distinct overlap created by the availability of electrical heating. On a broader institutional level, both regimes operate within the institutional framework of the UK energy sector, with partially shared regulations and key actors (for example, the OFGEM is the national regulatory authority for both gas and electricity providers). Caused by technological developments in the heating sector encouraged by a broader landscape shift towards low carbon energy provision, the regime overlap is progressively increasing, creating potential future scenarios of competition but also potential integration (although it remains to be seen whether this potential regime integration will be one of "equal partners", or one regime will perform what would be described as a "hostile takeover" in business terms).

This situation is exacerbated by possibly intentional public sector uncertainty about preferred regime development trajectories, leading key electricity and heating/gas regime actors to taking up defensive positions aimed at protection of existing assets and sunk investments, such as for example the ongoing modernization of the UK gas infrastructure with the aim of enabling the long-term use of renewable gas and potentially hydrogen. While this might be in line with a pragmatic "may the best technology win" government stance, it also creates potential risks in the form of developing technological and institutional incompatibilities, and significant investment losses for regime actors on both sides. Falling back to the interaction typology outlined above, a fitting description of the current regime interrelation would be a *partial semi-voluntary integration*, with shared institutional elements and actors (OFGEM, large utility companies), but separate utilized technologies and infrastructures, as well as separate codified market arrangements – the British Electricity Trade and Transmission Arrangements (BETTA) for the electricity capacity market and the 1995 Gas Act and 2005 Unified Network Code (Heather, 2010) for the gas market. A state of mutual interdependence is created through the embedding of both regimes in the broader landscape of the UK economy, while it might be conceivable that one regime could continue to function alone, a separation of the regimes or the dismantling of one of them would have major societal and economic implications.

The shared arrangements are partially the consequence of historic institutional spill-overs during the liberalization of the UK energy market from the late 1980s to the late 1990s, although an ex-post observation such as this work will reveal little about the direction of these spill-overs without engaging in more depth in the particularities of capacity market and gas market institutional development.

This type of regime interaction has a negative effect on CHP development, as there is too much interrelation between the regimes for niche actors and proponents to exploit potential opportunities created by regime competition (Raven, 2006; Raven and Verbong, 2009). At the same time, there is not sufficient overlap, especially in the regulatory/institutional dimension, to prevent the existence of an institutional gap in which neither electricity regime policies nor heating/gas regime policies are effectively applicable. Through the type of societal functions they provide, CHP technologies fall into that gap, with supporting actors and technology proponents forced to align development trajectories to one of the regimes, which directly reduces the potential benefits of the technology as in any case only one of the two functions is recognized and addressed:

“I think that the issue is that CHP falls in the gap between quite a few different things. If we look at the trilemma, the kind of traditional trilemma of cost, security and carbon, CHP does a bit of everything. You know, it’s most efficient use of fuel when producing power and heat, so you’re reducing carbon emission, you’re reducing gas imports, you’re reducing cost and you also improve security of supply because it’s flexible, it’s reliable. And because of that the policy developments for CHP, for things that CHP could be involved in do not capture all the benefits that it provides. So something like the capacity market is purely focused on securing supply, which CHP can do, but it has no regard for emissions or for cost. Something like the contracts for difference auctions, focused on carbon emissions, but again nothing for cost or security, again CHP can fit into the carbon but it also works in cost and… So you get this issue where there’s kind of a vacuum of a policy that captures everything in terms of security, cost and carbon, and therefore the benefits that CHP brings isn’t able to be captured.” (Policy Officer, interest association)

Future regime development towards either increased integration or competition followed by integration may create a more supportive environment for CHP development in the case of further development of the gas system towards green/renewable gas and potentially hydrogen. On the other hand, a progressive electrification of the heating regime would create a thoroughly negative environment for CHP at least for provision of low-temperature, residential heating, as competing technologies in the form of ground-source heat pumps are far better suited for development and diffusion in an electricity-only energy market. In this latter case, CHP could still remain viable for commercial and especially industrial schemes benefiting from on-site power and high-temperature heat generation, which virtually all competing technologies are unable to provide. However, CHP would also be rendered permanently unable to penetrate the broader low-temperature heating market, consigning the use of the technology to stable, but comparatively small niches.

6.5 Chapter summary

This chapter summarized the second of the two planned analytical stages: an extension of the system-based, internally focused TIS review towards reviewing external barriers to CHP development and the influence of contextual structures, conceptualized as the electricity and heating regimes, and the broader socio-technical landscape (Geels, 2002, 2005).

In a first step, the author outlined the analytical constructs used in this review: four distinct application areas for cogeneration technologies – district heating networks, public single site applications, industrial/commercial single site applications and microgeneration CHP, and the UK electricity and heating regimes. This was followed up by a barrier analysis based on the Strategic Niche Management concept of barriers for the development and diffusion of sustainable innovation, introduced by Kemp et al. (1998) and further refined by Smith and Raven (2012). Within the barrier analysis, the author initially reviewed general barriers applicable to all CHP technologies, followed by an investigation of barriers specific for one or more of the four application areas.

The barrier analysis was followed by a review of CHP niche processes, drawing on the refined concept of niches processes proposed by Smith and Raven (2012) and utilized in recent niche-based research (Verhees et al., 2013, 2015; Smith et al., 2014; Lockwood, 2016; Raven et al., 2016b). Analogous to the barrier analysis, an initial general review of niche process was followed up by a more specific review of niche processes in the four application areas.

In the last part of this chapter, the author reviewed dynamics external to the CHP industry, which nevertheless may have an impact on the development and diffusion of cogeneration technologies. These dynamics were observed as inter-regime interactions between the electricity, and gas/heating regimes based on a typology proposed by Raven and Verbong (2007, 2009).

In the next chapter, the author will discuss the most important findings of this study within the context of the three main research questions: an investigation of the socio-technical factors, barriers and developments which have influenced the development of CHP in the UK, a review of existing niche typologies (Levinthal, 1998; Kemp et al., 1998; Geels, 2002, 2004; Raven, 2006; Markard and Truffer, 2008; Schot and Geels, 2008; Smith and Raven, 2012), and an inquiry into transition pathways in multi-regime contexts, combining research on transition pathways (Geels and Schot, 2007; Geels et al., 2016) with insights into multi-regime dynamics (Raven and Verbong, 2007, 2009).

7 Discussion and findings

This chapter will summarize the insights gained from the two-stage analysis described in Chapters 5 and 6 of this thesis, drawing upon the main findings and discussing them within the context of the main and supporting research questions defined in Chapter 3. Throughout the discussion, the author will combine empirical findings with the theoretical concepts addressed in the literature review and integrated into the research design of this study; connections and comparisons with existing findings from other published work will be drawn into the discussion where needed. Following the main part of the discussion, in the final chapter the author will summarize the main findings and reflect on their contributions to Transitions Studies research, while at the same time outlining recognised limitations to this study and suggesting future lines of enquiry.

7.1 Socio-technical factors, barriers and developments influencing the diffusion and development of CHP in the UK

In both parts of the analysis, the author has identified a number of external barriers and internal factors which influence the diffusion and development of CHP in the UK, leading to its current development state and impacting the future prospects of the technology. In addition to the socio-political factors identified and discussed by Russell (1986, 1993, 2010) and Weber (2014), a number of structural issues, technological factors and knowledge-related barriers was identified. Some of these were already identified and reviewed in previous studies on specific CHP application niches (Hudson et al., 2011; Hawkey, 2012), however, the author intends to extend them towards the entire CHP industry reviewed as an technological innovation system (TIS) as well as from a niche-regime perspective informed by the multi-level perspective, in particular research on transition pathways (Geels and Kemp, 2007; Geels and Schot, 2007; Geels et al., 2016), inter-regime dynamics (Raven and Verbong, 2007, 2009; Konrad et al., 2008) and niche functions (Kemp et al., 1998; Raven, 2006; Smith and Raven, 2012). The discussion will start with a review of the internal factors influencing the development of CHP – structural causes for functional barriers (Bergek et al.,

2008) and/or system failures (Foxon et al., 2005; Klein Woolthuis et al., 2005) causing the CHP industry to be unable to provide the necessary shielding, nurturing and empowering functions for the technology (Smith and Raven, 2012). Drawing on the comparison between TIS functions and niche functions presented by the author as part of the research design, insights from the structural and functional analysis will primarily be used to described internal barriers, while SNM and MLP insights will be utilized to describe external barriers; in this way, the discussion will start within the borders of the CHP system, and subsequently extend outwards.

7.1.1 Structural issues in the CHP industry

As identified by the author, there are two core structural issues having a significant impact on the development, diffusion and future prospects of CHP: (i) the dual institutional framework created through the association of combined heat and power with two socio-technical regimes: the electricity regime and the heating (gas) regime and (ii) the lack of a strong network structure beyond the single umbrella network, the Association for Decentralized Energy (ADE). Additional structural issues are manifested through the lack of large supporting actors ("champions") and uncertainties about technological trajectories[22] arising from perceived incompatibility of current mainstream CHP technologies and future (more stringent) regulatory framework (mainly emissions and noise regulation) compounded by the absence of shared visions and expectations, especially at a macro-strategic level.

7.1.1.1 Lack of supporting actors and shared vision

The absence of powerful supporting actors is a recurring problem for CHP technologies, already observed in historic studies (Russell, 1986). Even in periods when one or several powerful actors expressed an interest in the technology, such as different UK government agencies in the two National Programmes (Russell, 1986, 1993; Hawkey, 2014) or industry actors (Russell, 1986;; Babus'Haq and Probert, 1996), this support was short lived; by the time more extensive change processes were set in motion, large actors lost interest or even turned hostile towards CHP.

[22] Here, the author follows Hekkert et al. (2011) by including technological factors into the structural discussion

Within this context, power is understood as innovative, destructive, constitutive, transformative and systemic (Avelino and Rotmans, 2009). Further on, Geels (2014) observations of the power of “big business” to exert their influence on policymakers to either encourage processes of change or, more frequently, resist these processes and gravitate towards maintaining a “lock-in” situation, was observed and discussed by Unruh (2000, 2002) on the case of carbon lock-in.

The absence of strong supporting actors for CHP observed in this study is directly related to further structural issues. The most prominent issue being that of powerful actors who can assume the role of champions and have a stabilizing and connecting effect on network development. To a certain extent this role is taken by the umbrella organization ADE. However, the range and strength of its activities are impacted by resource limitations. On a smaller scale, specialized consultancy companies and CHP developers can take the role of medium-power actors, but they lack the capacity and ultimately the transformative power to enact regime-level change. This lack of power is especially visible in situations where constructive or transformative agency is required, or where networks need to be established and strengthened, as is visible from the following quote:

“There isn’t really an institution or actor for the creation of local heat markets in the UK – this is important. Even though CHP is considered to be a transitions technology for DH, balancing the grid. A lot of these visions consider having widespread heat networks in cities, but the UK lacks institutional means to develop those networks as there are no actors with the capacity to assemble a large number of heat users.” (Research Fellow, UK university)

The lack of political power has a particularly strong impact on the development of larger-scale CHP schemes, especially the district heating networks which generally require a conducive policy framework in order to make their development viable. The crippling effects of lacking advocacy and political power on communal CHP have been extensively documented in a number of historical studies (Russell, 1986, 1993; Babus’Haq and Probert, 1996; Hawkey, 2014), although it must be stated that even the aborted National Programmes of the mid-20th century (Hawkey, 2009, 2014) have had positive effects in the form of increased energy generation and energy planning powers for local authorities (LA). Those increased powers have enabled local actors to both plan and implement district heating networks, but the need for political representation is ever-present, with some of the main current obstacles being side-effects of broader policy developments such as scaling down support for biogas, reductions to the Feed-In Tariff, or changes to embedded benefits which are currently reviewed by the government.

While most of these policy changes are not considered by the CHP industry as intentionally developed to impede the prospects of co-generation, they can, nevertheless, create formidable barriers to further development by removing existing protection or support, either active or passive, or by creating additional barriers for developers and operators of CHP schemes. The role of powerful actors, therefore, shifts from a more radical role as vectors of destructive and transformative exercises aimed at challenging regime incumbents (Avelino and Rotmans, 2009), towards a role of guardian/observer who exercises their power in order to highlight and mitigate negative side-effects of planned policies. Following Russell's (1993) notion of neglect towards CHP and his later ideas concerning both *accidental* and *systematic* exclusion of CHP (Russell, 2010), the author notes that the absence of champions only exacerbated this. Considering the *systematic* side of regime marginalisation of cogeneration, it needs to be noted that some of the resistance and power exercises observed (Geels, 2014) are connected to a broader competition between *centralized* and *decentralized* energy systems (Toke and Fragaki, 2008; Hawkey, 2013, 2014). While it could be assumed that champions of decentralized energy could have at least somewhat taken over the role of the absentee CHP champions, evidence indicates that, at least in the UK, decentralized energy generation has also suffered from a comparable lack of supporting major actors.

Champions can also play a key role in the formation of development expectations and visions (Raven, 2006) which form the groundwork for development trajectories, while at the same time criticising the dominant, regime-centred discourses (Avelino and Rotmans, 2009; Geels, 2014). In the current situation, there is a distinct lack of clear expectations for CHP, particularly evident at the national level. At the same time, there are multiple medium term visions for CHP future, ranging from very positive future visions with CHP playing an integral part in a future UK energy system; through CHP taking the role of a "bridging" technology enabling a smoother transition towards a future zero-carbon UK energy system: to somewhat negative visions where (non-renewable) CHP is seen as having no future in the UK energy mix. Due to the current reliance of conventional CHP units on natural gas as a fuel source (in 2015, 71% of the total electricity and heat output of UK co-generation schemes used natural gas as fuel (DECC, 2016)), future visions and expectations for CHP are also tied with the expectations for the future of the UK gas network (RTP Engine Room, 2015). Given the dominant role of the gas network in the provision of heating in the United Kingdom, this is effectively tied into future developments of the UK heating regime. While a continuous reproduction of the regime (Geels and Schot, 2007) may be unlikely due to growing external pressures arising from national and international policy changes and government activity aimed at reducing the carbon emissions of the broader UK energy sector, it still remains to be seen what form will a future change of the heating regime will take. It may take the form of a transformation process, based mainly on incremental change within the existing regime (Geels et al, 2016), or the transition may follow a reconfiguration pathway (ibid.) in which niche-innovations and niche policies have a higher chance of becoming a part of the new regime configuration.

Which of these options is preferable from the perspective of CHP actors remains open for discussion and largely depends on the understanding of what type of change process would constitute a transformation, and what would entail a reconfiguration, as well as on the development of a typology for the different types and sub-types of CHP. Somewhat telling, a number of CHP experts interviewed by the author insist on a separation of renewable and non-renewable CHP, the latter including the "conventional" CHP based mainly on fossil fuels, which forms the majority of the currently existing CHP schemes in the UK, while the latter includes different types of biofuels on the one hand, and technologically innovative concepts such as fuel cell based CHP on the other. One reason for this separation is lower emission level of biofuel down to almost non-existent emissions[23] for hydrogen fuel cells. Further reason is a positive overlap of visions of a fuel cell based CHP system with broader vision of a future hydrogen-based UK energy system; with fuel cells also retaining waste process heat which is a critical factor for the functioning of the cogeneration concept (Hawkey, 2009), illustrated in the following expert comment:

[23] The author is referring strictly to the operations stage of a fuel cell based CHP unit, and is fully aware that the generation of the required hydrogen fuel can and, at present, does cause emissions

"The fewer fossil fuels will be used, the lower the call for CHP will be; the exception to this is if a hydrogen-based economy will emerge as hydrogen power generation is still heat-producing." (Director, energy consultancy)

7.1.1.2 Low number and weak structure of networks

The next structural issue to be discussed is the non-existence of overarching networks with the exception of the Association for Decentralized Energy (ADE). Network formation is one of the key functions of niches within the SNM approach (Raven, 2006; Smith and Raven, 2012) and is seen as a key part of the structure of a TIS, supporting multiple TIS functions (Hekkert et al., 2007; Bergek et al., 2008). Romijn and Caniëls (2008) draw on social network theory in their study on the Jatropha sector in Tanzania to indicate the important role of strong, well-structured networks for the development of an innovative niche technology/industry. With these points in mind, it is hardly surprising that the absence of robust, more extensive networks of CHP actors in the UK has a detrimental effect on the prospects of the technology. In the course of this research project, the author was able to identify a number of causes and effects, which are discussed below.

One of the main causes for the absence of additional, stronger networks is the structural issue discussed in the previous section – virtual non-existence of large actors who would have the resources, political and material power and institutional backing to assemble and coordinate larger numbers of CHP proponents. Considering the often uninterested (Russell, 2010), hands-off attitude of government actors (despite periodic expressions of support), it is obvious that public sector support for strengthening and extending the networks is rather limited, particularly at the national level[24]. Within the private CHP industry, networking activities more often happen at a sectoral or even corporate level, with specialized combined heat and power consultancies and providers acting as knowledge repositories and intermediate actors between scheme operators (both public and private) and specialized providers of CHP-related services ranging from generators, supporting infrastructures to ongoing

[24] On a regional or local level there are multiple instances of CHP-centred networks being created, however, most of these networks had a rather short existence as they were bound to specific projects or actions, or fell victim to a lack of public sector resources

operation and maintenance (O&M). Despite evidence that some of these small networks are strongly connected and thoroughly functional, their strong boundaries created by business interests (while a commercial entity specializing in CHP certainly has a strong interest in maintaining close relationships and knowledge exchange with and between their customers, they are understandably less interested in maintaining these functions for any interested actor, especially if these actors can be considered prospective competitors) and sectoral borders limit their usability for the diffusion of CHP on a national level. These boundaries are further strengthened by a large proportion of specialized knowledge in the CHP sector, especially for larger-sized CHP schemes which in the majority of cases need to be tailored to specific local technical, geographical (in the case of heat networks) and institutional contexts. The role of the latter has already been thematised by Coenen et al. (2012) and further explored by Bergek et al. (2015), albeit on a regional/national scale. Several examples of specialized local knowledge on CHP can be seen in the following quote:

"The issue that we do find is that it's very different country to country, so, for example, our networks in Poland are very different because they don't… so within London, our issue is digging up the roads and they're very congested, there's lots of services they're all in there, there's bus lanes and all that kind of things. Whereas in Poland, they often, they don't have those problems because it's simply a different setup there. And so, you know, they don't even have the pipes below ground but have them mounted against things. So we actually find that some of the learnings aren't like-for-like, and so, really, within the UK we also have our Sheffield plant, which is an ERF but also (…) part of a district heating network. So we kind of do this… some shared learnings between us and them, but again, it's quite different because their network is about 30 years old. So even down to the technology that they were putting in 30 years ago, it's completely different from the technology that we've put in, even down to the way, the pipework." (Contract Manager – District Heating, utility company)

From a niche development perspective, this negative effect on transferability of knowledge directly affects learning, which is seen as one of the key functions of strategic niche management (Schot and Rip, 1996; Kemp et al., 1998; Smith and Raven, 2012). It also adversely affects the exchange of information between local-level experiments and an overarching niche described by Smith and Raven (2006).

Another important reason for the apparent weakness of networks is the lack of shared expectations and visions or, rather, the multitude of expectations and visions for cogeneration discussed in the previous section. In defence of the CHP industry, it is worth pointing out that individual actors on a micro-level have little motivation to connect to potential competitors supporting a different development vision. Although CHP is observed as an agglomeration of application niches and a technological innovation system, internal competition is still rife and reflects the uncertainty of the future development trajectory of the UK energy sector in the form of a competition between supporters of incremental change and more radical innovators within the niche. While the former are mainly established companies who, in some cases, have provided specialized CHP services for several decades, and in some cases operate as extensions or subsidiaries of large regime actors[25], the latter can be specialized small companies developing renewable (biofuels, fuel cells) types of CHP, some of which were developed as research project off-shoots[26] (Hudson et al., 2011).

Using a systemic perspective, it can be argued that development in and between sectoral innovation systems (SIS) overlapping the combined heat and power TIS (Markard and Truffer, 2008) translate into dynamics between CHP actors. Consequently, despite the necessity for internal cohesion, there is also a degree of CHP-internal competition. While this is indicative of fulfilment of the market development function (Hekkert et al., 2011), the question is raised whether intense competition can also reduce the overall development speed of the technology. The intention here is not to question the well-proven merits of competition in advancing innovation and technological development. Rather, the question revolves around the benefits of a *guided competition* compared to a fully unleashed free market, with findings from CHP development in the Netherlands (Raven and Verbong, 2007, 2009) and Germany (Weber, 2014) providing some support for the former. It, however, also needs to be stated that in the cases mentioned above, public actors took a more active role in setting the agenda and enabling development. While public actors in the UK

[25] The author has found that the majority of the “Big 6” energy sector companies as well as a number of other large utility providers maintain the capacity to provide CHP-type services; while some of them operate CHP as a division within the organisational structure, others control specialized, independently operating subsidiaries (for example, the former COGENCO was incorporated by Veolia as Veolia CHP)

[26] For example, Ceres Power (fuel cell CHP)

arguably can move towards a more active role in supporting CHP which includes supporting the formation of networks (DECC, 2009, 2011) this support is seldom sustained, as it can easily become collateral damage of shifts in the political landscape (Geels, 2014; Smith et al., 2014).

While the paragraphs above painted a somewhat negative picture of CHP networks in the UK, it is worth pointing out that the function of the existing network (ADE) as well as evidence on function of smaller, localized or sectoral network is quite good. The overall negative evaluation is mainly based on the fact that the reach of existing structures is ultimately limited by availability of resources and the power of the leading actors (Avelino and Rotmans, 2009). For example, the ADE spends considerable resources in the development of knowledge bases for CHP actors, and into organizing networking and knowledge exchange events aimed at supporting knowledge exchange within the industry.

7.1.1.3 Dual institutional framework and effects on availability of resources

The main internal structural issue of the CHP industry are the multiple effects of what is essentially a dual institutional framework created through the dual societal functions provided by cogeneration (heating and electrical energy) and the infrastructural and regulatory ties of the industry with the heating and electricity regimes. While both regimes themselves are part of the liberalized UK energy market (Toke and Fragaki, 2008; Pearson and Watson, 2012), the heating regime in the UK is effectively replaced by the gas regime due to the dominance of natural gas-based heating (around 85% of households in the UK are utilizing gas as a power source) and the regimes are governed by differing rule-sets. Further on, physical and technological differences between the provision of the two functions require the existence of two separate infrastructures – the UK National Grid providing electrical connections, and the (currently upgraded) National Gas Grid (Heather, 2010; UK Parliament, 2015) providing the gas pipework. While both regimes are subject to top-level regulations such as the Directive 2012-27/EU on Energy Efficiency, the EU Regulation on Energy Market Integrity and Transparency (REMIT), the Energy Act (2013 and, more recently, 2016), the Climate Change Act 2008 and the 2009 Low Carbon Transition Plan, as well as being under the oversight of the energy regulator OFGEM, the electricity capacity market and the traded gas market ultimately are governed by two sets of market rules: the British Electricity Trade and Transmission Arrangements (BETTA) for the electricity market and the Uniform Network Code (2005) for the gas market.

While the dynamics and effects of the institutions themselves, and their effect on the prospects of the development of CHP as a whole will be discussed in more detail in the review of transition pathways in multi-regime contexts (research question 4), the author will now focus on the (internal) structural issues caused by the dual institutional framework. As the main barrier, the author would like to highlight the practical non-existence of a *heating regime* in a narrow sense, which consequently means that there are no institutions regulating the trading of heat as a commodity, or the development of heat-specific technological infrastructures (pipeworks), the latter being especially visible in the lack of statutory powers for heat developers.

"Statutory powers need to be given to operators ("ransom strip" mentality – one householder can block the development of an entire infrastructure) – operators need compulsory purchase powers similar to the ones in electricity and telecommunications" (Director, energy consultancy)

From a Transitions Studies perspective it is clear that the lack of regime is a specific situation; while a strong, stable regime is certainly not conductive for transitions processes (Raven, 2006; Geels et al., 2016), the same is true for unstable regime situations (Verbong et al., 2010) in cases where niche actors attempt a hybridisation (Raven, 2007) or fit-and-conform empowerment approach (Smith and Raven, 2012). Drawing on the discussion on actor power and the role of the government in the previous two sections, the author concludes that while, in different circumstances, the lack of regime could be seen as conductive for *greenfield* developments of a new heating regime, the lack of government action coupled with the relative lack of power of CHP actors prevents them from exercising systemic power, mobilizing the resources necessary for the development of formalized regime structures.

"There isn't really an institution or actor for the creation of local heat markets in the UK – this is important. Even though CHP is considered to be a transitions technology for DH, balancing the grid. A lot of these visions consider having widespread heat networks in cities, but the UK lacks institutional means to develop those networks as there are no actors with the capacity to assemble a large number of heat users." (Research Fellow, UK university)

This is not meant to suggest that regime development for CHP actors is generally impossible, on the contrary, experiences from Continental Europe (De Paepe and Mertens, 2007; Toke and Fragaki, 2008; Streckienė et al., 2009) indicate that the establishment of heating regimes in liberalized energy market is possible provided sufficient support by both the industry and different levels of government. In particular, heat-based markets for excess heat capacities have been successfully developed in urban settings, as is indicated in the following quote which also highlights a lack of appetite in the UK for local heat markets:

"Studies on CHP development in Europe after energy market liberalization – is there an actor with the capacity to develop local heat markets; also is there an actors with a desire to get rid of a large amount of heat. Case study on European cases (heat and the city website) – Rotterdam and Bergen; actors needed to get rid of heat and district heating was a solution for that. No appetite in the UK to regulate in that kind of way." (Research Fellow, UK university)

The absence of a heating regime has further effects on the presence of a heat market, and the status of heat as a tradeable commodity, and on the availability of the technical infrastructure necessary for larger-scale heating schemes. While heating services are sold to end users in the UK's existing district heating networks, pricing structures are not always unified, and heat prices for consumers can turn out significantly higher than gas prices for comparable households, as they include standing charges and maintenance costs.

Further on, the traditional use of domestic heat generators (mainly boilers) instead of communal heating networks in the UK means that there is very little heating infrastructure readily available, with some of the existing infrastructure up to several decades old (Babus'Haq and Probert, 1996) and in need of a retrofit; while this is less of a challenge for greenfield developers, it is a significant issue for developers aiming to retrofit heating infrastructure to existing developments, as can be seen in the following quote by an high-level industry representative:

"This challenge is different for district heating – here the main issue are the extra costs of distributing the generated heat to others, as a third infrastructure is needed. Compared to parts of Continental Europe, there is next to no heat provision infrastructure in the UK and it can safely be assumed that development and installation

of such networks in the UK would be a contentious issue…" (Director, energy consultancy)

Additional problems are created through the lack of statutory powers mentioned above: compared to electricity, telecommunications or transport developers, heat developers can be subject to prolonged negotiation processes with landowners, local authorities and other utility and transport providers. While this is less of a problem for single-site developments where the land is usually leased long-term or outright owned by the developer, more extensive district heating networks face planning and development challenges. In order to illustrate some of the problems faced by network developers, the following excerpts have been taken from an case study interview with a supply-side heating scheme manager of a London-based public-private district heating CHP scheme:

"So actually agreeing the pipe route, even though the council were supportive there were quite a number of considerations to be taken into account, and the route itself actually changed a number of times. Reasons for changing the route were things like trying to avoid the bus routes, so even though they may be the most direct route, we're trying to like, you know, London's very congested so trying to avoid that. At one stage we were trying to literally go through a park, however there were concerns over tree roots so again, that couldn't be done. There's another issue with a road that had recently being resurfaced and if you then dig up the road within, I think it's 5 years, you then become responsible for that road. Because we didn't want to have that responsibility, again, we had to divert 'round. So there was quite a few numbers of diversions that were required." (Contract Manager – District Heating, utility company)

"But the pipe routes, nearly all of them do involve interacting with Network Rail. And so I think it's, I think it would be… and also, the other thing as well, is that, um, so if you're putting in a gas main, a water pipe or electricity, um, they have, they're statutory providers whereas district heating isn't at the moment. So again, it's just another thing where it's not quite a level playing field and even with council support it's not quite as easy as putting in other services. We're sort of a lower priority." (Contract Manager – District Heating, utility company)

While the lack of statutory powers directly limits the decision-making power and ability for agency of scheme developers, the widespread lack of pre-existing infrastructure, especially in urban areas which are the most suitable environment for developing communal heating schemes, creates additional technical and planning challenges, as well as increased development costs adding onto initial high investments (Hawkey, 2009).

7.1.2 External barriers and regime resistance

Extending on the discussion on the internal structural issues generated by the interaction of the CHP industry with the heating/gas and electricity regime, the author will next discuss the external barriers created by the regimes either in the form of their selection environments or through more active resistance. Drawing on the findings of the niche/regime analysis, the relationship between the two regimes can be defined as *partial integration*, with significant levels of interdependence created by the embedding of both in the broader UK socio-economic landscape, overlaps in the institutional framework and the use of gas as one of the key fuel sources for UK electricity production (30% of total fuel use (DECC, 2016)) and the key fuel source for heating (up to 85% of UK households). This, from the perspective of CHP, means that CHP developers need to operate within the constraints of two selection environments (Kemp et al., 1998) which creates additional issues for niche empowerment, especially if that empowerment is of the *fit and conform type* (Smith and Raven, 2012) as only the configurations fitting both regimes at once are viable. Furthermore, the existence of two selection environments complicate niche-regime transition pathways, seeing as the goal of CHP is less about replacing one (or both) regimes and more about entering a co-evolutionary process resulting in a hybridised state. This would ultimately also bridge the inter-regime gap and lead to spill-over interactions, ultimately resulting in regime integration (Raven and Verbong, 2009).

However, and as discussed in the previous section, there are no CHP actors or actor coalitions sufficiently powerful to enact such a change on their own. While there is landscape pressure in the form of the current uncertainty about the UK's energy future, regime actors seem to have little interest in considering CHP as a possible solution, preferring future scenarios such as nuclear/all-electric or a biogas/hydrogen future[27].

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[27] That being said, there are scenarios attesting a significant role to CHP in future transitions towards a low-carbon energy system, such as the Thousand Flowers

Furthermore, a major external limiting factor is the absence of holistic policies relating to the provision of both electricity and heating. This effectively negates the core advantage of CHP – efficiency increases through simultaneous generation of multiple types of energy – by forcing CHP developers to primarily focus on one type of generation. This subsequently can reduce the advantage of CHP compared to more conventional, single-output technologies to a level at which CHP operates at a disadvantage, especially when currently utilized calculation models and subsidy schemes are taken into account:

“No generators are going to be built without some form of contract or agreement (low-carbon or capacity agreements) – CHP is not well placed to follow either of these agreements.” (Director, energy consultancy)

This issue is further complicated by a technical paradox related to CHP scheme development and operation – in the UK, some of the most successful schemes are heat led, and the technology generally offers more efficiency benefits for its heat output. However, the main operating principle of CHP (Hawkey, 2012) is based on the production of electrical energy through exothermic processes.

Another impeding factor for CHP developers, investors and operators is created through regime-internal institutional changes and reconfigurations, particularly through frequent and extensive changes to policy frameworks (Russell, 1986; Geels, 2014; Smith et al., 2014). In the United Kingdom, these are a consequence of the close coupling of political activities with the energy sector, which makes political decisions affecting the provision of energy services a top of the agenda item for governments in the aftermath of elections and other major changes in political and economic programmes. CHP schemes, especially large-scale ones, require significant capital investment in the development phase, and subsequently have mid-term to long-term (ranging from ~5 years to 18-20 years depending on scheme size) returns on investment (RoI) periods which are calculated based on current conditions or forecasts for the RoI period.

These long payoff periods put CHP developers at significant risk from abrupt policy changes, one of the best examples being the abrupt downturn of large-scale industrial

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scenario (RTP Engine Room, 2015), however there is not much evidence to-date that those scenarios will unfold

CHP schemes following the introduction of the New Energy Trading Agreement in 2001 (Pearson and Watson, 2012):

“In the early days the outlook for CHP was better – however the BETA rules (2000) were punitive for inflexible CHP schemes – the amount of money people could make from electricity was reduced.” (Director, energy consultancy)

“So, during the times of electricity privatization you saw a proliferation of industrial CHP, so people who’ve had very energy intensive industries that would import their electricity and use boilers to meet requirements found that they could employ gas turbine technology, gas turbine CHP to good effect. It’s all coming to a halt with the introduction of the new electricity trading arrangement, um, and it was because of the level of risk around the electricity generation and pricing.” (Research Fellow, UK university)

Another example for the impact of abrupt policy changes would be the rapid expansion and quick downturn of biogas-based CHP. Initial support by policymakers allowed for swift expansion of this sub-sector, which was followed by a rapid downturn following significant changes and reductions to policy-side support arising from broader political change:

“And that’s very much what happened in the biogas market this year, with CHP. Last year, we did loads of anaerobic digestion projects, absolutely lots of people were getting them in, left right and centre, set them up, alright, (…) tariffs. This year, not a single one. The whole market went from being just chaos to… boom, just literally boom the (…) out. I believe it was the RHI, I think they capped off or ROX, one of the others they capped off, and all the financial cases just immediately fell apart.” (Sales Manager, specialist CHP company)

Further examples for policy change-related risks include regulations expected by industry actors, who react by preparing accordingly, only for regulations to be discarded by policymakers pre-implementation. A good example for this type of development is the planned Zero Carbon Homes scheme

“The rationale that was presented to the housing developers was that the DH scheme was essential for them to meet the zero carbon building standards, which were abandoned in the meantime – the case evaporated.” (Research Fellow, UK university)

From a niche perspective, these abrupt changes create significant challenges for actors involved in *fit and conform* niche empowerment, but also for actors engaging in the niche hybridisation strategy (Raven, 2007), as both approaches require matching niche structures to existing regime configurations; a process already complex due to the ambivalent position of CHP as a technology which can be described as “between regimes”. While actors who mainly focus on small-scale CHP can be more flexible in reacting to such developments (and in some cases, opt to develop their schemes as far outside of institutional support as possible), large-scale CHP developers as well as public bodies are often unable to react quickly. The former due to significant sunk costs and potentially existing service contracts and business models, and the latter due to their reliance on public sector support. This can lead to negative learning effects among actors impacted by these changes, leading to their adoption of a more negative stance towards CHP as a viable technological solution, or to the application of CHP in certain areas – with such developments observed in historical studies following periods of government support for CHP-DH (Russell, 1986, 1993; Hawkey, 2014) together with additional negative effects caused by a lack of technological maturity. More recently, negative learning effects can be observed in the development of large-scale industrial CHP since the regulation of the UK capacity market, with multiple large schemes becoming financially unviable and most of the remaining large operators withdrawing towards protecting existing assets. This can be seen from the following quote by a CHP policy officer who also highlights some of the challenges created by recent and current policy change in more detail:

“Industrial CHP is slow, there is not much movement, it is an expensive piece of kit. As of yet, the capacity market has not provided the right signal for new large scale CHP to come forward. Things such as threats, the embedded benefit removal, which is the avoided cost of not using the transmission network, so by on-site generation or; and that removal is sort of valued at £45/kW. That’s a huge amount of money for a lot of manufacturing sites that have CHP and chase triads and avoid the winter peak. So there’s some threats to the industrial CHP sector, again the carbon price flow is really important. It’s quite stagnant and that’s mainly because of their existing assets, they’re trying to protect themselves at the moment.” (Policy Officer, interest association)

A strong external barrier for CHP development is created by the electricity regime through high entry barriers for small producers (which includes most medium- and small-sized CHP schemes) attempting to join the UK capacity market. Caused by the institutional orientation of the electricity regime towards a large-scale, centralized electricity system, current electricity trading rules (BETTA) as well as planned changes to generation regulations (especially changes planned to Benefits-In-Kind) are seen as a significant challenge by CHP developers. This is particularly apparent when combined with increasing resistance by regional Distribution Network Operators (DNOs) who are responsible for regulating capacity market access and electricity production licenses:

"I'm seeing more and more across the UK that district network, DNO operators are becoming more and more sort-of anti-CHP, anti-decentralized generation, becoming trickier to deal with, to get project off the ground, fitting larger caps on what's allowed to be generated even if you're not planning to export anything. And certainly, and also preventing exports on a number of projects as well, even if the CHP was capable of producing more electricity that they could export to the grid, a lot of DNOs are just not allowing it." (Sales Manager, specialist CHP company)

While these barriers have been surmounted in other countries, such as Denmark, through aggregation of smaller scale CHP units into "virtual plants" operating as a single generator regarding their output to the capacity market, there has been little appetite for a similar approach in the UK (Toke and Fragaki, 2008; Fragaki and Andersen, 2011). Taking a bottom-up perspective, this barrier represents a major obstacle for the development of CHP, as it removes the capability of operators to create additional income by selling off excess electrical capacity. While solutions are developed at an individual basis and range from schemes based on on-site consumption of the entire electrical output, to schemes which export the majority of their consumption to the electricity market and remain competitive through the adoption of a peak price-led operational approach. Referring back to the weak network structure within the CHP industry, this case-based approach can and does create solutions on an individual level. However, the strongly heterogeneous nature of CHP scheme development prevents increased levels of knowledge transfer at a niche level.

It remains to be questioned to which extent the identified barriers have been caused, shaped or supported by the multi-regime context within which CHP is operating. While there is little evidence to support direct, proactive inter-regime agency with the aim of creating or managing barriers for CHP, developing inter-regime relationships can certainly change the joint selection environment, with negative effects on cogeneration diffusion and development created as collateral damage of regime-level changes. This kind of effect has been previously observed in a historical context (Russell, 1986, 1993), where the transition process for CHP, more specifically CHP-DH was influenced by regime-level changes at the time of the final decline of the British coal industry, with coal-supporting regime actors competing against gas supporters in the 1960s. Another observation would be on regime-level developments of the role and power of municipal governments, playing out in British public sector policies between the late 1940s and the 1970s. While part of that discussion was certainly the provision of heat and power by local actors, ultimately CHP proponents had relatively little influence or ability to steer regime-level developments (Russell, 1993).These earlier developments, however, are somewhat different from the currently observed situation in that the regimes and regime actors observed are different to the present electricity regime – heating (gas) regime interactions.

7.2 Niches in the CHP context – what is, exactly, a niche?

The second key part of this chapter relates to the second sub-question, reviewing the niche typology and the niche as an analytical concept within the scope of the chosen empirical case. Starting from the four different types of niches identified in the literature (Kemp et al., 1998; Levinthal, 1998; Ieromonachou et al., 2004; Raven, 2006; Smith and Raven, 2012), the author will review the definitions of the niche, their observed functionality, and their position in relation to CHP as a knowledge field-based technological innovation system (TIS) and the heating and electricity regimes.

There is a broad consensus in the field of Transitions Studies that the main characteristic of a *niche* is its protective function (Raven, 2006), enabling niche actors to operate in a changed selection environment relative to the broader selection environment generated by the incumbent regime or regimes (Kemp et al., 1998). While there have been efforts to provide a typology for this protection (Smith and Raven, 2012), the extent, nature and characteristics of the protection, as well as its relation to the niche technology have not been investigated in depth. One potential line of enquiry relates to the source and directionality of the protection offered, extending along the lines of *active protection – passive protection* distinction and questioning the amount and strength of protection necessary to define a certain (analytical) space as a niche. Drawing on Evolutionary Economics (Nelson and Winter, 1982) the question can also be reformulated, to observe the difference between the niche selection environment and the broader selection environment generated and maintained by the incumbents. In simplified terms, the question would be as follows: “How different does a niche selection environment need to be from the regime selection environment in order for a niche to be considered a niche?”.

Alternative definitions for niches have been put forward based on niches as application domains populated by user-actors with specific performance requirements (Levinthal, 1998; Smith, 2007). This approach moves the niche away from a technology or policy-centred analytical construct towards an application- and/or user-based one. In the course of this thesis, the author has drawn on a combination of both approaches in order to delineate the niches for combined heat and power technologies; while this could be described as a departure from theoretical orthodoxy, the second intention of the chosen approach was to relax and revisit the niche definition in order to be able to discuss the niche concept and the relation of niches to other analytical constructs utilized in Transitions Studies.

7.2.1 Niches as protective spaces and changed selection environments

While the findings of this study certainly cast some doubt upon the usability of the protection-focused niche approach for analysis of the dynamics and development of the various application areas for CHP, these application areas certainly do exhibit a number of protective characteristics, mainly related to *passive shielding*. For example, existing planning regulations and requirements, as well as location-specific planning requirements regarding energy efficiency or the utilization of more sustainable energy and heat generation technologies put forward by local councils can be utilized by CHP actors in order to facilitate the development of CHP schemes, supporting the diffusion of the technology. In cases where the CHP actors are the local councils themselves, this can even be extended into *active protection* through creation and implementation of development plans favouring combined heat and power technologies.

A different kind of development, more in line with the application/user-focused definition of niches, can be observed in the case of private single- and multi-site CHP schemes. While existing passive shielding measures are certainly utilized, decisions on the use of the technology are more often connected to the economical or regulatory usefulness of the technology. In order for cogeneration technologies to be used, they need to create economic benefits for the user (mainly through increased resource efficiency as a consequence of their dual output of heat and electricity) and/or they need to support the user in fulfilling voluntary or mandatory regulatory requirements. The former was observed in the case of a large CHP scheme located within one of the UK’s major refineries, where the main reasons for choosing CHP were increased energy efficiency and energy cost control, as well as a significant reduction in CO2 emissions. An example for the latter can be shown in the following quote from the site manager for a London commercial sector CHP scheme, explaining some of the reasons behind the company’s choice of cogeneration as a viable technology:

“Ok, [company] have got quite stringent targets to achieve energy reduction and CO2 reduction. And in 2009 we were looking at ways that we could drastically reduce the

amount of power that we're taking off the grid, of energy that we're taking off the grid. We were looking at particular ways, PV, solar hot water, wind turbines and things like that, none of which you can really operate to a large degree on a commercial office in the centre of London. So the only thing that really seemed to be available would be generating our own power and heat on site. This building was being built as the firm's major location in London, and it was suitable for CHP." (Scheme Manager, engineering company)

For the case of CHP it is therefore rather hard to establish whether sufficient protection or shielding exists across the different application areas to justify the use of the protection-based niche definition to outline CHP as a niche, or a series of sub-niches. On the other hand, different application areas for CHP do have selection environments which can differ from the regime-generated selection environment. However, the selection processes are mostly implemented within a limited spatial and/or institutional environment, such as within the borders of a council or municipality, or within a company or group of companies, an example for which can be seen in the quote above. A slightly more straightforward conceptualization of a CHP niche is given in the case of industrial/commercial single site CHP, especially on the industrial side where combined heat and power schemes are broadly used in a number of specific sectors such as oil refineries, the chemical industry or the paper industry. In those cases, a different selection environment is generated through specific demands within a particular sector – a good example being the above-mentioned case of CHP used in a major UK refinery, where high energy costs represent a significant challenge to the UK refining and petrochemicals sector, and high-efficiency performance of CHP providing a viable solution for that challenge. While it might be possible to explain this particular case by characterising the specific requirements of this sector as an instance of pre-existing requirements mobilised by CHP advocates (Smith and Raven, 2012) the question is whether and how much active mobilisation through deliberate agency actually took place.

A similar, cost-based selection environment was observed by the author in the second case study on the application of cogeneration in a plant nursery in Southeast England, although in that particular case there was some mobilization of pre-existing requirements observable in the actions undertaken by an intermediary actor. This actor, an energy consultancy which initially developed and is now operating the scheme on behalf of the nursery owners, utilised existing project specifications (energy security and price reduction) and elements of the existing selection environment (drive for lower energy costs, long-term energy price safety) to mobilise support for installation of a CHP scheme, which was accepted by the site owner:

"So, (the) reasons for CHP was not just given by the end customer, they just wanted cheaper costs with what I just explained. (…) We introduced CHP because we as an energy developer, we're taking a certain view around where power prices go over the next years. And this project that we did here is, we're taking a long-term view, we're looking at the next 20, 25 years. The energy deal is for that period of time, not just next 5 or 10 years. We want the long-term energy supply service for this site, and the site wants security over their supply, not being dependent on any fluctuation and price speculation, if you want to be honest." (Scheme Manager, specialist CHP consultancy)

With respect to niche protection/ the shielding function of niches, this case was exceptional in the fact that the intermediary actor specifically excluded the utilization of any active or passive protection measures from the scheme development and management process. While this is partially related to the external barrier and increased risk created by policy instability and abrupt policy changes, a particularly interesting facet of this observation relates to the fact that CHP in industrial and commercial contexts can operate within a changed selection environment even when mobilisation of active or passive protection is expressively excluded.

7.2.2 Niches as specific application domains defined by user-actor expectations and requirements

The second potential definition for niches draws on the niche concept utilized in marketing and (strategic) management (Levinthal, 1998) of niches as specific application domains with actors willing to accept cost and performance inefficiencies, and invest in and support the development and diffusion of a new technology (Smith, 2007). While CHP in most of its application areas is a mature technology[28] without any obvious shortcomings in its technical performance, cost-related factors can affect

[28] One exception to this are renewable, biofuel-based CHP units and fuel cell CHP, where the technology is still in a development stage (Hudson et al., 2011)

actors in two different ways. In some application domains, especially industry and commercial applications ,as well as some public sector applications, CHP technologies represent long-term energy cost-savings beyond the initial investment, while for other application domains, particularly CHP utilized within communal heating networks, the need for extensive infrastructure development translates to major upfront investments. This indicates that the first group of application domains could be described as (traditional) market niches, while the second group of domains is, from a conceptual perspective, closer to the niche definition outlined above.

Following the niche development trajectory discussed by Schot and Geels (2008) an observation of the CHP case seems to indicate that the different application domains for CHP could be described as niches at different stages of development, ranging from domestic micro-CHP at the technological niche stage to industrial/commercial CHP forming a well-developed, relatively stable market niche. The different stages of diffusion and development for different domains are noted and commented on by CHP actors, which can be illustrated in the following selection of quotes on CHP applications:

(on industrial CHP)

"Ok, so I still think that at the industrial scale there is a case for CHP but I guess all these industries now have CHP if they're going to have them. (…) CHP is probably being shut down in many industries as well because of the complexity and risk, probably don't mind paying a bit more for energy as long as its' they can forecast it and allow for, so chemical plants et cetera." (Senior Manager, regional government)

"Industrial CHP is slow, there is not much movement, it is an expensive piece of kit. As of yet, the capacity market has not provided the right signal for new large scale CHP to come forward. (…) "It's quite stagnant and that's mainly because of their existing assets, they're trying to protect themselves at the moment." (Policy Officer, interest association)

(on micro-CHP)

"The domestic micro-CHP sector is, there is very little happening, if anything. Our members are really, a couple are involved in it at a very minor level. I think that it's an

expensive thing and the scheme that Government put in place just wasn't appropriate to bring forward micro-CHP." (Policy Officer, interest association)

"I think, if it got released and it proved not to be reliable, it could damage the reputation of domestic CHP irreparably which is why I'm not being… it why I would assume that the market hasn't taken off as of yet. I would assume that they're trying to pin down that reliability before they really go mass market on it." (Sales Manager, specialist CHP company)

(on public sector, single-site CHP)

"So, DH NHS fantastic, as well as universities, very traditional CHP customers, we've been looking after since the 1990s. Leisure centres as well, so again, that's mostly public sector, but again one of the clear, obvious applications of CHP due to the high consistent heat demand. I mean it's always going to be a very good financial case there." (Sales Manager, specialist CHP company)

(on different application areas including smaller-scale commercial CHP)

"CHP in industrial and commercial sectors have the greatest potential. Every site with a constant or even seasonal and high heat load is most suitable. Hospitals, Hotels, Manufacturing processes, chemicals, and oil refinery, transports are our identified fields for future developments as those are highly heat intensive." (Manager, specialist CHP consultancy)

At this point, a parallel could be drawn between the observed application areas and the niche accumulation strategy discussed by Raven (2007) as a potential transition strategy for niche actors. Niche accumulation is defined as the "application of a technology in different niche markets so that technology/market combinations become robust"; such a development can easily be reconstructed from the history of CHP application in the UK. However, the final aim of niche accumulation strategy is more radical regime change, analogous to "stretch and transform" niche empowerment identified by Smith and Raven (2012).

While some of the underlying concepts of the district heating application domain, such as the requirement for local-level energy production and increasingly decentralized energy systems, do require more radical regime reconfigurations, developments in other application domains, especially public and private single-site CHP has been more similar to a hybridisation pattern, or “fit and conform” empowerment (Raven, 2007; Smith and Raven, 2012). Ultimately, this points towards the absence of any larger-scale strategy deployment, in line with the observations of Verhees et al. (2013) on niche actor agency in unfriendly contexts, which is described as a pragmatic, piecemeal approach characterized by reactive actions following regime changes and reconfigurations. Translated to the CHP case, the author infers that the deployment of cogeneration technologies in different application domains might be more a case of choosing promising niche markets based on the present situation at a given point in time, than any form of long-term strategy. While a strategic approach might have been present during earlier CHP development, especially related to CHP-DH (Russell, 1986, 1993; Hawkey, 2014), the more recent rapid diffusion of CHP in commercial applications (DECC, 2015) seems to be a case of CHP supporters probing and testing for viable niche markets.

The application niches all exist within a broader, more diffuse CHP system, delineated for the purposes of this study in the form of a technological innovation system based on the principle of heat and power co-generation as a knowledge field[29]. This follows the niche-within-TIS approach put forward by Markard and Truffer (2008) and applied by Wirth and Markard (2011), allowing for a simultaneous observation of micro-level dynamics particular to the different application domains, the interaction, especially in the form of learning and knowledge exchange *between* the application domains and the interactions between the domains and the broader CHP industry as a TIS.

From this latter point it is obvious that the application domain-based niches still fulfil multiple niche functions (Kemp et al., 1998; Smith and Raven, 2012) – especially learning, development and articulation of visions and expectations and, to some extent, empowerment functions and network development. However, and as previously noted, there is relatively little evidence of protection in the form of either *passive* or *active shielding* at any level of aggregation beyond localized experiments or highly specific applications. This brings up the question of the dynamics of shielding in the course of niche development. While new, technological niches require extensive

[29] For a more detailed description of the delineation process, refer to Chapter 5 of this thesis

and focused protection in order for the central technology to remain viable in the face of selection pressure, this might not be the case for older, more stable niches, which are defined by "traditional" niche markets and groups of user-actors preferring the technology. At the same time, other niche functions – nurturing and empowerment – do not decline. This reasoning would be in line with Kemp et al. (1998), who argue for the deconstruction of niche protection over time in order to enable (sustainable) innovations to compete in a market environment rather than becoming "white elephants" depending on continuous protection.

7.2.3 Reviewing the niche typology

Continuing on the discussion above, and in line with proposals for future research in Transition Studies made by Markard et al. (2012) the author will discuss the niche definition with regard to the perceived key functions of niches, as well as potential changes to these functions in the course of ongoing transition processes, considering the different types of transition pathways (Geels et al., 2016) as well as the role of niches within innovation systems (Markard and Truffer, 2008; Wirth and Markard, 2011).

As discussed in the literature review section, as well as at the beginning of this sub-chapter, the key function of niches in Transitions Studies is a protective one (*shielding*), creating an environment in which the focal technology can be developed and trialled outside of the rigours and selection environment of the broader economy. In addition to the protective function, and no less important, a niche also provides *nurturing* processes, in which expectations are articulated, actor groups are developed into growing networks and learning processes, especially second order learning and global-local learning (Schot and Geels, 2008) are supported. Following Smith and Raven (2012) in their comparison of the niche perspective to the TIS approach, nurturing processes appear to be key in transforming a technology-centred system[30]

[30] The author is consciously using the term "system" for both niche and TIS in order to highlight both the conceptual similarities (a niche can be understood as either part of a TIS (Markard and Truffer, 2008) or a TIS at a very early stage of development) and the material dimension of the constructs in form of the focal technology or group of technologies. With the exception of a policy niche (Petromonachou et al. (2004), all other niche types are centred on a particular (technological) innovation.

from an early, *formative* stage to a *growth* stage. Finally, the niche also provides an *empowerment* function (ibid.), with niche actors engaging in deliberate action in order to engage the niche innovation with the dominant regime – either by aligning to it (*fit and conform*) or by attempting to change/replace it (*stretch and transform*).

Despite this extended typology, mainstream Transitions Studies very often attempt to define and characterise niches primarily through their protective role; while, and as mentioned earlier, a breakdown of protection is often described as one of the key steps, this breakdown is seldom investigated in more depth in empirical studies following the Strategic Niche Management (SNM) approach. Based on the findings of this research projects as well as insights from previously published work reviewed by the author, the question is put forward whether a niche's defining function undergoes a shift across the different types and, by extension, whether the niche definition and typology should be reviewed in order to better characterise niche spaces in latter stages of development.

Using the empirical case of this thesis as an example, it can be stated with a reasonable degree of certainty that most of the observed niches within the broader CHP system show little evidence of protection, especially active shielding protection. Nonetheless these spaces can a) be observed as separate spaces within the broader UK energy sector defined by a number of characteristics; and b) continue to exhibit a number of other niche functions supporting the development and diffusion of CHP as a technology or, more precisely, a knowledge field based on a technological principle. These spaces could be observed as "classical" market niches, although their function seems to go beyond this as knowledge and actors are transported between the different areas, some of which are also undergoing constant growth[31]. Most actors within these niches have also not simply conceded their positioning as a niche technology, and are actively trying to position CHP relative to and/or within the heating (gas) and electricity regimes, which is similar to niche actors' strategies discussed by Raven (2007), Schot and Geels (2008), and Smith and Raven (2012). An important part of these actions is their *persistence*, a characteristic that will be discussed in more depth in the third and final sub-chapter, with actors willing to shift narratives and

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[31] The best example, currently, would be small-scale CHP in public and commercial applications, where the UK market is one of the quickest growing ones in Europe.

expectations in reaction to regime- and landscape-level changes, repositioning the group of niches/TIS in relation to one or both regimes, and often reacting to setbacks with repositioning (even interpretable as a "rebranding") instead of withdrawal.

The only CHP niche currently exhibiting what could be described as "typical" niche behaviour is the micro-CHP niche, where applications of small-scale domestic CHP (especially for fuel cell CHP) are supported by and deployed within experimental or pilot schemes, supported by government and private sector funding, with the schemes guided and evaluated by actors or actor groups (Allen et al., 2008; Hudson et al., 2011). Due to the relative inefficiency of microgeneration in general (Geels, 2014; Smith et al., 2014) and micro-CHP in particular strong protective functions are necessary in order to enable otherwise wavering domestic users to trial the technology (Sauter and Watson, 2007). Looking at its development history, micro-CHP is also by and large the youngest of the four observed CHP niches, with the first usable applications appearing only in the late 1990s.

On the other hand, there is little protection remaining within the two oldest CHP niches – CHP-DH and single site commercial/industrial CHP; with these spaces essentially functioning as market niches, yet exhibiting both nurturing and empowerment functions. This is particularly visible in case of CHP-DH, where there is still a significant amount of learning and knowledge transfer, with single actors and organisations transferring themselves and their knowledge between schemes:

"We've recruited a team of experts in the industry to make this happen. It's a very small number of people that actually know how to do this, so we've recruited a few of those, um, I think, a very, very experienced team that have done this in Europe and in the UK. We've also, at board level we've bought in industry experience, so (…), he's on our board, um, we've also got a guy called (…) who's got experience of heat networks in Aberdeen with Aberdeen Heat and Power so they bring that industry expertise at the board level. The operational team itself has been there, done it and learned the lessons." (Head of Sustainability, local government: Interviewee describing the development of a DH scheme in the Greater London area)

"Well, they certainly used to have a scheme called (…) run by someone called (…), it's unclear as to whether that's still running, I was at a presentation he gave a few months ago that seemed to imply it wasn't. But obviously, now the (…) that says it is,

so… We would love to speak to them, because they helped us do a heat map for this borough years ago, and we'd certainly love to talk to them about securing that support again if it is still running. (Energy and Carbon Reduction Manager, local government: Interviewee describing the support available for DH in Greater London)

Moreover, CHP-DH actors also actively engage in niche empowerment, positioning the deployment of cogeneration-based communal heating schemes as a potential scenario within the broader context of decarbonisation of the UK energy and heating sector[32].

Finally, smaller commercial and public sector single-site CHP exhibits all three types of niche functions, but can be distinguished from micro-CHP by a notably lower reliance on active or passive protection; as a matter of fact, several actors interviewed as experts or within case studies note a trend towards actively developing CHP applications outside of protected areas. This decision seems to be at least partially based on the negative effects of abrupt policy change discussed in the first part of this chapter, but is also indicative of the development of a market niche within which the technology can develop and diffuse further based primarily on user characteristics and expectations. Certainly, this type of development can be described as a stage of a successful process, yet some parts of this market niche seem to have retained niche functions and characteristics despite the absence of a noticeable overt transition progress.

Therefore, the author would like to propose the following function-based definition of niches based on their stage of development, as well as the dominant/key function provided by the niche. This typology serves as an extension of the technological niche (Raven, 2006) and technological/market niche distinction (Schot and Geels, 2008) definitions proposed in previous works; the intention is to both sharpen these definitions, and at the same time account for the observed cases of sustained niche-like spaces providing functions highly similar to the niche functions discussed within the SNM approach (Kemp et al., 1998; Raven, 2006; Smith and Raven, 2012).

[32] This was noted as one of the key topics at multiple CHP- and heat-focused industry conferences, which the author attended as an observer

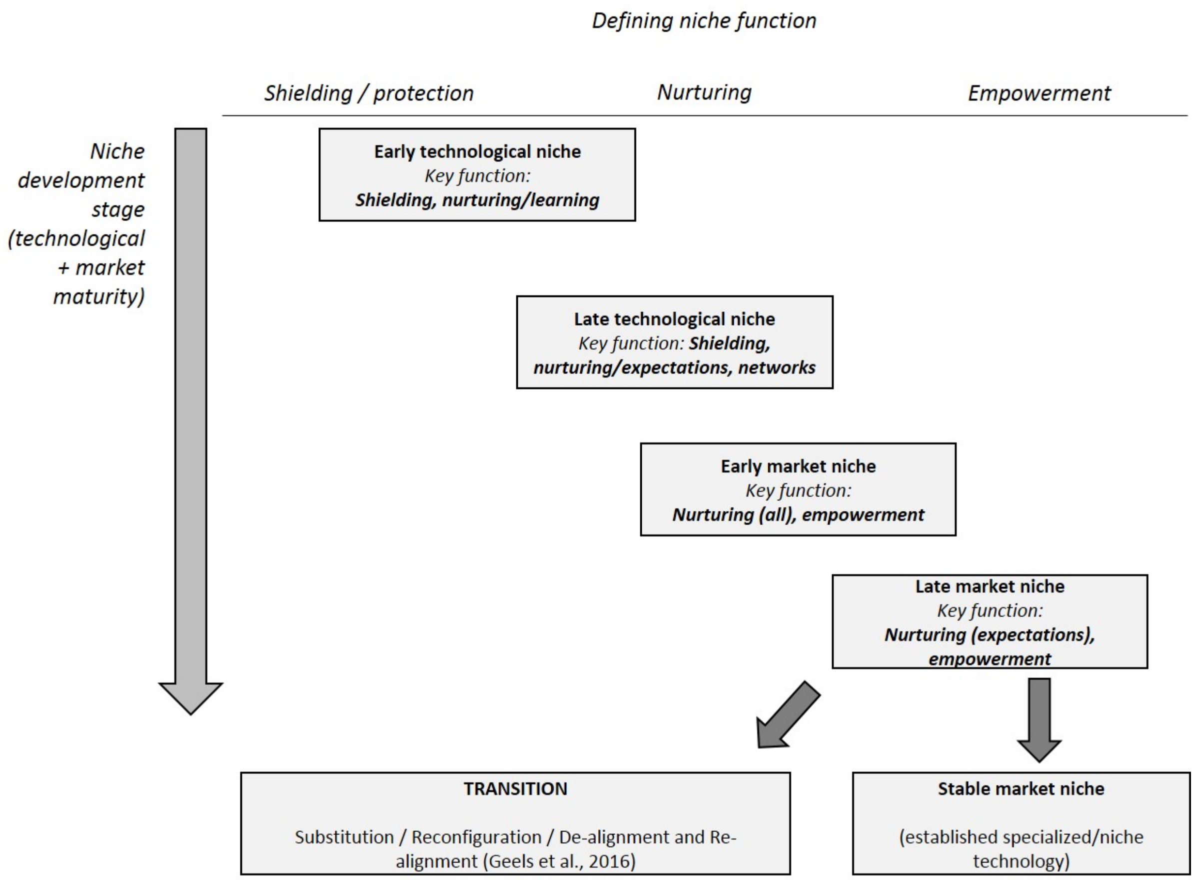

Figure 10: Proposed extended niche typology

The presented typology separates niches within Transitions into four types: early and late technological niches, and early and late market niches. The vertical axis of the Graph represents the stage of niche development with respect to technological and market maturity (i.e. the development stage of the technology related to performance expectations and capabilities; and the state of niche market spaces defined by user groups willing to work with specific functionalities and accept teething problems (Smith, 2007)). On the horizontal axis, the author lists key niche functions (Kemp et al., 1998; Smith and Raven, 2012), with the horizontal position of the niche type indicating the importance of particular functions at this stage of development. At the stage with the highest level of technological and market maturity - *late market niche* - the author presumes two potential development scenarios. The niche technology might complete a transition process, following one (or more) of the transition pathways discussed by Geels et al. (2016) that include niche-regime interaction: substitution, reconfiguration or de-alignment and re-alignment[33]. The other possibility includes the niche remaining a stable market niche, defined through specific application domains and niche users who are using the technology because of its characteristics and performance. The distinction to *late market niches* is created through actor agency – while the previously-developed actor networks, expectations and narratives might still exist, there is very little to no action supporting further developments toward transition, or challenging elements of the regime. The regime might remain unchanged, or it might enter a transition process of the transformation pathway type, with little to no knowledge or technology exchange with niche actors. Following is an overview of the four proposed niche (sub)types:

7.2.3.1 Early technological niche

The early technological niche represents the earliest stage of niche development, where the technology itself is at a prototype stage, supported by a limited group of often highly specialized actors. There might be little public knowledge about the technology, and expectations and visions for future application are limited. The focal technology is underdeveloped, with possible performance issues arising from yet unresolved technological issues; there might even be multiple versions of the technology competing against each other, in order for one to be acknowledged as the dominant design. At this stage, competition against incumbents within the regime selection environment is impossible, and would lead to almost certain failure. Therefore, early technological niches are dependent on and defined by **shielding**, both passive and active. A second important function is **learning**, observed as a part of the broader nurturing function – both first- and second-order learning processes need to be started and managed in order to foster the development of the niche technology and supporting structures; a special focus should be on learning related to technology implementation and performance in real-life experiments[34]. Following the parallel of SNM to the TIS approach discussed by Smith and Raven (2012) the

[33] The possibility of an additional pathway characterised by multi-regime interactions, which would better reflect the observed empirical case, is discussed in the last section of this chapter

[34] A recent review of the role of experiments for and within sustainability transitions has been published by Sengers et al. (2016); following the experiment typology proposed therein, the experiments discussed here would mainly be *niche experiments*

functions of **knowledge development** and **diffusion**[35] play an important role at this stage, which is also similar to the pre-development stage of a TIS outlined by Hekkert et al. (2011). Considering the case of CHP in the UK, all observed niches have already passed this stage, the latest being micro-CHP which may have been described as an early technology niche in the early 2000s (Hudson et al., 2011). Early technological niches can be seen as mostly identical to the R&D niches discussed by Raven (2006) – the technology is still within a variation environment, and no market-ready technology developments need to have ever taken place.

7.2.3.2 Late technological niche

The next step in the proposed niche development process, late technological niches are defined as protective spaces within which the technology has passed the prototype stages, while actor networks have started expanding and creating momentum through the articulation of expectations and visions. Direct competition against regime incumbents is still impossible, but the technology and its supporting structures have reached a more advanced level of maturity, enabling them to be utilized in a broader range of experimental settings/pilot projects, and being implemented and operated by less specialized actors. **Shielding** remains the key function of the niche space, and can be applied in a broader range including the appropriation of already existing protected spaces. While **learning** remains a highly important function within the niche, **articulation of expectations** and **development of networks** become more important due to the need to increase the number of niche actors and its proponents, and communicate the expected benefits of the niche technology to a broader audience. This niche sub-type, together with the early market niche most closely represents the niche as outlined in previous SNM research, as well as Multi-Level Perspective (MLP)-based work (Raven, 2006; Geels, 2005). For the case of CHP in the UK, micro-CHP can be described as a late technological niche – while there is a number of market-ready designs for CHP-based microgeneration units in the form of Stirling engines, Organic Rankine Cycle (ORC) engines, other internal combustion (IC) engines and

[35] Knowledge development and knowledge diffusion/exchange are defined as a single function by Bergek et al. (2008), while Hekkert et al. (2007, 2011) observe them as two separate functions. This distinction has been discussed in more detail in the literature review chapter.

fuel cells (Allen et al., 2008; Hudson et al., 2011), there is little indication of an existing, functional market, with most applications of the technology taking place in shielded, localized settings. Due to perceived inefficiencies of the technology and competition by other niche technologies (Allen et al., 2008), diffusion is limited and dependent on shielding. Improved articulation of expectations is necessary to improve acceptance and adoption by domestic end-users (Sauter and Watson, 2007). Other examples of late technological niches researched in the literature include biofuel-based power generation (Verbong et al., 2010); hydrogen-fuelled personal vehicles or tidal wave power generators.

7.2.3.3 Early market niche

Compared to late technological niches, the defining characteristic of early market niches is the existence of (small) markets within the regime selection environment, consisting of actor networks willing to utilize the niche technology, either based on their expectations of the technology's future performance or due to specific application settings within which the technology exhibits advantages against regime incumbents which outweigh its still-existing drawbacks and inefficiencies.[36] In these niche markets, the technology is able to compete against regime incumbents, although its general usability in the market is limited. While still important, **shielding**, especially active shielding is reduced, with **nurturing** and **empowerment** functions taking the key role in the definition of the niche. An early market niche can therefore be defined through **actor networks** and/or **application areas**. While the selection environment in these spaces is still different from the regime selection environment, these differences are based more on the characteristics of application areas and actor/user preferences than on deliberate shielding. For this type of niche, fit-and-conform and/or stretch-and-transform empowerment becomes increasingly important, as the gathered momentum enables the niche technology to develop towards a transition pathway. However, at this stage actors might refrain from committing to strategic choices (Raven, 2007; Smith and Raven, 2012; Verhees et al., 2013) due to large power imbalances relative

[36] Examples for this would be the utilization of fuel cells in remote polar regions, or as power sources in space exploration; within the UK CHP case, this would be the case for early applications of cogeneration engines in sectors defined by strict efficiency and emission requirements (for example, the NHS)

to regime incumbents, and the necessity to remain flexible in the face of regime- and landscape-level changes (Verhees et al., 2013; Smith et al., 2014; Geels et al., 2016). Considering TIS development stages, this type of niche most closely resembles a system in the take-off stage (Hekkert et al., 2011), although there might be less legitimacy creation compared to the late market niche stage as niche actors might not yet feel ready to fully engage with the general public. For CHP in the UK, CHP-DH can be considered an (well-developed) early market niche; despite its long development history and technological maturity, the market for CHP as a district heating option is quite limited. While there is a number of schemes implemented throughout the UK, the actor network is not strongly developed[37] and there is a level of uncertainty regarding future expectations for the technology in the face of a changing UK energy system.

7.2.3.4 Late market niche

The fourth and final niche type proposed by the author, late market niches are primarily defined by relatively well-developed niche markets comprised of a larger number of actors/users sharing well-defined expectations for the technology. While market niche actors in early market niches can be characterised as innovators and a limited number of early adopters, late market niches are comprised of early adopters and partially, users belonging to the early majority (Rogers, 2003, p. 282). Within the market niche, the innovative technology usually represents the best available technological choice; it can also be competitive in the general market, but is still constrained by the regime selection environment. While the niche may still exhibit some shielding, especially passive shielding, the space is primarily defined through the actors, actor networks, application areas and defined expectations, all of which are elements of the niche's **nurturing** function. Niche actors engage in strategic actions, attempting fit-and-conform and/or stretch-and-transform **empowerment** in order to increase the niche technology's competitiveness in the regime selection environment, and/or influence the selection environment with the aim of changing it into more favourable configurations (Smith and Raven, 2012) by transforming or removing existing barriers (Kemp et al., 1998; Smith and Raven, 2012). Late market niches can also be observed

[37] See also the section discussing structural issues in the CHP industry at the beginning of this chapter

as niche markets from the marketing/strategic management point of view, although they can be distinguished from them through the still-ongoing technological development and technology diffusion, as well as the intention of niche advocates to present the niche technology as a viable complement and/or alternative to incumbent technologies (Raven, 2006; Geels et al., 2016). Using a TIS point of view, late market niches can be considered similar to TIS in their take-off and acceleration phases, with the most important functions being market development, resource mobilisation, creation of legitimacy and ongoing guidance of the search (Hekkert et al., 2011). Entrepreneurial experimentation is another important function, especially in the case of niche actors engaging in niche accumulation strategies which include continuous experimentation in the form of implementation of the niche technology in new application areas (Raven, 2006). In case of CHP in the UK, both private industrial/commercial single site CHP and public single site CHP can be considered late market niches. In both cases there are well-defined user groups and application areas in which co-generation technologies can be utilized efficiently even with the existence of the twin regime selection environments.

"So, DH NHS (is) fantastic, as well as universities, very traditional CHP customers, we've been looking after since the 1990s. Leisure centres as well, so again, that's mostly public sector, but again one of the clear, obvious applications of CHP due to the high consistent heat demand. I mean it's always going to be a very good financial case there. Hotels, hotel sector, is again very high heat user, we've had contracts with Hilton and Marriott since the mid-90s, who've obviously (had) fantastic financial and carbon savings from CHP, and continue to do so now. (…) Obviously, the biogas sector and the anaerobic digestion sector, particularly wastewater treatment, it's… most wastewater treatment plants now have CHPs, it would appear. Sure there's a few out there that still don't, but that seems like a very obvious use for anaerobic digestion into CHP." (Sales Manager, specialist CHP company)

Highlighting the differences from "traditional" niche markets discussed earlier, CHP advocates active in these niches continue to support the diffusion of the technology into additional application areas, and engage with regime actors in positioning CHP towards becoming a part of the energy regime[38] and counteracting resistance such as changes to embedded benefits for on-site power generation, and a potentially adverse reform of the RHI. Multiple renewable energy generation technologies can be considered later market niches, such as photovoltaics (Smith et al., 2014), wind energy, ground source heat pumps (Allen et al., 2008), bio-SNG (Wirth and Markard, 2011).

As a summary of the previous sections, the following figure illustrates the development stages of the four identified CHP niches, using the proposed typology. Microgeneration-CHP is defined as a late technology niche, depending on sustained shielding and nurturing, while CHP-DH, public single site CHP and private single site CHP are all defined as market niches, with CHP-DH in a relatively early stage of development, and public and private single site CHP being well-established, late market niches.

[38] In these niches, empowerment is mostly fit-and-conform, with advocates attempting to improve the performance of CHP within the existing regime selection environment

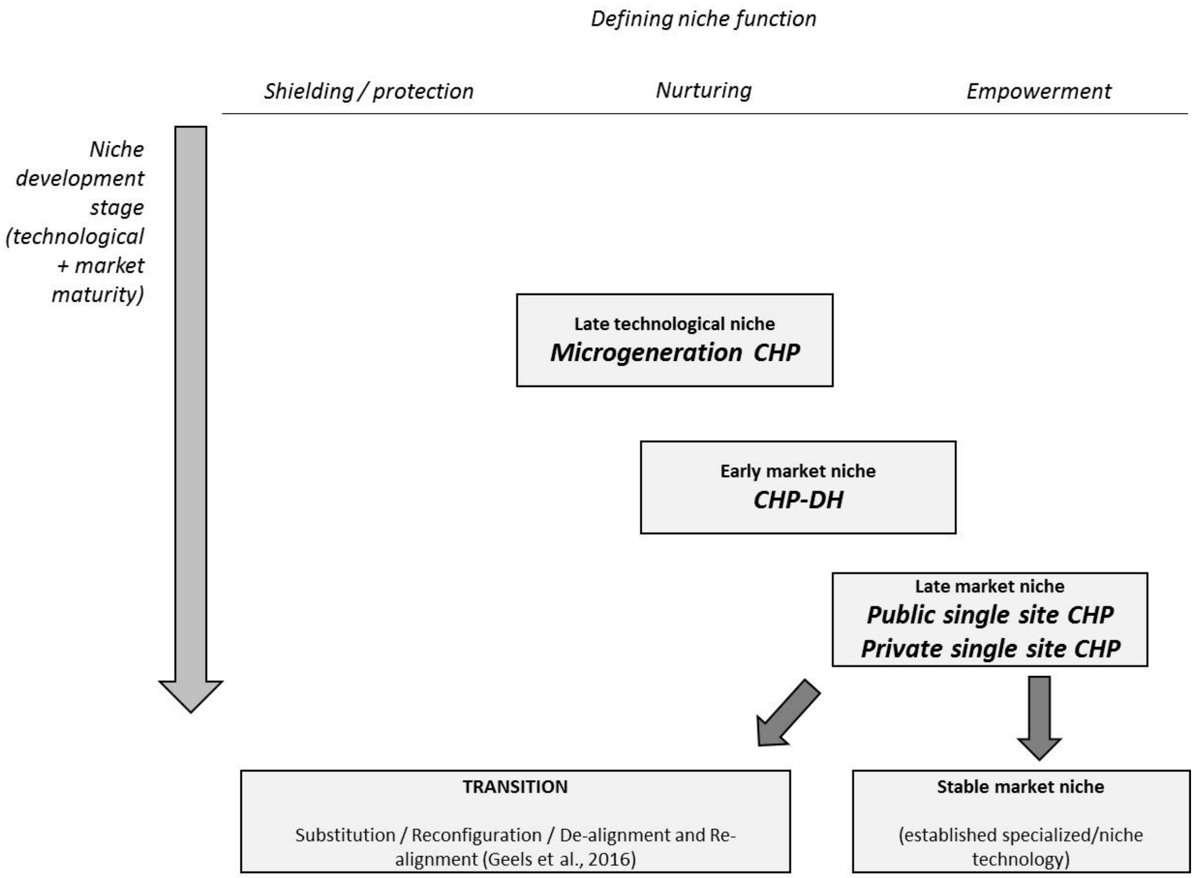

Figure 11: Development stages of CHP niches

7.3 Transitions of (sustainable) technologies in a multi-regime context

The third sub-section of this chapter discusses transitions in a multi-regime context, utilising the empirical case of CHP in the UK in order to review existing transition pathways (Geels and Schot, 2007; Geels et al., 2016) in the case of an innovative technology interacting with multiple regimes in the course of the transition process. Multi-regime interaction is reviewed by using a typology developed by Raven and Verbong (2007, 2009) and Konrad et al. (2008), and expanded towards a combined niche-regime-perspective based on Markard and Truffer (2008) and Wirth and Markard (2011).

Transitions research drawing on the niche-regime-landscape relationship utilized in the multi-level perspective (MLP) and strategic niche management (SNM) often focuses on dyadic (triadic if the landscape is observed to a broader extent) relationships – one or multiple niches serve as development spaces for prospective sustainable technologies, one of whom ultimately develops to a sufficient extent to enter a transition process with the incumbent regime. This initial approach was extended to account for regime-focused, incremental transformations (Geels and Schot, 2007) and for instances of competition where the dissolution of an incumbent regime creates competition between multiple prospective entrants (Geels et al., 2016). Four different types of transition pathways are currently identified by researchers:

1) **Substitution** – radical innovations substituting existing technologies, regime changes can vary from minor (incremental adjustments) to major (disruption, displacement)
2) **Transformation** – incremental improvements within the existing regime which might include incorporation of niche innovations; regime changes can vary but are usual not radical
3) **Reconfiguration** – transformation of existing regimes through alliances between regime incumbents and new (niche) entrants; regime changes are usually limited
4) **De-alignment and re-alignment** – incumbent regime collapses because of landscape pressure; new regime is created by and around new niche entrants

who might compete against each other if multiple prospective entrants are present; regime changes are usually major (disruption)

The most recent reconceptualization (Geels et al., 2016) of transition pathways includes the possibility of shifts between pathways in the course of transition process, acknowledging the non-linear, non-deterministic nature of transitions. Endogenous factors manifested as struggles between actors as well as exogenous regime and landscape influences can cause a shift, with multiple different types of pathway changes possible.

A less often discussed dimension of transition processes is the presence of multiple incumbent regimes and the effects of multi-regime interactions. Research by Raven and Verbong (2007, 2009) and Konrad et al. (2008) reviewed different types of interactions, with the former developing a typology based on the relationship between regimes and the effects of niche innovation on that relationship. Four different types of multi-regime interaction were proposed: competition, symbiosis, integration and spill-over (Raven and Verbong, 2009). While instances of transition processes including multiple integrated or, to an extent, symbiotic regimes can be discussed using the above-described transition pathways, this is not necessarily the case for transitions in multi-regime contexts where the regimes are in a state of competition or spill-over. The cases of CHP (Raven, 2007) and bioenergy (Raven and Verbong, 2009) in the Netherlands represent instances of regime symbiosis leading up to integration, with landscape influences on regimes as well as shared use of innovative technologies enabling regime integration processes; however there is little further research on transitions in multi-regime settings, particularly on ongoing or failed transition processes.

While the author describes the inter-regime relationship between the electricity and heating/gas regimes in the UK as a state of partial integration, the case of CHP in the UK is still notably distinct from the Dutch CHP development. This is a result of the incomplete nature of regime integration, especially in terms of institutional/policy integration, resulting in instances of competition[39] as well as “holes” in between the

[39] One example of competition between the electricity and gas regimes is the question of the future development trajectory of the UK heat sector, where two markedly different scenarios (biogas/hydrogen future respectively an all-electric future) are supported by electricity and gas regime actors

regime's institutional frameworks, both of which have been found to act as barriers to CHP diffusion and development. As mentioned earlier in this chapter, this negative effect is further exacerbated by the dependence of conventional[40] co-generation on the stability of both regimes; destabilization of one of the regimes, which would be one of the stages of a substitution or de-configuration and re-configuration pathway would have mixed effects on the development of CHP as a technology due to the effects of this destabilization being transferred to the other regime and further on to CHP in the form of barriers or even direct resistance by regime incumbents belonging to both regimes who might try to resist or reverse destabilization by opposing CHP (this sort of development has been observed in historical studies on CHP in district heating (Russell, 1986.; Hawkey, 2014)).

The next major issue in this discussion is explored by utilising a joint framework approach, conceptualizing CHP as a knowledge field-based technological innovation system (TIS), comprised of a number of niche markets, or specific application/user areas. While the entire CHP TIS interacts with both regimes and is affected by their interactions at an industry levels, the different application niches within the system are tied to both of the regimes in different ways, and may react differently to regime-level changes as well as regime responses to landscape pressures.

[40] Steam/gas turbine and reciprocating engine based CHP prime movers fuelled by natural gas or oil derivates (fuel oil, diesel)

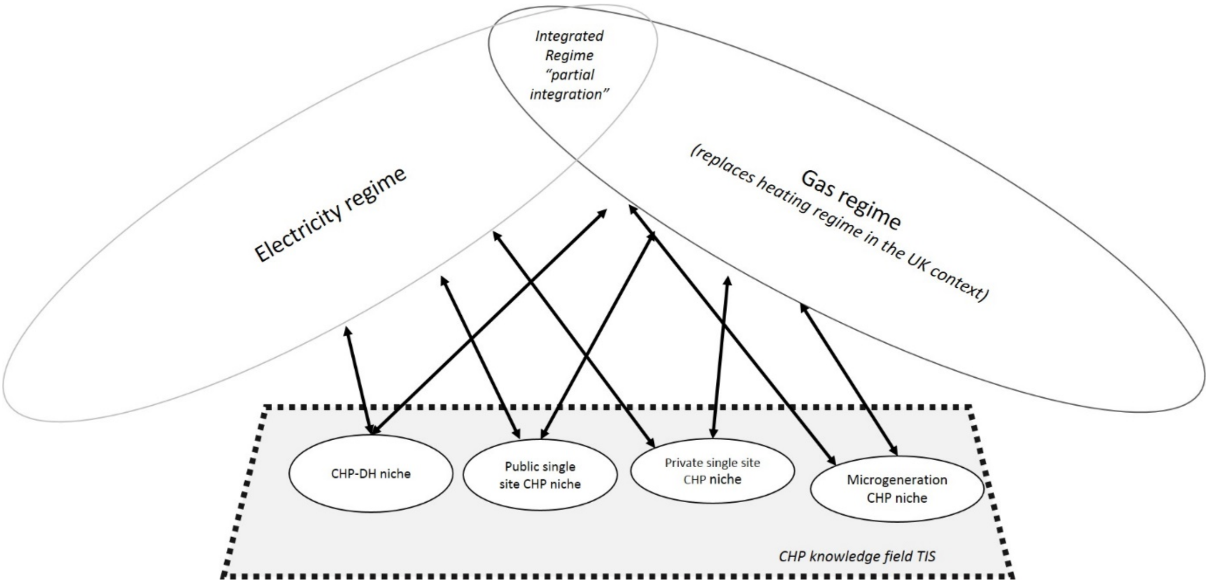

Figure 12: Integrated framework displaying the relationship of the CHP TIS and its internal niches with the electricity and gas regimes

In practice, the TIS-regime and niche-regime relationships are most clearly seen in the effects of regime policies on the development of the CHP industry: while policies developed in one of the regimes might be supportive to one or several of the niches, they do not affect the entirety of the CHP industry and might even have negative effects on other niches. One example of the different effects of regime developments and system functions (in this case, regulatory frameworks at regime level and availability of financial resources) can be seen in the following quote by a CHP policy expert:

"But those projects predominantly are dependent on things like the carbon price flow and regulatory requirements and exemptions whereas in the smaller scale CHP it's much more about just getting the money, and less about the regulatory framework." (Policy Officer, interest association)

Also, policies intended to be supportive of the development of low-carbon technologies can be deployed by regime actors either on their own accord, or in response to niche or landscape developments. In a single-regime transition scenario, this would be a development characteristic for a transformation or reconfiguration-type pathway. However, in the double-regime context encountered by cogeneration technologies in the UK there is a clear risk of these policies remaining contained within the regime, potentially benefitting competing low-carbon single output[41] technologies. This risk of falling “in between” regime developments is highlighted in the following quote from an expert interview:

“And because of that the policy developments for CHP, for things that CHP could be involved in do not capture all the benefits that it provides. So, something like the capacity market is purely focused on securing supply, which CHP can do, but it has no regard for emissions or for cost. Something like the contracts for difference auctions, focused on carbon emissions, but again nothing for cost or security, again CHP can fit into the carbon but it also works in cost and… So, you get this issue where there’s kind of a vacuum of a policy that captures everything in terms of security, cost and carbon, and therefore the benefits that CHP brings isn’t able to be captured. I think that there needs to be a, there’s a huge role for CHP in filling all three of those areas, but as of year there is not a vision or clear policy development for that to happen.” (Policy Officer, interest association)

This “in-between” position has a general negative effect on transition speed and direction, as it can impede efforts by niche actors to engage in hybridisation or fit-and-conform strategies with regime actors. From a top-down perspective, it also creates barriers for regime actors supporting the developing technology, as regime-level policies intended to support the development of the niche may prove ineffective, or exhibit unforeseen negative side-effects. An example would be the recent government policies supporting micro-CHP (Hudson et al., 2011) which have almost completely failed to fulfil the intended targets:

“The domestic micro-CHP sector is, there is very little happening, if anything. (…) I think that it’s an expensive thing and the scheme that Government put in place just wasn’t appropriate to bring forward micro-CHP.” (Policy Officer, interest association)

Extending the focus to the historic development of CHP (Russell, 1986; Hawkey, 2014; Weber, 2014) similar patterns of “in-betweenness” can be readily observed, with CHP being historically, from an institutional point of view, aligned alternately and at times simultaneously with the gas and electricity regime (Russell, 1993). Further, regime actors belonging to either regime were at times supportive of the regime, even in the

[41] The term “single output” refers to the production of only one energy output – electrical energy, or usable heat

case of actors who were earlier actively resisting the development of CHP, such as the British coal industry (Russell, 1986). While there were a number of attempts at developing holistic policies supporting the development and diffusion of co-generation, these policies were ultimately unsuccessful, such as in the case of the two National Programmes for district heating (Hawkey, 2014), as well as more recent developments, although in all cases there was limited diffusion and learning through pilot projects established in the early stages of the programmes.

7.3.1 Barriers to transition processes in multi-regime environments

In addition to the “usual” transition barriers generated by the regime selection environment (Kemp et al., 1998; Smith and Raven, 2012), the author has identified a number of additional barriers, as well as internal niche and system structural issues that appear to be specific for transitions taking place in multi-regime contexts. For the purpose of this thesis, these barriers are observed at the niche-regime and system-regime levels, utilizing the integrated framework presented above.

Internal structural issues specific for multi-regime settings are related to the *nurturing* function of niches, observed in greater details through the fulfilment of CHP TIS functions reviewed as part of the TIS analysis executed in this research. Two functions the fulfilment of which is particularly affected are *guidance of the search (F4)* and *counteracting resistance to change/legitimacy creation (F7)*, with *resource mobilization (F6)* also being affected if significant amounts of resources are procured through regime actors, or by interacting with regime structures. The main internal effect of a multi-regime environment for guidance of the search, as well as legitimacy creation seems to be connected to the directionality of the change, with system actors struggling to develop clear trajectories, at times shifting the focus of the expected development trajectory between regimes. The uncertainty is manifested in the lack of a shared vision or expectations, which was noted as one of the main barriers for the CHP system, as well as potential system-internal competition or competition between niche actors, who might attempt to mobilize or appropriate available resources in order to support their vision for the future development of technology, thus causing internal fragmentation. While this type of development has not been observed in the case of CHP, actors within CHP supporting particular technologies such as biofuel-CHP or fuel cell-CHP at times have acted within the narrower confines of the application areas relevant for their technology sub-type, diminishing the possibility of system-wide concerted efforts.

In observing external barriers, the author utilizes the SNM-based approach due to its increased focus on system-external dynamics and niche-regime relationships compared to TIS (Smith and Raven, 2012; Markard et al., 2015). External barriers are manifested in two main forms: the presence of dual selection environments created by only partially symbiotic regimes, and the reduced efficiency of hybridisation, or “fit and conform” based approaches, caused by the need for the technology to simultaneously align with both regime selection environments. Further on, there is a distinct possibility of different niches within the broader global niche (observed as a TIS) being affected in different ways, resorting to differing shielding measures by mobilizing existing sector-specific protection and niche actors engaging in different types of empowerment (“fit and conform”, “stretch and transform”, or “fit and conform *and* stretch and transform”). Although the latter developments are by no means unique, having been observed in studies on solar photovoltaics in the Netherlands (Verhees et al., 2013) and the UK (Smith et al., 2014), they have negative effects on system-wide concerted efforts, and can reduce niche momentum. Examples for this in the CHP case can be found by comparing single site commercial/industrial and public CHP with CHP-DH and microgeneration CHP: while the former two niches develop CHP towards competitiveness within the incumbent selection environments, and mainly interact with the electricity regime, the latter two niches represent more radical application of cogeneration technologies particularly relative to the incumbent electricity regime. Necessitating the development of a decentralized electricity system, with either local (CHP-DH) or individual (domestic microgeneration) actor-producers, further development of these niches needs a more radical change of existing structures, requiring actors to gravitate towards “stretch and transform” empowerment, embarking on substitution or de-alignment and re-alignment type pathways. As an additional complicating factor, future expectations for CHP development tie the future of CHP in with the future of the UK heating sector, as can be seen in the following quote:

“Only way forward for CHP through the heat side – decarbonisation, efficiency improvements (there’s a lot to be done)” (Director, energy consultancy)

This requires technology advocates to maintain focus on the gas regime while at the same time aligning with and/or enabling change in the electricity regime. An additional, compounding negative effect can be indicated from potential increased future competition between the electricity and gas regimes on the future of UK heating, rooted in the two strongest future scenarios: an all-electric future requiring full integration of heat services into the electricity regime vs. a biogas/hydrogen future, in which both regimes would remain at least partially separated, reflecting the current state[42] of partial regime integration.

Reflecting back on the four types of transition pathways, it becomes clear that *transformation* pathways are somewhat non-viable in multi-regime environments, unless there is sufficient top-down agency and policy support to enable simultaneous, guided regime transformations that include knowledge, technology and policy exchange with niche actors. Regime *reconfigurations* can, and often do take place as separate reconfigurations, with even simultaneous reconfigurations likely excluding niche actors from engaging in co-evolutionary processes. This leaves the two pathway types more oriented towards radical change: *substitution*, *de-alignment and re-alignment*. Radical, substantial change however is harder to implement, and requires substantial effort on behalf of niche advocates as well as regime disruptions and/or landscape pressures reducing the regime's own dynamic stability (Raven, 2006; Geels et al., 2016). In case of multi-regime environments, there is furthermore no guarantee that both regimes will be affected equally, generating a number of possible outcomes ranging from the de-alignment of multiple regimes at one extreme to the substitution of a single regime at the other. While the former example would, in theory, open a space for the niche technology to potentially even replace both regimes, in practice this type of change would require monumental, avalanche changes in the socio-economic landscape.[43] In general, analysts investigating transitions including multiple regimes are likely to observe multiple pathway shifts (Geels et al., 2016) with niche

[42] This, of course, does not mean that future closer integration, or other types of multi-regime interactions would not be possible. Comparing the case of CHP in the UK with the case of CHP in the Netherlands observed by Raven and Verbong (2007, 2009), the main difference seems to be the far lower level of policy integration in the UK compared to the Dutch system

[43] While such changes do happen, and have happened in human history, their rarity in the author's opinion precludes them from being discussed as a non-exceptional option

actors reacting to newly developed spaces and discourses by revising expectations and changing the development trajectory between the incumbent regimes.

7.3.2 The possibility of additional transition pathways – the shifting/persistence pathway

Drawing on the previous discussion as well as the focal empirical case of this study, the author will discuss the applicability of the four reviewed pathway types, focusing on the multiple pathway shifts observed in multi-regime transitions, with a particular focus on changing interactions with regimes (*re-focusing*) through strategic shifts and pragmatic utilization of available resources and spaces, reflecting both regime-level and landscape-level developments. This discussion is understood as an extension of the pathway shift discussion introduced by Geels et al. (2016), which is broadened by the possibility of both sequential shifts (which are to a certain degree covered in previous works) and the bi-directionality of observed shifts in reaction to changes in multiple regimes. The latter posits that a multi-regime transition might shift from a “fit and conform” pathway to a “stretch and transform” one, as presented by Geels et al. (2016) on the case of offshore wind technologies in the UK (Kern et al., 2014), but might later shift back towards a “fit and conform” pathway if changes in either regime create a more hostile situation for the focal technology or improve the change of hybridisation-type engagement with regime incumbents. Further on, the process can happen multiple times, and might include periods of dormancy in the transition process, with technology advocates engaged in system-internal developments or shifting into a defensive dynamic, protecting existing assets.

From a process perspective, this type of transition would not only include pathway shifts in reaction to internal or external developments, but would actively include multiple, repeated and bi-directional shifts between pathways as a method of achieving a transformative process. This viewpoint includes large amounts of pragmatic action by technology advocates, a phenomenon that has been discussed in recent studies on energy sector transitions (Verhees et al., 2013; Kern et al., 2014; Smith et al., 2014). Therefore, in this case pathway shifts become an integral, expected and necessary part of the transition process instead of potentially occurring phenomena – which is a characteristic that, in the author’s opinion, sets the discussed case apart from the different types of shifts observed in previous literature (Geels et al., 2016).

The proposed pathway will subsequently be illustrated and discussed on the focal empirical case of this thesis – co-generation technologies in the United Kingdom. In terms of transitions, this case can be described as an ongoing transition process – while some parts of the CHP industry have developed towards stabilized late market niches, there is certainly sufficient activity by CHP advocates within the cogeneration system (in particular with regard to CHP-DH and micro-CHP).

Drawing on CHP history, in particular the work of Russell (1986, 1993, 2010), Babus'Haq and Probert (1996) and Hawkey (2012, 2014), the first transition developments within the then-fledgling CHP industry can be traced back to the development of the National Grid in the mid-to-late 1920s. Fuel shortages in the post-First World War period created a general discourse on efficiency in energy generation, which created potential openings for CHP proponents who deployed expectations and future visions based on the fuel and therefore cost savings made possible by the technology. While these expectations were readily taken up in a small number of specific sectors (industry, some public institutions), the broader diffusion of cogeneration was cut short by significant barriers created by the mismatch between the localized, decentralized nature of CHP and the developing, centralized public energy system manifesting through the National Grid (Russell, 1993). Technology advocates initially adapted an orientation towards the energy regime, however, this proved to be unsuccessful, causing a withdrawal into small, localized experiments and specific application areas (Russell, 1986; Babus'Haq and Probert, 1996). From a transition pathway perspective, this initial push could be described as a *reconfiguration* pathway changing towards a *transformation pathway*, ultimately slowed down due to a technical, infrastructural reconfiguration of the regime that excluded interaction with niche actors.

A second opportunity window for CHP advocates opened following the broad, deep landscape-level changes caused by the Second World War and the post-war rebuilding and re-nationalization efforts. The broad discourse around CHP did not change significantly from the efficiency visions utilized in the 1920s, however additional expectations could be shaped through the inclusion of the social dimension, putting forward cogeneration as a technology able to deliver affordable heating, fitting into the post-war Labour government aims of developing a mixed economy and a welfare state (Russell, 1993). Government support enabled the implementation of a National Programme for CHP-DH. However, shifting government focus towards a centralized command-and-control structure (Hawkey, 2014) meant support was cut short, enabling only the development of a number of pilot projects. Additional restrictions for CHP-DH development surfaced in the forms of limited powers of local governments, who initially had no general powers for generating electricity, and had to promote local bills in the British Parliament on a case-by-case basis (Russell, 1993). Despite this, technology advocates jumped at the opportunity, and developed proposals for multiple major schemes in urbanized areas. From a pathway perspective, niche actors initially shifted back to a *reconfiguration pathway*, with proposed radical changes to the institutional framework around power generation that were necessary in order to enable localized operation of CHP schemes. However, government support waned, and with initially sympathetic regime actors taking on a harder stance, niche-regime interaction became more complicated, closing this opportunity for closer alignment of the CHP niches with the electricity regime (ibid.)

The third opportunity window for CHP occurred soon thereafter, and was marked by a repositioning of CHP from the previous goal of close alignment with the electricity regime to a trajectory of interaction with both the electricity and heating regimes. The trigger for this opportunity window was in part increased competition between the electricity and heating regimes as well as regime-internal reconfigurations within the heating regime as part of the shift from coal towards oil as the main fuel (Russell, 1986). This caused regime-internal competition between coal and gas advocates, with the former shifting from opponents of CHP to supporters of district heating schemes, resulting in the opening of a potential developing market for co-generation technologies. Within this context, CHP advocates could engage on a *reconfiguration pathway*, but with the focus of the transition shifted to the heating regime instead of the previously engaged electricity regime. However, their attempts were hampered by the technological immaturity of CHP as well as the increasing popularity of gas, further exacerbated by consumer resistance and negative experiences caused by several hastily proposed schemes (Russell, 1993). These negative experiences caused increased active resistance to the technology by disappointed users and public actors, causing CHP advocates to slow down attempts at enabling a transition.

The next opportunity window for combined heat and power was caused by landscape-level shocks in the form of the oil crises of the late 1970s and early 1980s. Government interest in efficient resource use sharply increased (Russell, 1993; Weber, 2014), culminating in the implementation of the "Lead Cities Programme". At regime level, the electricity and heat regimes remained mostly separated, with the heat regime becoming absorbed by the gas regime due to ever-increasing use of gas as the main heating source, and the development and consolidation of the nationwide gas infrastructure (Hawkey, 2014). After the re-orientation in the post-war period, CHP remained "in between" the regimes, although most developments through the "Lead Cities Programme" indicated a slight shift from the previous heating (gas)-oriented reconfiguration pathway to a more complete *substitution* pathway in which CHP-DH networks would replace individual heating as the dominant heating solution in urban areas. However, and quite similar to the ultimate fate of the first National Programme, government support for the programme decreased significantly (Russell, 2010; Hawkey, 2014), coinciding with a general government withdrawal from public projects in line with a broader landscape change from active government participation in public sector developments to government divestment and privatisation, creating a "hands-off" relationship (Bolton and Foxon, 2015). As the (mostly public) actors supporting and developing CHP schemes could do little in order to improve the economic feasibility of large-scale CHP schemes in a selection environment that was not significantly changed, the programme ultimately ground to a halt, marking the beginning of yet another phase of actor withdrawal and protective niche consolidation focused on maintenance of existing schemes.

However, continuing rollback of state functions (Pearson and Watson, 2012) and increasing privatization of nationalised industries, in particular the energy and heating/gas industries (Hawkey, 2014) soon created the next opportunity for CHP advocates, although in significantly changed conditions (Weber, 2014) where the public debate, and particularly the government discourse moved towards supporting free energy markets and market "self-regulation". The privatisation of the gas regime (in and around 1986) and the subsequent privatisation of the electricity market in the late 1980s and early 1990s (Pearson and Watson, 2012) caused significant transformations and reconfigurations at the regime level, which affected and changed the selection environments in which CHP had to compete. In the early years of the privatised energy market, there was a strong surge in the development of large-scale cogeneration plants on industrial sites, as well as an increase in the implementation of small-scale, “plug and play” CHP engines utilized in smaller public and private settings. However, this rapid increase in private interest and the diffusion rate was equally rapidly cut short by the implementation of a regulatory framework for private electricity trading in the form of the New Electricity Trading Agreements (NETA, later renamed to BETA) (Pearson and Watson, 2012), which made the majority of the large industrial schemes developed using power generation algorithms economically unfeasible:

“It’s all coming to a halt with the introduction of the new electricity trading arrangement, um, and it was because of the level of risk around the electricity generation and pricing, because it was connected to the network, and therefore input power at times could be extremely powerful, and I think almost overnight the industrial CHP market was booming everywhere, and then became heavily predicated on power-optimized schemes, so we had these energy services companies, ESCOs if you like, building very large scale CHP or CCGT CHP, using host sites to generate surplus electricity and provide the host with the heat. (…) And I think under that change in the electricity market, where the generator was more exposed to the volatility of the market, that killed industrial CHP off at a stroke.” (Senior Manager, regional government)

In this phase, CHP advocates again shifted from a substitution pathway towards a reconfiguration pathway, attempting to utilized the changed selection environment in order to make co-generation competitive within its constraints (this could also be described as an instance of *fit and conform* development). Simultaneously, the orientation of the planned transition trajectory was shifted from the heating/gas regime to the electricity regime in order to exploit economic advantages of electricity generation enabled by the new regime configuration. While further changes to the institutional framework somewhat slowed the speed of this development, especially for large-scale industrial CHP applications, small-scale public and commercial CHP schemes remained viable, with the diffusion rate remaining relatively high.

The final observed pathway shift occurred following another change in the public discourse followed by regime-level reconfigurations in the institutional framework: the increasing relevance of environmental concerns and the development of international (Kyoto Agreement and EU policies), national and regional/local environmental policies (Pearson and Watson, 2012; Geels, 204; Hawkey, 2014; Weber, 2014). CHP advocates could, in a sense, “resurrect” expectations and visions of increased energy efficiency that were prominent during the second National Programme (Russell, 1993; Hawkey, 2014), reframing them towards generating improved environmental performance through resource efficiency, in addition to the previously employed visions of increased energy independence and cost efficiency (Rogers-Hayden et al., 2011). However, focusing the new transition trajectory on either one of the regimes proved to be challenging: while the barriers for small-scale generators created through the NETA/BETA, as well as further resistance by the electricity market and distribution network operators (DNOs) made interactions with the electricity regime difficult (Toke and Fragaki, 2008; Bolton and Foxon, 2011; Hawkey, 2014; Weber, 2014). The dominance of gas as the main heating source, combined with the lack of an institutional framework for heating as an utility meant that an orientation of the transition towards the gas/heating regime would be equally challenging, as it would require the creation of a new regime based around the provision of heat as a societal function, for which there was and is little appetite among public sector actors and large private actors. Current and future development of CHP technologies is also negatively influenced by a lack of shared visions and a general uncertainty about their future development trajectory – visions for the future use of CHP range from the technology being an integral part of the future UK low-carbon energy system (Foxon et al., 2010; Foxon, 2013; RTP Engine Room, 2015), to a potential discontinuation of the technology in the case of a transition to an all-electric energy system. General actors consensus seems to lay in between these two extreme options, considering CHP to be either a good “bridging” technology in the development towards a zero-carbon energy system, or considering cogeneration to be a viable technology in particular development scenarios.

Due to the ongoing nature of the current transition period it is rather hard to define the pathway type chosen by the actors, with evidence pointing to potential niche fragmentation within the CHP system – while actors in some CHP niches develop towards hybridisation with the existing regime(s), following a reconfiguration-type pathway, other niche actors, in particular advocates of CHP-DH and microgeneration CHP develop towards a substitution pathway with the main aim of replacing the incumbent centralized energy system with a more decentralized one.

7.3.3 Defining the shifting/persistence pathway

Following the above discussion, as well as the findings of the empirical case, the author is proposing an addition to the existing pathway typology (Geels and Schot, 2007; Geels et al., 2016) in the form of a shifting/persistence pathway. Following on Geels et al. (2016) comments on pathways shifts in transition processes, as well as the insights of Raven and Verbong (2007, 2009) and Konrad et al. (2008) on transition processes in multi-regime environments, the proposed pathway illustrates transition processes in which the focal developing technology is interacting with multiple regimes, which in turn are influencing each other while at the same time being subject to landscape-level changes. Extending the idea of single-event pathway changes influenced by niche or regime developments, the shifting/persistence pathway consists of a sequence of intentional, pragmatic pathway shifts initiated by niche actors and regime proponents of the niche technology. These changes are initiated in response to landscape changes or regime and inter-regime reconfigurations, with the aim being either a restructuring of niche visions and expectations following a change in the public discourse (Rogers-Hayden et al., 2011), or a reaction to increased regime resistance (Geels, 2014; Hawkey, 2014). Further on, the proposed pathway is in line with the observations of Verhees et al. (2013) on a “piecemeal strategy” employed by niche actors, changing between deliberate, strategic empowerment and pragmatic utilization of existing spaces and resources.

7.4 Chapter Summary

In this chapter, the author discussed the implications of the study’s findings with regard to the three main lines of enquiry followed in this thesis – empirical insights into the socio-technical factors, barriers and development influencing the development and diffusion of CHP in the UK, a practice-informed theoretical discussion on the niche definition and typology, and an investigation of the effects of multi-regime environments, and inter-regime dynamics on the trajectories of (sustainable) transitions. The first line of enquiry resulted in a list of internal structural issues of the CHP industry, related to actors, actor coalitions and networks, and negative effects of the dual institutional framework within which CHP proponents need to operate. A review of external barriers and regime interactions revealed additional, external factors influencing the development of CHP.

The second part of the discussion reflected on the different definitions of niches, and the development and importance of individual niche functions (Smith and Raven, 2012; Verhees et al., 2015; Raven et al., 2016) along a niche’s development trajectory (Geels and Raven, 2006). Building on an existing niche typology (Raven, 2006; Smith and Raven, 2012), the author proposes an extended niche typology which provides additional explanations for the internal structure and functions of later-stage niches.

In the third part of the discussion, the author draws on existing research on transitions pathways (Geels et al., 2016), reviewing the proposed typology in cases of multiple regimes included in the transition process (Raven and Verbong, 2007, 2009). Based on the observed case of CHP in the UK, as well as insights from existing research (Raven and Verbong, 2007, 2009; Konrad et al., 2008), the possibility of additional pathways specific for multi-regime environments is explored. This part of the enquiry is concluded by proposing one such pathway: the shifting/persistence pathway, and defining its probable trajectory along with a call for further research and application on additional empirical studies.

These findings will be reflected upon within the broader context of the research question and the three sub-questions in the following and last chapter, which will also contain a short outline of research limitations and challenges for future research.

Besides addressing the research question, the chapter will also be used to reflect on other interesting findings and insights gained in the course of this research project.

8 Conclusion, limitations of the research and further challenges

This chapter will be used to revisit the main findings and insights generated by the study, reviewing both theoretical discussions and proposals, and the empirical findings feeding into the theoretical review. The focus will be on the outcomes of the two analytical stages – Chapter 5 which centred on a technological innovation system (TIS) analysis of the combined heat and power industry in the UK and Chapter 6 where combined heat and power was investigated as a group of niche operating within a multi-regime context. Prior to that reflection, the author will briefly revision the rationale for the utilization of integrated frameworks in Transition Management, in line with proposals by Markard and Truffer (2008) and Wirth and Markard (2011) and following comments made by Markard et al. (2012, 2015).

Further, the research question and the three sub-questions derived from it will be revisited, calling upon the findings of the discussion undertaken in Chapter 7 in order to provide responses to each of the sub-questions, as well as the overarching research question.

Finally, the author will reflect on the limitations of this research study, highlighting particular areas in which further enquiry would be needed, as well as potential future research pathways with the aim of both focusing and extending the findings of this study. Research limitations and further challenges will be observed from both a theoretical and empirical perspective, with suggestions for further lines of enquiry provided.

8.1 Observation of the development of CHP in the UK utilizing transition theories

In this section, the author will briefly reflect on the potential of transition theories focusing on innovation system analysis and niche-regime interaction applied in the form of a combined framework to provide useful insights into the development of CHP in the UK, observed as a case of a sustainable technology transition. The author was drawing primarily on the TIS-MLP joint framework proposed by Markard and Truffer (2008) and utilized by Wirth and Markard (2011). For the purposes of this study, the author utilized a broader concept of the framework (niches existing within technological innovation systems, which coexist with regimes), although the analysis of the niche-regime interactions and the CHP technological innovation system was executed in separate stages. Following this approach enabled the author to focus both on the internal structure and functions of the CHP industry observed as a technological innovation system (TIS) and to subsequently extend the analysis to the system's environment, reviewing distinct CHP market niches existing within the broader system, and the UK electricity and heating/gas regime with which these niches interact. The second part of this approach was implemented in reaction to criticisms (Smith and Raven, 2012; Markard et al., 2015) of the TIS approach based on its system-centric focus; while recent research has responded to these criticisms by conceptualizing system-external contextual structures which influence its internal structure and functions (Bergek et al., 2015), the inclusion of niche-regime (Raven, 2006; Smith and Raven, 2012) and especially multi-regime (Raven and Verbong, 2007, 2009) dynamics enabled to not only observe structural couplings of system elements to external context, but to review system (and by extension, niche)-independent dynamics which influence the selection environment within which the focal technology is developing.

In the course of the analysis, the author noted multiple merits of the chosen approach, allowing for both deeper and broader insights into the observed technology transition, and for the inclusion of an increased number of actors, networks and institutions as well as dynamics taking place beyond the "system border" of a more traditional approach (Bergek et al., 2008). The main advantage was the ability to use the respective advantages of the two approaches: the author had the ability to select the approach deemed more appropriate for the analysis of a given segment of the broader observed case. As outlined above, the author primarily relied on the TIS approach to analyse the system's structure, the fulfilment of (internal) system functions and internal, structural barriers to further development and diffusion of the technology. Subsequently, insights from the multi-level perspective and strategic niche management were used to investigate system-external dynamics and activities of internal actors aimed at interacting with external actors and/or institutions (mainly by using the shielding and empowerment niche functions). While the SNM approach also recognises a nurturing niche function, this part of the analysis was supplanted by the TIS analysis, which is recognised to provide a more elaborate approach for investigating nurturing processes (Smith and Raven, 2012, p. 1027).

The advantages of the chosen approach were particularly suited for the observation of the chosen empirical case, with the focal technology field (combined generation of heat and power) operationalised as a technology innovation system (TIS) following Bergek et al. (2008), and in a second analytical step subdivided into a number of application niches interacting with two partially integrated regimes; extending the TIS analysis both towards the micro-level, and beyond the set system boundaries. The latter part of the observation was found to be particularly interesting, as it allowed the author to account for effects of inter-regime dynamics between the electricity and heating (gas) regimes influencing combined heat and power technologies. In a standard innovation system analysis, these factors would have been outside of the scope of the analysis, limiting its completeness and reducing available information.

Reflecting on the main research question, the author can conclude that the application of transition theories focused on innovation system analysis and niche-regime interactions does indeed allow for valuable insights into the development of CHP in the UK, in particular when these theories are applied in the form of a joint framework. Insights were primarily gathered at three levels: by observing CHP as a technology field based TIS, the system structure and (internal) system functions were analysed, uncovering a number of structural and functional weaknesses influencing the development and diffusion of the technology. The author was able to investigate a number of structural issues, and assess their impact on the performance of the CHP TIS.

The second level of observation focused on specific application areas for CHP, aiming to identify both general and niche-specific externally generated barriers inhibiting the technology's diffusion, while also expanding and reconfirming the findings of the TIS analysis through investigating the fulfilment of niche-internal functions.

Finally, the third level of observation took a broader view on CHP, taking into account not only the dynamics between incumbent regimes and the focal technology, but also the relationship between the two observed regime and any potential positive or negative side-effects of inter-regime dynamics not directly connected with CHP. This was particularly useful to review the "between regimes" position of cogeneration technologies, and the specific barriers generated by the interaction of the regime selection environments. Further, inter-regime dynamics were also useful for a reflection on the side-effects of regime-specific policy changes, at times having negative impacts on regime-external actors and institutions.

8.2 Utilization of integrated frameworks in Transition Management

This section will expand on the discussion on the merits of integrated frameworks by reviewing the potential of utilizing the integrated framework for other technology cases, and in a more general context. Starting with a reflection on the characteristics of the applied integrated framework, the discussion will then touch on potential future areas of review, and briefly comment on other empirical cases where utilization of an integrated analytical approach might be considered.

The strengths of an integrated framework approach lie in its versatility and ability to investigate context using a number of different analytical constructs. This can be seen as a “layered” approach in which separate, consecutive attempts at creating meaning and developing causal chains can be performed in order to broaden and deepen the data gathered from the analysis. Also, the possibility of utilizing a number of analytical concepts to accumulate knowledge about observed phenomena reduces the risk of analytical “tunnel vision”, in which the analyst might attempt to force the data to fit into a particular construct. Further, the utilization of an integrated framework should provide the researcher with the ability to shift between different points of observation, as was demonstrated in this study by moving the focus between a bottom-up perspective derived from SNM, a top-down perspective utilized for the regime analysis, and finally shifts between the system components and the system environments. This will reduce the potential of bias towards a particular viewpoint, which was a noted criticism of early-stage transition studies analytical approaches (Geels and Schot, 2007; Geels, 2011, Geels et al., 2016).

While this form of integrated framework does not represent a departure from analytical rigour due to a high level of conceptual similarity between the different analytical constructs (Markard and Truffer, 2008), there is a definite risk of repetition of similar analytical steps in the course of the review. This is however considered by the author to be an acceptable trade-off, as it allows for independent verification of the main recognized patterns, dynamics and barriers by employing multiple, separate viewpoints, as well as a simple form of triangulation in case of differing results. Therefore, this type of approach can have merits in the case of reviews of complex transition processes, as well as in cases where multiple viewpoints on transition barriers and other constraining factors are preferred. It is the opinion of the author that utilization of integrated frameworks might offer potential solutions to the challenge of improving and specifying conceptual framework and methodological underpinnings put forward by Markard et al. (2012).

Considering the inherent complexity of many of the current socio-economic and technical challenges, an integrated framework approach might prove to be a usable instrument due to its multi-layered nature and the above-discussed utilization of multiple viewpoints. Furthermore, this approach allows the analyst to provide useful insights for actors whose main activities are at different levels; this includes both meso-level observations for policymakers and specific, micro-level advice for project developers. The extension of this approach beyond the boundaries of a system-type observation by including inter-regime dynamics might be useful in including collateral effects of external changes, in particular institutional changes. While current research on TIS-style analyses has extended the scope of a TIS analysis to include context structures (Bergek et al., 2015), an integrated framework approach allows the researcher to utilize multiple viewpoints on these external elements, both deepening the scope of observation and allowing for triangulation of the gathered knowledge.

Another potential application of an integrated framework would be the parallel review of existing institutional frameworks on multiple levels of observation, combining a broader, meso- or system-level review with a micro-level review focusing on the effects of an existing framework on individual projects and actors. This could potentially be extended even further by the addition of system dynamics modelling to the TIS analysis part of the framework, allowing for scenario-building through quantitative testing of the effects of particular policies[44]. Therefore, the integrated framework approach might be particularly useful as a supporting tool for development of holistic, complex policies, using its broader scope compared to more traditional approaches in order to ensure both planned and unintentional policy impacts are taken into account.

Finally, the author would like to reflect on potential real-life application cases for the framework. As mentioned in the above paragraphs, the strengths of the framework lie in its ability to review complex cases, with innovative technologies developing in

[44] This approach is discussed further as a challenge for future research in Chapter 8.6.

interaction with multiple regimes. Therefore, potentially interesting cases would be various biofuels and bioenergy technologies, which are interacting with the energy, food production/agriculture and waste regimes, or electric cars, developing within the transport regime but also interacting with the energy regime due to infrastructural requirements and their potential function as energy storage within smart networks. This is further supported by already existing research, where elements of an integrated framework were used to review bioenergy (Raven and Verbong, 2009) and Bio-SNG biogas (Wirth and Markard, 2011).

8.3 Structural issues of innovation systems – the role of actors, networks and expectations

In the attempt to review the causes and contributing factors to the low rate of diffusion of CHP in the UK compared to other West and Central European countries (Raven and Verbong, 2007; Weber 2014) the author has undertaken a TIS analysis, focusing on the structure of the CHP system and external barriers and blocking mechanisms, the latter compounded by a SNM-based analysis where external, regime-generated barriers were investigated both for CHP in general, and for its application areas. This two-stage analysis has yielded a number of results which can be seen as indicative both for explaining the specific case of cogeneration in the UK, and for increasing understanding of under-performance and transition failure for other technologies.

The first important finding was related to the lack of powerful advocates ("champions") for CHP, which directly related to the observed lack of a strong, shared vision and the relatively low number and limited reach of CHP networks. Strong proponents for an innovative technology are seen as crucial in both MLP/SNM (Geels, 2002; Raven, 2006; Smith 2007; Smith and Raven, 2012) and TIS-type (Hekkert et al., 2007; Bergek et al., 2008) analyses. The lack of "champions" therefore will not only have a negative effect on the fulfilment of external-oriented functions (shielding, empowerment) and internal functions (TIS functions, nurturing niche functions) but can also weaken the actor-network structure of the system as well as the generation of expectations and visions, which results in the generation of legitimacy.

Two effects related to the lack of "champions" which were identified as being particularly significant for the development of CHP in the UK were the absence of a regulated market for heat and the negative effects of government regulation not directly aimed at CHP. The former was identified as one of the key reason for a relative diffusion failure of CHP in district heating schemes, an application area that was considered focal for a large part of the technology's development history (Russell, 1993; Babus'Haq and Probert, 1996). With little interest for the creation of the required institutional framework on the side of regime incumbents[45], and increasing

[45] Both heating/gas and electricity regime incumbents, with a particular focus on the former

detachment of public actors from large-scale institutional and infrastructural developments, the task of developing a heating market/regime could only have been fulfilled by CHP advocates exercising *constitutive* power (Avelino and Rotmans, 2009). However, in practice there were no actors available with the capacity to exercise that power, turning the task into an impossible one. An similar effect was observed when considering the negative side-effects of government programmes on the diffusion speed and development of CHP – while the policy changes were mostly not targeted at the technology itself (Russell, 1993; Weber, 2014), they nevertheless had significant consequences, slowing the diffusion and making certain development trajectories impossible, for example the development of large-scale industrial CHP schemes following the implementation of the NETA (New Electricity Trading Arrangements) (Pearson and Watson, 2012). In this case, sufficiently powerful actors could have exercised *systemic* power manifested through active shielding and empowerment (Smith and Raven, 2012), protecting the technology from the negative change in the selection environment. However, again, no "champions" were available to both provide feedback and exercise influence on public sector actors, and to utilise available resources in order to protect the technology.

Another key structural issue of CHP is related to the lack of strong networks. Network building and management are recognised as a key niche function (Kemp et al., 1998; Raven, 2006; Smith and Raven, 2012) and networks are considered a core structural element of a TIS (Hekkert et al., 2007; Bergek et al., 2008); further on, research by Caniëls and Romijn (2008) has indicated the important role of strong, stable networks in supporting transition processes. While a central, umbrella network for CHP actors exists in the form of the ADE (Association for Decentralised Energy), and network members and managers put in significant effort to increase the number of actors participating in the network, and enable knowledge exchange between then, these efforts are limited by resource availability and the power of the actors maintaining the network. While further, smaller networks and network-like structures do exist, they are mainly active in local or, at best, regional environments, and might be limited to the duration of R&D projects or public development programmes. Network weakness is directly connected to the above-discussed lack of actors having the power and resources to assemble and maintain network structures, and results in limited knowledge exchange across the CHP industry, with information flows relying on intermediaries[46], especially for new entrants and prospective new users.

A third main issue related to the lack of powerful advocates, as well as to the lack of networks is the lack of strong, shared expectations and visions, forming the groundwork for development trajectories and offering *performance promises* to external actors and prospective new users. Such expectations and visions are often developed by "champions" (Raven, 2006), who can use their ability to exercise power and their resources to strengthen and communicate these expectations, increasing the core technology's legitimacy (Hekkert et al., 2007; Bergek et al., 2008). While historical reviews show multiple major expectations and leading visions for CHP (Russell, 1993, 2010; Babus'Haq and Probert, 1996; Hawkey, 2014), a review of the current state of the cogeneration system showed no such dominant vision, with multiple sets of expectations on the role of CHP in the future UK energy sector competing and co-existing. Considering the history of CHP, expectations and visions for the technology have had a somewhat deterministic effect on perceived success and failure – while CHP is often considered to have had a less-than-successful transition process with regards to the UK electricity and heating/gas regimes, the technology is in fact broadly and successfully used in specific application areas, such as the petrochemical and paper industries, hospitals, leisure centres or wastewater treatment plants. However, as the leading expectations for CHP were often connected with the used of cogeneration plants in large public heating schemes (Russell, 1986; 1993; 2010; Babus'Haq and Probert, 1996; Hawkey, 2009, 2014; Kelly and Pollitt, 2010; Weber, 2014), a vision that was never fulfilled, the history of the technology is seen as one of failure by some authors (Russell, 2010; Weber, 2014).

The first research sub-question was investigating the socio-technical factors, barriers and developments which have influenced the peculiar development of CHP technologies in the UK. In the course of a two-stage analysis, combining a system-centric TIS analysis with a context-including, bottom-up niche-regime SNM review, the author has identified the structural issues and factors described above. Further on, the research has identified a number of external barriers influenced by the dual regime-

[46] For CHP, the role of intermediaries is mainly taken up by energy consultancy companies and/or companies specialized on developing and implementing CHP schemes

generated selection environment, as well as barriers created by an individual regime. The most relevant barriers are the lack of available heating infrastructure, which was seen as particularly limiting to the development of heat network-centred CHP schemes (CHP-DH), high entry barriers for small producers joining the electricity capacity market (Toke and Fragaki, 2008) created by regional Distribution Network Operators (DNOs), and the lack of a heating regime in the sense of a market for heating as a commodity. Further barriers to development are manifested through a general uncertainty about the future prospects of CHP or, indeed, the desired future configuration of an UK low-carbon energy system among public sector actors, as well as negative effects of abrupt, significant policy changes, whose side-effects included the reduction of competitiveness of entire sub-sectors of the UK CHP industry. One final, important regime-generated barrier is created through the institutional lock-in (Unruh, 2000) of the UK energy sector to a centralized system, which is the conceptual opposite of a decentralized system for (electrical) energy and heat generation envisioned by CHP advocates, especially actors supporting CHP-DH and domestic micro-generation solutions based on CHP technologies.

8.4 Niches as distinct spaces in transition processes

Further findings of this study centred on a review of the role, delineation and functions of niche spaces in transition processes, especially regarding long-term transitions and niches at advanced stages of development. After reviewing both the concept of niches as protective spaces, and niches as application areas, the author drew on a distinction between technological and market niches (Schot and Geels, 2008) based on their stage of development, and extended the typology by separating both technological and market niches into early- and late-stage types. The main aims of the proposal were to develop a more precise typology in order to reflect the shifting focus on and between niche-internal functions depending on the stage of development of the focal technology and its supporting structures, and to account for decreased levels of shielding in older niches, which are nevertheless still exhibiting transition-oriented behaviour, separating them from “conventional” market niches in the understanding of marketing and strategic management studies.

The proposed extended typology includes *early technological niches*, *late technological niches, early market niches* and *late market niches*; while sustainable innovations will usually develop through all four stages, the development is neither deterministic nor necessarily linear, with developments skipping one of more niche types, as well as regressions in reaction to significant, negative regime- and landscape-level events and developments all possible. In an idealized case, the technology would start in the early technological niche, which is comparable to the concept of an R&D niche as discussed by Raven (2006). With the technology in an immature, experimental stage, competition within the regime selection environment is impossible, making niche shielding a key function at this stage together with learning in the form of knowledge development and dissemination. As the technology matures past the prototype stage and actor networks start to form, the niche develops into a late technological niche, characterised by the development and communication of visions and expectations, and further development and expansion of networks. Shielding and learning remain key functions, and can be expanded across multiple areas (Raven, 2007; Smith and Raven, 2012), while there is also increased focus on the articulation of expectations and development of networks. A late technological niche is similar to the general niche concept utilized in the Multi-Level Perspective

(Geels, 2002), and is still largely separated from the market, existing within clearly defined protective spaces. The next step in niche development happens once initial, small niche markets develop for the focal technology, defined by actors who are willing to take into account inefficiencies (Levinthal, 1998) due to the technology's promised performance and/or performance in specific application settings. While shielding is still necessary to some degree due to the technology's lack of competitiveness compared to regime incumbents, the key functions at this stage are nurturing and empowerment, with the niche itself defined through its actor networks and application areas. Empowerment (Smith and Raven, 2012) and strategic choices by niche advocates (Raven, 2007) increase in importance, although actor agency is still limited due to lack of power and/or available resources. A potential transition pathway manifests itself, although the trajectory can still be uncertain. Through expansion of niche markets, ongoing empowerment and expansion of actor networks, the niche develops into a late market niche, differentiated by a larger number of more stable markets in which the niche technology usually represents the best available technology, and its users belong to the early majority group (Rogers, 2003, p. 282) compared to the innovator/early adopter users in earlier stages of niche development. Some instances of shielding can still be exhibited, but the niche is primarily defined by its actor networks, application areas and expectations/visions. Concurrently, nurturing and empowerment are considered key niche functions, with empowerment being more focused and strategic than in early market niches. From a TIS perspective, late market niches can be compared to TIS in take-off and/or acceleration phases (Hekkert et al., 2011). They are also similar to niche markets from a marketing perspective, but can be differentiated by the presence of transition-related activities, expectations and visions focused on the technology either co-evolving with or substituting the incumbent regime, and a usually visible transition pathway.

The further development of a niche past the late market niche stage can take multiple forms, with the two main trajectories observed in the course of this study including either the niche technology entering a successful transition pathway (Geels et al., 2016), or the niche technology remaining in a stable market niche. While the later trajectory certainly implies an unsuccessful transition from the viewpoint of Transitions Studies, it does not necessarily mean a complete failure of the technology and its surrounding system structure. The technology can still continue to be used in particular application areas, becoming a specialized technology, however, transition-focused visions and expectations for further development will fade out, as will niche advocates focused on enabling (especially radical change-based) transitions.

In the second research sub-question, the author aimed to investigate and discuss the niche typology utilized in MLP and SNM, especially regarding the structure, delineation and behaviour of niches at advanced stages of development, such as some of the CHP niches observed in the course of this study. Contrasting a protection-based niche definition with an application- and actor/user group based one, and relating to conceptual connections between niche structures and functions and TIS structures, functions and dynamics, an extended typology was proposed, containing additional niche (sub-)types with the aim of allowing for a more precise definition of a niche's development stage, and explaining the internal structure, delineation against external contexts and dynamics of niches at more advanced stages of development which are still parts of transition processes.

8.5 Transition processes in multi-regime contexts

In this part of the study, existing insights on transition pathways (Geels and Schot, 2007; Geels et al., 2016) were reviewed on the somewhat under-researched case of multi-regime transition processes. Drawing on research by Raven and Verbong (2007, 2009) as well as existing knowledge on system-internal (Hekkert et al., 2011) and regime-generated (Kemp et al., 1998; Smith and Raven, 2012) barriers the author has reviewed existing barriers on the empirical case of CHP in the UK, noting a number of specific challenges related to "fit and conform" empowerment (Smith and Raven, 2012), hybridization-type niche actors strategies (Raven, 2007) and transformation and reconfiguration-type pathways (Geels et al., 2016) in case of incomplete regime integration and instances of inter-regime competition. These challenges necessitate a higher-than-usual amount of reactive action from niche advocates, reacting to developments affecting either of the regimes, both regimes, as well as "unintended consequences" of changes in the inter-regime dynamic that are not a result of deliberate resistance by incumbents (Geels, 2014). Therefore, the case of multi-regime transitions in cases of incomplete regime integration cannot be represented by the existing pathway typology with a high degree of accuracy.

Based on the findings of this review, the author proposes a potential additional transition pathway, provisionally named as the "shifting/persistence pathway". The proposed pathway is characterised through the active role of multiple regimes in the observed transition process, incomplete integration between the regimes and the reliance of niche technology advocates on pathway shifts and trajectory changes between regimes as a key tool in order to further the transition process, protect, and adapt the niche technology to landscape- and regime-level shifts. While the non-linearity of transitions and possibility of pathway shifts were discussed by Geels et al. (2016), they are mainly discussed as singular events in response to institutional or technological change. Within the proposed pathway, pathway shifts are occurring in sequences, and are being actively utilized by niche actors as a transition tool, following at times a "piecemeal strategy" of combined strategic niche support and pragmatic utilization of available resources and spaces which was observed by Verhees et al. (2013).

From an empirical point of view, the “shifting/persistence pathway” may be usable for the analysis and description of cases where initially promising innovations remain in a developing stage for a long period of time, neither managing to become a part or replace dominant technologies and supporting regimes nor fading away as failed innovations. In addition to the case of CHP in the UK discussed in this thesis, further examples can be found in the bio-energy sectors[47], transport sectors and to a certain extent in cases of IT-based technologies expanding towards providing multiple societal functions. Even if a Transitions Studies-based analytical review starts as a “typical” niche-regime-landscape observation, the presence of some of the identified niche advocate behaviour patterns can indicate the existence of an additional selection environment, i.e. the presence of additional regimes in the transition process.

Falling back to the initial research question about the viability of the current pathways typology in a multi-regime context, the author can conclude that while existing concepts and pathway types can be used to analyse and describe multi-regime transitions, a new type of pathway may represent a more efficient option, extending the analytical framework of the pathway-based view towards including multi-regime interaction dynamics and their influence on niche technology development, and the development of regime selection environments and presence of barriers for technology development and diffusion.

[47] Some of the published work on multi-regime dynamics reviews the case of bioenergy in the Netherlands (Raven and Verbong, 2009)

8.6 Limitations of the research and further challenges

While this research study was subject to multiple limitations, this section will be utilized to summarize the most relevant ones, as well as briefly outline their potential impact on the study's findings and the theoretical and practical recommendations derived from it.

One core limitation of this study in terms of its additions to theoretical knowledge is its reliance on a single case study. While it is certainly true that in-depth exploration of long duration, information-rich cases has been often and repeatedly used in Transitions Studies (Geels, 2002, 2006; Geels and Raven, 2006; Raven and Verbong, 2007; Negro et al., 2008; Verbong et al., 2010; Geels and Verhees, 2011; Verhees et al., 2013; Smith et al., 2014), this reliance and potential analyst bias in the choice and delineation of the investigated cases has been subject to repeated criticism (Genus and Coles, 2008; Markard et al., 2015). While relying on a single case study certainly requires the analyst to adopt an inductive approach to knowledge generation, this has been recognised as a valid approach to qualitative data analysis (Thomas, 2006). Furthermore, utilizing the concept of deviant and paradigmatic cases (Flyvbjerg, 2006) allows the author to obtain information on unusual cases, of which CHP is certainly one, as well as to develop metaphors for this particular type of case.

A second limitation of the thesis also relates to the research methods utilized, specifically data collection which was done through expert interviews, case studies primarily relying on interview data and an extensive document analysis, with data triangulation utilized to cross-reference gathered data, and validate findings (Bryman and Bell, 2015; Yin, 2014). While the amount of collected data was limited by the number of case studies, and the number of interviewees with whom "elite" interviews could be implemented, multiple repetitions of expert interviews would have enabled the author to utilize a Delphi analysis, increasing the precision of the information available. Furthermore, the author recognises the limitations in the choice of case studies caused by his geographical location, possibly

Thirdly, conclusions about the ultimate success or failure of the CHP transition process were limited by the circumstance that the observed transition is still ongoing. Therefore, the main part of the discussion undertaken in this thesis could only be done based on the combined findings of a historical review and a state-of-the-moment analysis. While the latter does not represent a significant hindrance for a TIS analysis, and can also be done for the purposes of a SNM-based investigation, a large number of published studies were based on completed transitions (Geels 2002, 2006a, 2006b; Raven and Verbong, 2007, 2009; Verbong et al., 2010) or set time periods (Raven and Geels, 2010; Verhees et al., 2015).

A fourth limitation to the thesis is caused by the author's delineation of the observed constructs, limiting them to the legal and physical borders of the United Kingdom. While a spatial delineation is considered a necessary step in the TIS analytical process (Bergek et al., 2008), it has also been criticized for excluding foreign and global parts of the observed system (Markard et al., 2015). Furthermore, the limitation to the United Kingdom removes the possibility of comparisons of the development and diffusion of CHP to the performance of the technology in other countries, an approach that was taken by Weber (2014). While spatial aspects are not as prominent in the MLP/SNM approach, limiting the extent of the observation will still increase the possibility of missing relevant. Therefore, the author would recommend extending the research towards a comparison of the UK CHP industry with other European countries following the analytical approach taken in this thesis.

Following the summary of research limitations, the author will put forward four main research challenges derived from this thesis. The challenges are either connected to the findings of the thesis, their main purpose being to explore further the ideas put forward by the author, or related to the limitations of the study's research design and applied methods.

The first challenge for further research is to continue the review of transition pathways in multi-regime transitions, exploring the theoretical soundness and practical viability of the proposed "persistence pathway". This can be done through an extended review of the theoretical foundations of transition pathway research, going beyond the limits of this thesis, and through reviewing further cases of multi-regime transitions, exploring the applicability of the proposed concept. The theoretical review should focus on the conceptual distinction between the four identified pathways (Geels et al., 2016) and the newly proposed pathway, in particular the further clarification of the theoretical but also empirical difference between singular pathway shifts observed by Geels et al.

(2016) and the continuous re-adjustment and re-configuration process identified as a central element of the “persistence pathway”. Further, additional research should be done in order to assess the changes in transition dynamics in the presence of a multi-regime environment, drawing, among others, on the work of Raven and Verbong (2007, 2009) and Konrad et al. (2008). Finally, future researchers could investigate the role of the landscape in multi-regime dynamics, adding on existing research and moving towards addressing a recognised criticism of the MLP (Geels, 2011).

The identification and selection of appropriate empirical cases is expected to pose a particular challenge for future researchers due to the specific characteristics of a transition process proposed by the author as a pre-condition for a “persistence pathway”. While CHP can be considered a “typical case” for such a pathway, and has indeed been researched by Raven and Verbong (2007, 2009), further technologies have also been investigated, such as bioenergy (Raven and Verbong, 2009) and multiple low-carbon technologies (Konrad et al., 2008). Further potential technologies interacting with multiple regimes could be found in the transport sector, such as bicycles (transport, leisure/sport) or electric cars (transport, electricity through smart grids).

Closely connected to the first research challenge, the second research challenge is focused on the theoretical and empirical assessment of the proposed extended niche typology, with the aim of solidifying the theoretical grounding, and expanding empirical research through the analysis of additional case studies. A key theoretical challenge would be further review of the niche as an analytical construct in transition studies, further reviewing the niche definition as well as its structure and processes. This would need to further take into account the definition of niches as protective spaces (Smith and Raven, 2012) and consider potential extensions of this definition depending on the development stage of the niche. Therefore, long-term niches respectively niches in long-term transition processes would be particularly interesting observation objects. While virtually any innovative technology could, theoretically, be investigated using the extended typology, the author would recommend future researchers to focus on specific, exemplary cases, especially in the case of later-stage niches. Besides further reviews of CHP, fuel cells, battery-electric cars and biofuels could be interesting objects for enquiry.

The third research challenge concerns the role of actors in transitions, and can follow multiple lines of enquiry. Firstly, scholars working with concepts of power and agency could attempt to investigate further the role of champions in transitions, relating to the author's findings about a lack of powerful actors being a significant structural issue for the CHP industry, hindering the fulfilment of multiple system and niche functions. Secondly, the roles of actors in networks, and the characteristics of the networks could be investigated by drawing on insights from Social Network Analysis (SNA), following previous research by Caniëls and Romijn (2008b). Thirdly, the role of coalitions in shaping expectations and developing narratives and the dynamics of changing coalitions could be reviewed, possibly coupled with an enquiry into actor power and the ability of niche actors to influence policy-making. The latter has been the focus of recent attention within SNM research with multiple published studies (Verhees et al., 2015; Lockwood, 2016; Raven et al., 2016a, 2016b).

The fourth research challenge is related to the methodological and design-related limitations of the thesis. In further research, authors should attempt to develop the format of this thesis towards a more representative longitudinal study, including repeated visits to schemes used as case studies (particularly relevant for schemes still under development) and development of the expert interviews towards a Delphi-type enquiry (Linstone and Turoff, 2002), potentially forming focus groups and extending data collection methods towards IT-based approaches. Another possible methodological extension would concern the inclusion of quantitative data, for example from statistics on power generation or financial industry data (Bryman and Bell, 2015). The inclusion of quantitative data would enable future scholars to model the dynamics of the CHP TIS, improving the understanding of virtuous and vicious cycles (Hekkert et al., 2007) and motors of innovation (Suurs, 2009).

This approach would in particular enable prospective researchers to draw on System Dynamics modelling in order to provide more precise evaluations of an innovation system's performance, drawing on the conceptual connections of virtuous/vicious cycles and innovation motors (Suurs, 2009) to system dynamics processes (Walrave and Raven, 2016). As demonstrated in recent publications, once the internal dynamics of a chosen innovation system are modelled as a system dynamics model, this model can be run and evaluated in order to establish predictions about its future performance and assess the viability of the observed system (ibid.). Provided sufficient data is available, quantitative approaches to system dynamics modelling can also be used for testing the effects of specific actions and/or policies on the development of a technology or set of technologies. This could be tied in with the advice to policymakers, which is already forming part of the output of a TIS-based analysis, potentially by proposing a number of potential policies and actions and then simulating their likely effects on the investigated transition process.

The increased inclusion of quantitative research within Transition Studies is an emerging topic in the broader research community, enabling scholars to extend the mainly qualitative-based analytical approaches towards including specific economic calculations based on numerical data, and quantitative scenario planning methods (Amer et al., 2013) supplementing the already utilized qualitative approaches. An example for a mixed methods approach to the modelling of transitions can be seen in the work of Foxon et al. (2011) and Foxon (2013) on developing and evaluating transition pathways for a UK low-carbon energy future.

Further, utilizing mixed methods approaches would allow researchers to combine the relative strengths of different approaches, both with regard to the scientific validity of results and with regard to the presentation and impact of the results to actors outside of the scientific community. As an example, while a MLP-based analysis of a transition process will provide a holistic overview of the process and capture both quantifiable and non-quantifiable factors influencing the development of the focal innovation, if might fall short on delivering pin-point quantitative “hard” data on the behaviour of particular variables, which is often used by policy-makers and in communicating with the broader public in order to steer the direction of a particular debate. By including “hard”, quantitative data in a transition research project, the researchers can, at will and dependent on the recipient of the results, switch between providing holistic overviews and macro-level pictures and generating specific, meso- and micro-level data showcasing the behaviour of particular elements of the observed analytical construct, such as the price of a particular utility, the projected rate of market diffusion or uptake rate for a technology, or the projected development of a region’s or country’s energy mix. Overall, the broader range of available data would have improved the impact of the transition researcher’s work, building upon one of the main aims of the field (Markard et al., 2012).

8.7 Recommendations to policy-makers and implications of research findings on future energy policies

This section draws on the findings on both parts of the analysis in order to provide a short discussion of current CHP-relevant policy along with a series of recommendations to policy-makers. These recommendations are aimed at tackling the main limiting factor and barriers identified in the analysis, and creating a more favourable environment for further development and diffusion of CHP technologies. TIS literature (Hekkert et al., 2007, 2011; Bergek et al., 2008; Markard et al., 2015) considers recommendations to policy-makers as one of the stages/outputs of a TIS analysis; the recommendations focus on key policy issues (Bergek et al., 2008, p. 423) respectively the identification of obstacles for policy goals (Hekkert et al., 2011, p. 13). This stage was not implemented in Chapter 5 of this thesis, with the author concluding the analysis with a discussion of the main barriers and blocking mechanisms, therefore, a number of key policy issues and recommendations for overcoming them will be discussed in the following paragraphs. Going beyond the findings of the TIS analysis, the discussion will also draw on insights generated in the niche and niche-regime analysis, and the findings of the entire integrated framework.

8.7.1 Lack of holistic policies affecting both heat and power

One of the key policy issues related to the somewhat stunted development of CHP in the UK is tied to the only partially integrated nature of the electricity and heating regime within the broader UK energy system. Therefore, policies and institutional arrangements are implemented within one of the regimes, with potential unintended negative consequences for the other regime, which have been identified as a negative factor influencing CHP. Further on, the lack of holistic policies forces developers to implement CHP schemes primarily led by one of the outputs, somewhat negating the technological efficiency advantage provided by co-generation, and putting CHP technologies at a disadvantage when compared to technologies which may be more efficient in single-output mode. Finally, the lack of holistic policies is closely tied with the lack of holistic visions for the UK energy future: despite general commitments for a future low-carbon energy system (DECC, 2009c, 2011a), there seems to be relatively little consensus about desirable development trajectories and potential future configurations of such a system. Overall, the recommendation to policymakers with regard to this barrier would be to a) develop and deploy holistic policies on energy efficiency and sustainable energy generation affecting the entire energy system, while taking into account potential unintended side-effects of policy change on individual technologies and generation methods and b) put forward more specific visions and expectations for the future UK energy system, opening spaces which can be exploited and filled in by CHP developers, with a secondary positive side-effect of increasing the public visibility of and awareness about combined heat and power technologies.

8.7.2 Lack of statutory powers for heat network developers

The second key policy issue discussed in this section is the lack of statutory powers for heat network developers, which creates significant issues for developers and operators of CHP-DH networks and large-scale brownfield CHP schemes. Due to a distinct lack of heat infrastructure (piping) in the UK compared to other European countries, implementation of larger-scale schemes necessitates the deployment of extensive infrastructure. Without statutory powers providing an institutional framework backing the development of the necessary infrastructure, CHP-DH schemes are often frustrated by the necessity of negotiating step-by-step with multiple landowners, which increases costs, time delays and organisational requirements. The recommendation to policymakers with regard to this issue is to review the statutory powers granted to other utilities developers with the aim of equating heat developers with telecommunications and electricity developers.

8.7.3 Lack of long-term policies and abrupt policy change

A third issue, connected with the lack of holistic policies and broad visions for the UK energy future is the relatively short duration of policies i.e. a relative lack of long-term policies and plans aimed at supporting specific technologies, consumer behaviour patterns and/or desirable future configurations of the energy system. In addition to this, policy changes tend to be abrupt, causing major disruption and overall increasing uncertainty among CHP developers. This is especially the case with indirect negative effects of policy changes, which can take the CHP industry by surprise, as CHP actors are not always included in consultation and planning processes. As a follow-on effect, the confidence of potential investors is decreased, leading then to adopt more cautious approaches to large-scale projects or even abandon these projects altogether (this happened following the abrupt reduction in economic viability of large-scale industrial CHP plants after the introduction of the NETA). Policy short-termism and abrupt change can also affect small-scale developers, down to the individual household level – an example for this can be seen in the abruptly decreased viability of domestic micro-CHP following the reduction of the FiT done by the Conservative government voted in in 2010 (Geels, 2014). The solution for this issue can hardly be found in the implementation of specific policies, but rather as an overall orientation towards longer-term policy aims (in line with the holistic policy issue discussed earlier in this chapter) as well as improved review and consultation procedures for energy policy changes, with the aim of checking for and including co-generation if there is an expectation that CHP will be affected by the policy change.

8.7.4 Trading heat as an utility

A fourth identified policy issue is related to the current state of the heat market, more specifically the trading of (usable) heat as an utility compared to electricity and gas, for which there are existing markets. The lack of a more specific heating regime has a number of direct negative effects – lack of regulation, lack of customer information, and missing knowledge regarding applicable business models and contracts for the provision of heat. Here, the proposed solution includes the at least partial implementation of a heating regime, including necessary trading regulations analogous to the BETTA respectively the Unified Network Code (UNC).

8.7.5 Simplification of access for small generators to capacity market

The final identified policy issue is related to the current high entry barriers for small electricity generators attempting to join the capacity market, manifested in the form of licensing agreements, the current prediction-based planning of the capacity market, and potentially prohibitive costs for small energy producers. While those barriers are recognised throughout the industry and localised attempts at solving these issues have been put into place (for example, the licence light), a broader roll-out of supportive measures may be necessary in the future in order to create a more supportive environment for small-scale electricity producers. One possibility for this would be the possibility for small generations to act as collectives and interact with the capacity market as a larger “virtual plant”, following the Danish model discussed in a study by Toke and Fragaki (2008).

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10 Appendix 1: Selected case study summaries

In this appendix the author will provide detailed summaries for three selected case studies reviewed during the fieldwork phase of the research project. Drawing on findings from Chapters 5 and 6, as well as the discussion on socio-technical factors and barriers in Chapter 7.1., the focus will be on describing the institutional context of the cases, the main barriers faced by the actors implementing the CHP schemes central to the studies, and their actions supporting the uptake of CHP in response to these barriers. In order to provide a varied, broad overview of the different application areas for CHP, the author will select one case study each from three of the four application niches identified in Chapter 6: CHP-DH, public single site CHP and private single site CHP[48]. The case studies presented in further detail are:

1. A CHP-DH network in South-East London, representing **CHP-DH**
2. CHP scheme in a public leisure centre in South London, representing **public single site CHP**
3. CHP scheme in a plant nursery in Kent, representing **private single site CHP**

Each case study will be presented over several pages in the form of a sub-chapter, commencing with a short outline of the scheme in question, and then focusing on the institutional context and socio-technical factors and barriers influencing the scheme. While describing the context, factors and barriers, the author will discuss decisions and actions taken by relevant actors, relating them to concepts from Transitions Studies where possible.

[48] The author identified a fourth application niche, domestic microgeneration CHP, however no case studies from this niche were reviewed during the fieldwork phase due to a combination of practical issues and the presence of an up-to-date body of academic and non-academic literature reviewing microgeneration CHP

10.1 CHP-DH: A district heating network in South-East London

This case study is used to review and illustrate a medium-to-large scale district heating network in South-East London, managed by a large utility company in cooperation with a number of local authorities (councils). Data for the study was gathered through two in-depth interviews with key actors on the scheme (Contract Manager-District Heating working on-site for the utility company, and an Energy and Carbon Reduction Manager representing one of the councils), a site visit and analysis of existing documents describing the scheme. The scheme has been developed as part of a waste incineration facility, and consists of two heat exchangers with a combined capacity of 30 MW, although the current peak requirement of the connected DH network does not exceed 9-10 MW. There is the possibility to install additional heat exchangers with a capacity of 10 MW on-site, but this is not considered at present due to below-limit heat demand. The heat generated on-site is fed into an existing district heating network in a South-East London borough, while the generated electricity is exported into the National Grid, with around 2 MW of electricity being used on-site.

The scheme was implemented following a long development process of approximately 20 years (initial construction of the incineration facility was done in 1994, while the district heating scheme became operational in late 2014/early 2015), initially starting with a round of conversations between the utility company and multiple local authorities (councils) with the goal of developing a waste incineration facility capable of generating usable heat. However, the first round of planning run to a standstill after some of the councils opted out of the planned scheme, preferring differing options for waste treatment. The utility company was partnered with the councils in developing these different options (mechanical-biological treatment (MBT) instead of thermal treatment/waste incineration), but the actors discovered that carbon savings mandated by existing policies could not be achieved by mechanical-biological treatment, necessitating them to fall back on the initial plans for a waste incinerator-based DH system. The by then built incineration facility was subsequently equipped with heat exchangers and connected to four existing smaller-scale district heating networks providing usable heat to around 2500 council properties, which were previously equipped with smaller gas boilers. While developing the required infrastructure, the main actors outsourced parts of the development process to a specialized engineering company, and drew on other specialized firms in order to source the required equipment.

In the course of planning and building up the heat infrastructure, significant resistance was encountered when planning the pipe route – lacking the statutory powers held by other utility developers, such as for example gas, water of electricity, the pipe routing had to be negotiated individually with third parties such as Network Rail. Despite the support of the council, this took a fair amount of time, and resulted in increased costs for the project developers. Following is a quote by the utility company contract manager illustrating some of the problems encountered, and summarizing the perception of the current policy framework by the Contract Manager working for the utility company:

"And so I think it's, I think it would be… and also, the other thing as well, is that, um, so if you're putting in a gas main, a water pipe or electricity, um, they have, they're statutory providers whereas district heating isn't at the moment. So again, it's just another thing where it's not quite a level playing field and even with council support it's not quite as easy as putting in other services. We're sort of a lower priority." (Contract Manager – District Heating, utility company)

On the contractual side, the scheme was set up as a 20-year contract between the utility company and the council, with the utility company making the initial investment for both the on-site equipment (heat exchanger, supporting machinery) and the pipe network. This capital investment is then recovered over time from the council, who are paying a fixed charge for the heat service for the duration of the contract. It is worth noting that this contract is heat-only, i.e. the utility company does not provide the council with electrical power, which is fed into the network subject to a purchasing agreement with another large utility company, renewed on a yearly basis. While the utility company would prefer a private wire system to this agreement, there are no potential customers large enough to be able to use a significant portion of the scheme's electricity production.

The current operation of the scheme is considered to be a success by both the utility company and the council, with the council able to achieve significant carbon savings (around 8000 tons annually). The utility company is actively considering expanding the scheme to the other two interested councils and to private developers. However, negotiations with private developers have to be done on a case-by-case basis, somewhat slowing the process, while negotiation and planning processes with the other two councils that were initially participating in the scheme are subject to similar barriers (lack of statutory powers, logistical challenges) to the ones encountered while planning and implementing the initial heat network.

This case acts as a good example for the development of a district heating network in an urban environment, highlighting a number of common barriers to development and both positive and negative factors influencing the scheme. The scheme was developed through a type of partnership common for the public sector – one or more public authorities cooperating with a company specialized in CHP, employing additional specialized actors for specific parts of the project. A relatively unusual factor was the long development time of the scheme, with the initial proposal for a waste incineration facility with CHP capabilities abandoned and subsequently taken up again due to the need to fulfil policy requirements. This also highlights the enabling role of existing carbon reduction and energy efficiency policies for developing CHP-DH and general CHP schemes, although it needs to be pointed out that these policies do not support the technology itself but rather set carbon reduction and efficiency aims that need to be fulfilled by public actors and other project developers[49]. Cogeneration technologies are therefore competing in an open market, and are selected based on technology performance and cost efficiency.

Regarding the effect of policies, this case quite clearly illustrates the negative effect of lacking statutory powers for heat developers, in itself a consequence of a missing/weak heat regime, discussed in earlier chapters of this thesis. While developing this scheme, the lack of statutory powers forced the utility company to undergo multiple re-planning steps in order to accommodate existing developments, in particular multiple rail lines operated by Network Rail. Further, other potential hurdles and increased costs had also to be taken into account – for example the presence of tree roots under a local park area, local bus lines and recently resurfaced

[49] While carbon reduction an efficiency policies can be considered an enabling factor in this and similar cases, it is worth pointing out that further policy development towards the goal of a low- or zero-carbon energy system can also be a risk for conventional fossil fuel CHP, as in the future conventional prime movers might be unable to fulfil strict emission requirements for urban areas

roads. While none of these issues proved to be unsurmountable, they added considerable complexity and costs to the project, and are also influencing planned future extensions of the scheme.

The utilized business model represents a rather standard agreement, while it is worth noting that the contract between the utility company and the developer includes only one type of output (usable heat), while the generated electricity is exported to the national grid. The latter connection requires a second contract between the utility company and another utility company who acts as an intermediary. This contract is perceived as a sub-optimal solution by the utility company, but the lack of sufficiently large local energy users prevents the development of a private wire scheme. Further, there seems to be an amount of dissatisfaction with the market position of the utility company, who consider themselves to be at a disadvantage compared to large scale utility companies (especially the so-called “Big Six”) both in energy pricing and project development costs.

The scheme was initially financed by the utility company, who made the capital investment necessary for the on-site technical equipment and the pipework, which will be recovered over time through a long-term contract with the council. Similar to the third case study discussed in this section (the private single site CHP scheme in a plant nursery) a long-term contract is utilized, highlighting the necessity for mid-to-long term planning and commitments due to the significant initial costs of developing a larger-size CHP scheme. Neither the utility company nor the involved councils used CHP-specific funding in order to finance and/or maintain this project, although this was mainly due to the specific circumstances of the project, being developed out of a waste-focused private finance initiative (PFI). However, the council actively considers utilizing available support for future extensions of the scheme with a broader heat master plan, but has not yet identified the appropriate funding and support programmes. This highlights the need for improved information for public sector actors – while CHP advocates such as the national umbrella organisation (ADE) are perceived as supportive and helpful, improved access to information would likely simplify and accelerate the development of future public CHP-DH schemes.

10.2 Public single site CHP: A public leisure centre in South London

In this case study, the author investigates the case of a newly developed public leisure centre in South London, owned by a local authority (a London council) and operated by a private, specialized company. The study was conducted in the form of a site visit and two in-depth interviews with the Leisure Contract Officer working for the local authority, and a Regional Technical Manager working for the leisure management company. The scheme is limited to the leisure centre itself, and uses a 150 kW engine provided by a specialized CHP company that generates heat and electricity for the leisure centre. While all heat is used on-site, manly to heat the pools inside the leisure centre, excess electricity is effectively "dumped" as there is no feed-in connection with the grid – this was considered uneconomical. There is also a provision for heat dumping; however there was no necessity to do so as of the time of the interviews.

The scheme, as well as the leisure centre itself, was developed as part of a £20 million regeneration project aiming to regenerate the entire area, funded by the regeneration fund. Due to the latter, the developers did not need to draw on existing public support, although there is awareness about the existence of different support schemes, and willingness by both the council and the management company to draw upon them for future projects or extensions of existing schemes. The use of cogeneration technologies was not specifically requested during the development, rather there was a general desire to make the leisure centre as energy-efficient as possible, aiming for a "very good" BREEAM rating. Detailed planning was left to a contractor, who proposed CHP as a potential solution. This was taken up by the council for a number of reasons, the main ones being a quick return on investment period, and a "natural" match between the performance profile of CHP engines and the energy demands of a leisure centre[50]. Subsequently, the engine was procured and installed by the building contractor, meeting only limited resistance, mainly due to potential noise pollution caused by the placement of the prime mover. However, once the engine was installed, development of the scheme was paused – no communications link for remote control

[50] This was further confirmed in one of the expert interviews, where leisure centres were identified as traditional customers and stable markets for CHP developers

and monitoring of the engine was set up[51], and no operations and maintenance (O&M) contract was set in place.

At this point, management of the leisure centre was taken over by the management company, who had to complete the implementation of the CHP scheme by developing the communications link and setting up the O&M contract. Overall, the management company took over interaction with the O&M provide on behalf of the council. A contract was set up, although the management company has since expressed its dissatisfaction with the terms of the contract and the performance of the O&M provider. The main issues were identified as the reactivity of the operator, particularly in cases of prime mover downtime, prime mover underperformance (actual generated power lower than power rating) and the lack of penalties for the O&M provides for instances in whom the CHP engine is inoperable. However, CHP as a whole is still seen in a relatively positive light, mainly due to the good match between the energy output and the energy demands of the leisure centre. With regard to the contracting issues mentioned above, the management company would prefer a different type of contract, in which the user supplies the gas fuel to the operator and is in exchange provided with heat, while purchasing electricity at a lower set rate. Further, in this model the engine (prime mover) remains the property of the operator, who is also responsible for O&M.

Due to the continuous heat demand, the prime mover is operated in continuous operation mode, operating at full power for approximately 18 hours daily, followed by around 6 hours of reduced operation, reflecting the working hours and effective demand of the leisure centre. Operation is interrupted only for regular servicing and in the case of failures. As this particular scheme was developed only recently, neither of the interview partners was able or willing to make a definite judgement on its success before a minimum observation and data recording period is completed. The management company, despite mixed experiences with this and a number of other schemes, still considers CHP to be a viable option, provided a number of basic, site-specific demands can be met:

[51] Due to the relatively small size and wide geographical spread of CHP engines in leisure centres and similar applications, remotely controlled systems are the industry standard

1) Appropriate size of the CHP unit
2) Functional and economical operations and maintenance contract
3) Location enabling fuelling and maintenance access

However, future CHP units would likely be downsized due to a broad-range energy efficiency programme, except in cases where the sale of excess electricity back to the grid would be considered viable. Further, new technologies such as more efficient turbines or modular systems have also opened the market, with some of these competing technologies representing viable alternatives for CHP. Regarding the council, CHP is also considered a viable technology for the leisure sector, again provided certain conditions are met, although there is also a number of issues such as management of excess heat. The scheme is being monitored by the council, with decisions on further development likely to be taken after the evaluation of the gathered data.

This case represents a good example for the development and use of a small-scale CHP scheme in the public sector, in this case, a leisure centre. The scheme has been commissioned by a public actor (the council), although it is interesting to note that CHP was not initially specified as a technology of choice, but rather chosen due to the technology's outputs and performance. Further, development, implementation and management of the scheme were split between three different actors: the initial building contractor, the management company currently running the leisure centre, and the specialized CHP company that initially provided the prime mover unit, and currently holds the O&M contract for the site. This increased number of actors led to multiple communication and coordination issues, especially regarding the transfer of the scheme from the building and development phase to full operational capacity.

As the management company has reported encountering similar situations in multiple instances, this might represent a broader issue in this application niche, which would need to be investigated by further research. Some of the communication issues were subsequently extended into the present, with the management company expressing dissatisfaction with the quality of communication with the prime mover operator, as well as the current terms of the O&M contract. At this point, it needs to be noted that the prime mover operator was dominating the market at the time of scheme development, providing them with knowledge and negotiating advantages. Therefore, knowledge imbalance within the CHP sector might have played a somewhat negative role in the development and operation of this scheme. Further, the lack of satisfaction with available business models indicates a potential necessity for the development of more flexible models (in terms of financial responsibility, but also exchange of information and scheme ownership), which might increase the attractiveness of CHP for future developers.

Similar to the third case study, there was little use of existing subventions for scheme development, although this was mainly caused due to the type of funding (regeneration funds) used for the broader project, of which the leisure centre was only a part. Government policies towards CHP are perceived as being mainly neutral, although a degree of uncertainty exists regarding future policy changes, particularly carbon charges and policies affecting the self-generation of electricity. However, building policies and standards, in particular BREEAM, played an important role in the development of the scheme, with the council's desire to obtain a "very good" BREEAM rating shaping the initial set of specifications for the scheme.

With the scheme outputs used exclusively on-site, there were no issues regarding connections to the electricity grid and/or generation licences. The actors involved in the scheme considered the benefits of exporting electricity and heat, but considered it a question of economic viability (depending on prime mover size and output) for electricity respectively access to local heat users for heat. Overall, the actors preferred to use the outputs of the CHP unit on-site, reflecting the approach taken by other smaller-scale industrial and public users. It is somewhat questionable whether existing barriers in accessing the capacity networks influenced that decision, although a simplified approach for small producers may still have a positive effect on the decision of small scheme operators to export excess capacities.

In summary, the observed case highlighted a number of common issues with small public sector CHP schemes, mainly related to the availability of information, the structure of current business models and technology performance in a cost-sensitive environment. Compared to other public schemes, access to funds was not identified as an issue, although this is likely related to the non-standard funding source used to develop this scheme, which might not be available to the majority of prospective scheme developers.

10.3 Private single site CHP: A plant nursery in Kent

This case study reviews a CHP plant providing heating and CO2 to a plant nursery in Kent; the study itself was conducted in the form of a site visit, an in-depth interview with the site manager and subsequent e-mail and phone communication. The scheme consists of 2 CHP engines (Rolls-Royce gas turbines) providing 7.5 MW of electrical output each, and was developed as the first scheme of this particular type by the developer, an energy consultancy company specialized on CHP.

Regarding the background of this particular case, one interesting fact is that the scheme was not specified as a CHP scheme by the nursery operator; the original project specification merely required an improvement of the then-existing gas boilers that had relatively low efficiency (~70%) as well as high operating costs. Based on that specification, the consultancy company opted for a CHP engine as a potential future solution, after reviewing multiple different options on a 25-year planning schedule. The sizing of the engine was the object of some discussion, although it was ultimately subject to the strategic plans of the nursery, who have include potential extension of the site into their mid- to long-term planning. Taking into account the uncertainty regarding the long-term availability of public subventions and/or other support for CHP, the consultancy together with the nursery operator decided to develop the scheme and plan its operation in a way that made it independent from subsidies such as the ROC, the RHI or feed-in-tariffs, the leading thought behind the design phase being the following:

"What I mean by this is, you don't want… we as a business don't want to rely on subsidy. (…) But, your business model must work assuming this extra income from the government is 0." (Scheme Manager, specialist CHP consultancy)

In the course of scheme planning, further obstacles were encountered in the form of limited capacity of the local distribution network. While the consultancy company was able to obtain the necessary permission to connect to the electricity network, the connection did trigger a reinforcement of the network which increased the overall implementation costs. Further resistance to scheme development was encountered in the course of the planning procedure, with local planning officers taking a negative stance towards the scheme due to the use of a flue stack. In contrast, connection to the gas grid in order to establish a fuel supply was easy as a gas connection was already in place on-site, remaining from the previous boiler scheme.

The final part of scheme planning included the development of a suitable business model for scheme operation which would secure the (financial) viability of the scheme over the above-mentioned 25 year period while at the same time minimizing costs to both the scheme operator (the consultancy) and the customer (the nursery). Based on these requirements, as well as the operational requirements of the site, the consultancy decided to run the CHP scheme as a peaking plant while at the same time using heat storage in order to ensure a continuous supply of usable heat independent of the actual operating hours of the engines. This approach enabled the operator to produce and sell energy to the electrical grid at peak prices, with engine operating hours set on a weekly basis based on short-term electricity price forecasts. The mode of operation, also called a “peaking engine” mode, also reduces the number of working hours for the engine compared to a permanently running plant, creating cost savings due to longer servicing periods and decreased engine wear and tear. The business model itself has the form of a 20-year Energy Service Agreement between the nursery (the customer) and the consultancy, with the nursery owning the plant and the ground, which is then leased to the consultancy who directly own the grid and gas connections.

While developing the project the consultancy was in constant contact with the customer, who used connections in their industry (plant nurseries) in order to gather information about CHP use in the sector. This was seen as important by the consultancy as it allowed access to actual usage data, which was then used to inform the development of the business model. Further contact was made with the umbrella organisation for CHP, the Association for Decentralised Energy (ADE, CHPA at the time of project development), who were able to provide information on available subsidies, applicable policies and CHP market development. Project-relevant information was also gathered from engineering companies, who were important partners during the selection of the prime movers.

Overall, the observed case study represents an interesting example of a self-contained, long-term CHP scheme run in a partnership between a consultancy that served as project developer and has subsequently taken the role of on-site management, and a primary sector company. Two specific characteristics of the scheme can be highlighted: the conscious decision to develop the scheme independently of public subsidies and available support, and business model planning coupled with technological solutions (in the form of heat storage) with the aim of maximizing profits and reducing operational costs. The former indicates a lack of trust in public sector support, in particular in the long-term availability of support mechanisms, reflecting the issues related to abrupt policy changes and the lack of long-term policies and visions identified in the earlier stages of this analysis. Therefore, while the scheme still had to be viable within the existing institutional framework, steps were taken to ensure a high level of independence.

The relationship between the nursery owner and the consultancy reflects the role of intermediary actors within the CHP industry, discussed in Chapter 5.2.1., with intermediaries offering multiple solutions across the CHP value chain. In this case, the consultancy took over planning and scheme implementation, providing a turnkey solution for the customer, and then switched into the role of scheme operator/O&M provider, minimizing the necessary interaction between the customer and the energy sector, and allowing the customer to concentrate on their primary business activities. However, the information flow was not completely one-sided, as the nursery was able to draw upon sector-specific knowledge regarding both scheme performance requirements, and experience gained by other nursery operators. Further, following the completion and initial successful operation of the scheme, the consultancy was able to use the applied knowledge in developing two further CHP schemes in nurseries, one in the North-West and the other in the South of England. Therefore, the knowledge flow and learning processes taking place between the two main actors in this scheme can be described as bi-directional: while the nursery was relying on the consultancy to plan, develop and operate their new CHP scheme, the consultancy was utilizing the nursery's sector-specific knowledge, as well as knowledge gained throughout the development of this particular project in order to develop further similar schemes.

One final reflection on this case study is related to the resistance encountered while developing and implementing the scheme: resistance not specifically related to CHP in the form of planning permissions (local planning officers raising issues concerning a building with a built-in flue stack), and energy-specific issues in the form of increased costs due to triggering a network capacity reinforcement. The latter reflects a more general barrier encountered by CHP developers – while in this case it was possible to obtain an electricity network connection following the reinforcement, there is a real risk of developers not obtaining necessary permissions and licences from the local distribution network operator (DNOs). According to the consultancy, obtaining the necessary permissions is tied to a quite particular paradox – while in certain areas of the UK a network connection can be set up without too many problems, these areas often have a low heat demand. Conversely, areas with existing high heat demand, which is important for economic operation of CHP schemes, tend to have well-used transmission networks, making obtaining a grid connection more complicated or even completely unlikely.

In summary, the observed case study represented a relatively rare type of application for a CHP scheme, especially with regard to the utilization of a third type of output in the form of CO2, which can be used by the plants in the nursery. Further interesting aspects of the scheme are a deliberate exclusion of public sector support, which is seen as “nice to have” but was not included in the development of the business model. Finally, the scheme also includes an interesting technological solution in the form of a heat storage tank, which allows the scheme operator (the consultancy) to both provide constant heat to the customer, and run the scheme’s prime movers in an optimized mode of operation (peaking plant guided by electricity market prices respectively the spark spread).

11 Appendix 2: Detailed information on interviews conducted during fieldwork phase

In the table below, the author provides detailed information on the interviews conducted during the fieldwork phase of the research project. This includes information on the purpose of the interview (expert interview or case study), the interviewee (information limited by individual interviewee's permission to share data), the location of the interview, the duration of the interview and the type of data collection (e-mails, written/typed notes, audio recording). The interviews are listed by the original date at which the interview took place.

#	Date of interview	Purpose	Interviewee	Duration of interview	Data collection type
1	15.04.2015	Pilot case study on CHP engine installed on university campus	Policy officer in CHP research project	00:26:54	Written notes Audio recording
2	17.04.2015	Pilot case study on CHP engine installed on university campus	Senior project associate in CHP research project	00:24:04	Written notes Audio recording
3	06.01.2016	Pilot expert interview (Interview 1)	Director of policy at umbrella organization	Approx. 1:30	Written notes
4	07.01.2016	Pilot expert interview (Interview 2)	Former Director of policy at Big 6 energy company	1:00	Written notes
5	20.01.2016	Case study in plant nursery (Case Study 8)	Manager working for energy consultancy operating the site	3:30 total site visit 00:37:45 interview	Written notes Photographs Audio recording

6	22.06.2016	Case study in 2 NHS Trust hospitals (Case study 5)	Former project manager for both sites	n/a	E-mail interview
7	30.06.2016	Expert interview (Interview 3)	Research Fellow at UK University	0:55	Written notes
8	07.07.2016	Expert interview (Interview 4)	Senior Manager at public authority	01:16:46	Written notes Audio recording
9	08.07.2016	Expert interview (Interview 5)	Senior Manager and Manager in public corporation (2 interviewees)	00:40:36	Written notes Audio recording
10	11.07.2016	Case study in private CHP-DH development (Case Study 2)	Project director at housing development company	00:37:00	Written notes Audio recording
11	22.07.2016	Expert interview (Interview 7)	Professor at UK University	00:46:05	Written notes Audio recording
12	26.07.2016	Case study in private CHP-DH development (Case Study 2)	Engineering manager at utilities company	1:30 total site visit 0:30 interview	Written notes Photographs
13	18.08.2016	Expert interview (Interview 8)	Energy Project Manager at local authority	00:29:56	Written notes Audio recording
14	10.10.2016	Case study on CHP-DH scheme in N London (Case Study 4)	Business Development Director at LA-organized ESCo, Head of Sustainability at local authority	00:22:44	Written notes Audio recording
15	10.10.2016	Case study on CHP-DH scheme in SE London (Case Study 3)	Contract Manager – DH at CHP plant working for large utility company	1:30 total site visit 00:36:24 interview	Written notes Audio recording
16	12.10.2016	Expert interview (Interview 6)	Project manager working for	n/a	E-mail interview

			specialized energy consultancy		
17	04.11.2016	Expert interview (Interview 9)	Sales manager working in CHP division of large utility company	2:30 total site visit 01:02:15 interview	Written notes Photographs Audio recording
18	30.11.2016	Case study on CHP schemes in two office buildings	Head of Building and Technical Services at major private company	00:20:00	Written notes
19	01.12.2016	Case study on CHP-DH scheme in SE London (Case Study 3)	Energy and carbon reduction manager at local authority	00:36:31	Written notes Audio recording
20	04.01.2017	Case study on CHP in public leisure centre (Case Study 6)	Leisure Contract Officer at local authority	00:40:00	Written notes
21	09.01.2017	Case study on CHP in public leisure centre (Case Study 6)	Regional Technical Manager at public-private corporation	00:59:19	Written notes Audio recording
22	24.01.2017	Expert interview (Interview 10)	Policy Officer at umbrella organization	00:54:49	Written notes Audio recording
23	06.02.2017	Case study on CHP schemes in two office buildings	Two managers representing the engineering subcontractor running the scheme	00:37:06	Written notes Audio recording

Table 20: Detailed information on interviews conducted in fieldwork phase

All audio recordings done in the interviews were transcribed by the author; while the transcripts are not attached to this thesis for practical reasons, anonymised versions of the transcripts are available upon request.