Title: Assessment of full life-cycle air emissions of alternative shipping fuels

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Abstract:

There is a need for alternative fuels in the shipping sector for two main motivations: to deliver a reduction in local pollutants and comply with existing regulation; and to mitigate climate change and cut greenhouse gas emissions. However, any alternative fuel must meet a range of criteria to become a viable option. Key among them is the requirement that it can deliver emissions reductions over its full life-cycle. For a set of fuels, comprising both conventional and alternative fuels, together with associated production pathways, this paper presents a life-cycle assessment with respect to six emissions species: local pollutants sulphur oxides, nitrogen oxides, and particulate matter; and greenhouse gases carbon dioxide, methane, and nitrous oxide. While the analysis demonstrates that no widely available fuel exists currently to deliver on both motivations, some alternative fuel options have the potential, if key barriers can be overcome. Hydrogen or other synthetic fuels rely on decarbonisation of both energy input to production and other feedstock materials to deliver reductions in greenhouse gas emissions. Similarly, bio-derived fuels can be an abatement option, but only if it can be ensured that land-use change whilst growing biomass does not impact wider potential savings and the sector is able to compete sufficiently for their use. These examples show that crucial barriers are located upstream in the respective fuel life-cycle and that the way to overcome them may reside beyond the scope of the shipping sector alone.

1. Introduction

Climate change is an inherently global issue. The Paris Agreement recognises it as an urgent threat and sets the mitigation goal of limiting the global temperature increase to well below 2˚C and ideally below 1.5˚C. While greenhouse gas emissions have continued to rise (Le Quéré et al., 2016), rapid, deep cuts are required to achieve this goal (Anderson and Bows, 2011, Allen et al., 2009). A sector where such debate has gathered momentum in recent years is the shipping sector (Gilbert and Bows, 2012). In 1997, the Kyoto Protocol devolved action to limit greenhouse gas emissions from international shipping upon the International Maritime Organization (IMO). In 2011, the IMO implemented modifications to MARPOL ANNEX VI, the air pollution element of its environmental convention, by adopting the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) (Bazari and Longva, 2011, Lloyd's Register, 2011). However, these measures fail to address fully the emissions arising from the absolute growth in shipping trade (Smith et al., 2014, Bazari and Longva, 2011), which requires in addition, a step-change to the sector's activities (Anderson and Bows, 2012), including the need for regulation at appropriate scale (Rahim et al., 2016). As international shipping (together with international aviation) has been excluded from the Paris Agreement, the IMO developed a roadmap for the reduction of greenhouse gas emissions, with the aim of defining the sector's strategy and its role in supporting the Paris Agreement. Consequently, it seeks to assess opportunities for greenhouse gas reductions, explicitly including alternative fuels (MEPC, 2016).

1.1 Rationale for, and definition of alternative fuels

The rationale for alternative fuels in the shipping sector is twofold. Firstly, in the short-term the sector is required to reduce fuel sulphur content to 0.1% in Emission Control Areas since 2015 and to 0.5% globally from 2020. In addition, MARPOL Annex VI includes regulation on NO_x emissions and there is also a need to address particulate matter (PM) emissions at a localised level. Secondly, as detailed above, there is the longer-term need to reduce greenhouse gas emissions. This defines important criteria for an ideal choice of fuel and raises the question of alternatives to conventional fuels currently used, namely heavy fuel oil and marine diesel oil (HFO and MDO). Here, alternative fuels (or non-conventional fuels) are defined as any other fuel that can be used for powering ships. The alternative fuels assessed in this study are: liquefied natural gas (LNG), methanol, liquid hydrogen (LH_2), biodiesel, straight vegetable oil (SVO) and bio-LNG. These fuel choices are motivated and detailed in Table 1 and Section 2.3.

1.2 Challenges for alternative fuels

There is uncertainty in the environmental and technical performance of alternative fuels, if and how they can be deployed widely across the sector, and the subsequent impact this would have as a whole (Rehmatulla and Smith, 2015, Gilbert et al., 2015). Assessing the potential of an alternative fuel to become a viable option, in terms of wide-scale uptake and delivering sector wide emission reductions, requires an underpinning analysis that cuts across technological, environmental, economic and social domains. There will be trade-offs and, given the long lifetime of ships and maritime infrastructure, a fuel strategy that is optimally suited to existing regulation may not be optimally suited to the longer-term prospect of greenhouse gas emissions regulation. Considering the environmental life-cycle impacts of these fuels in isolation is thus an essential step to ensure that any alternative fuel is able to deliver meaningful emissions savings for the sector as a whole. Fuels may incur the release of emissions at various stages of their life-cycle, for example during refining or

transportation, or during the cultivation of the fuel if it is bio-derived. The latter may have impacts associated with cultivation, land-use change, and agricultural inputs such as fertilisers. Although the upstream emissions are not attributed to the shipping sector, it is essential to ensure wider implications of fuel switches are accounted for. Failure to take upstream emissions into account in any sectoral assessment risks embedding, or locking in, carbon intensive solutions.

1.3 Research goal and questions

An attributional life-cycle assessment approach (aLCA) is used to assess the emissions of upstream processes and ship operation. Including upstream emissions provides a more comprehensive account of the scale of sectoral emissions and helps avoid misapprehensions arising from examining operational emissions in isolation. Here, operational emissions are assumed to be the emissions to air relating to the combustion of the fuel in the main engine only. An aLCA provides inventory data and associated impacts of the processes used to grow and/or manufacture, distribute, use and dispose of an alternative fuel (Brander et al., 2009, McManus and Taylor, 2015).

The emissions quantified in this study are three greenhouse gases (CO_2, CH_4, and N_2O) and three local pollutants (SO_x, NO_x, and PM[1]). The analysis provides the level of upstream and operational emissions released per unit of power delivered by the engine. The research aims to be both timely and novel and looks to achieve this by fulfilling the following objectives. Aiming to account for the uncertainties associated with selecting one specific pathway for each fuel at a given moment in time, a sensitivity analysis with respect to the main parameters of fuel production and operation is given. An accompanying temporal analysis assesses how emission factors may change due to changes in the fuel cycle over time, specifically improvements in grid carbon intensity and process energy efficiency.

Section 2 presents the scope and boundary of the study, as well as the system definition of the fuels, the approach for the sensitivity, and temporal analysis and an overview of the inventory data; Section 3 presents the results; Section 4 provides a discussion; and Section 5 concludes.

2. Scope and boundary

2.1 Existing studies

Assessments of life-cycle emissions can be divided into studies that adopt an attributional (i.e. per specified *unit* of fuel or service) or a consequential (i.e. per activity at a sectoral or regional level) approach. Furthermore, several studies assess the impact of fuels on the performance and emissions of marine engines, including biodiesel blends (Petzold et al., 2011, Roskilly et al., 2008).

Attributional LCA literature on marine fuel initially focused on conventional marine fuels such as HFO, MDO, marine gas oil (MGO), and in addition on LNG, as well as biodiesel blends. For example, Corbett and Winebrake (2008) and Winebrake et al. (2007) show that for conventional fuels, greenhouse gas emissions do not vary significantly, whereby fuel switching is more impactful for local pollutants. The potential for alternative fuels (including H_2 and bio-derived fuels) to achieve

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[1] For particulates, emission data is expressed in total particulate matter (TPM) with an upper size limit of 100μm in aerodynamic equivalent diameter.

emission reductions has been assessed (Moirangthem, 2016), collating direct and upstream life-cycle results in terms of fuel energy content. Here, the emissions associated with renewable and bio-derived fuels (including renewable hydrogen) exhibit variability depending on the assumptions made, as they exclude direct carbon emissions while reflecting diverse fuel-cycle pathways. However, within these studies the results are not expressed in terms of transport work nor is there an attempt to quantify actual sectoral level environmental impacts.

Other recent studies have adopted a consequential LCA approach, seeking to assess the sectoral impact of fuel switching on emissions, within a defined annual provision of shipping services (Bengtsson et al., 2011b, Bengtsson et al., 2012, Brynolf et al., 2014). Whilst these studies are region specific, they seek to represent a sectoral transition from MDO to LNG and methanol. Here, significant greenhouse gas reductions are only achievable through a more dramatic fuel switch to liquid bio-gas and bio-methanol. Seeking to deviate from comparing fuels based on a single Global Warming Potential "pulse," Thomson et al. (2015) examine the GHG impact of a fuel switch to LNG for the operation of different groups of ships, satisfying an maintained demand for shipping across time, based on different assumptions on vessel replacement, engine type, different rates of emissions per life-cycle stages etc.

The results of the literature review demonstrate the various ways in which life-cycle emissions can be compared, but crucially establishes the value in moving from a static to a more dynamic representation of upstream emissions. For example, simply comparing results per quantity of fuel does not take into account engine efficiency improvements, or differing engine types. Expressing results in terms of engine power arguably provides a more useful comparison for a diverse range of fuels, as well as being more useful to stakeholders in industry, as it incentivises both upstream and direct efficiency. Furthermore, there is a benefit in identifying potential fuel cycle sensitivities that may contribute to a change in overall emission estimate for today and out into the future. Given the prominent role of fuel switching in many emission scenarios across different sectors, appreciation of fuel cycle or life-cycle issues is particularly important, especially for emerging fuels such as hydrogen and bio-derived fuels, where full life-cycle carbon dioxide emissions are discounted or absent from analysis. In particular, the literature demonstrates that securing significant reductions across all emission species through fuel switching is likely to be difficult to achieve, highlighting the trade-off between reducing greenhouse gases and local pollutants. Through consideration of a range of sensitivities this study seeks to identify under what conditions a significant reduction in fuel cycle emissions may be achieved and whether life-cycle emission reductions due to fuel switching are ultimately within the remit of the shipping sector, fuel production or other economic sectors – providing a novel contribution to the literature. Failure to consider the potential range and variability of the whole life-cycle emissions of alternative fuels risks not achieving full life-cycle emission reductions and provides an incomplete insight for the industry.

2.2 Emission scope and functional unit

The emission scope for each fuel in the aLCA covers upstream emissions for each stage of the life-cycle up until delivery onto the vessel, and the operational emissions when the fuel is combusted on the vessel. Combined, this is termed Well-to-Propeller (WTP). The functional unit chosen is grams emission/kWh delivered to the shaft. WTP emissions per tonne of fuel combusted are mapped to this unit using an engine's specific fuel consumption (sfc), which refers to the the fuel efficiency of an engine design in terms of power output. Total greenhouse gas emissions from all three species

considered are also presented in terms of CO_2e, using 100-year global warming potential factors of 34 for CH_4, and 298 for N_2O (IPCC, 2013). Emissions of NO_x, mainly due to its impact on atmospheric CH_4, and of SO_x, as a precursor of sulphate aerosol, both have a large negative, and highly uncertain radiative forcing impact (IPCC, 2013). However, both species are mainly regulated as local pollutants; and the effects from both are short-lived in comparison to CO_2 and N_2O. Therefore, they have been omitted from the calculation of total greenhouse gas emissions in terms of CO_2e.

2.3 System definition for alternative fuels

The fuel pathways considered in this study are derived from extensive consultation between academics and industrial partners within the RCUK EPSRC funded Shipping in Changing Climates project (EPSRC, 2013, Low Carbon Shipping, 2017) and are also based on the academic literature. They represent a) fuels that are currently the focus of the sector in order to comply with current and upcoming sulphur regulations and b) fuels that are anticipated to be deployed as the sector seeks to decarbonise.

The resultant life-cycle pathways chosen to reflect each fuel, presented in Figure 1, are described in the paragraphs below and a summary of the main fuel characteristics are outlined in Table 1. Within each paragraph the following information is provided:

- *The region where the fuel is manufactured.* This is based on where major manufacturing/biomass hubs are currently located. This assumption impacts specifically travel distance and emission factors associated with electricity use and technology maturity.
- *The conversion pathway.* This outlines the main process steps that incur an environmental penalty or benefit.
- *The engine type.*
- *The main fuel-cycle hot-spots.* This states the components of the life-cycle that could have an impact on the overall emissions. Here, an indication is given as to whether these hot-spots are tested in the sensitivity analysis (Section 2.4). Considering these hot-spots assists in the identification of the stages and processes that are likely to be most impactful when seeking to manage upstream emissions. In some cases the impact of a sensitivity choice is based on the imposition of best practice, or best available technologies, which could be realised in the short- to medium-term.

No primary inventory data is developed in this study. The aLCA uses secondary data to generate the emissions inventory for the fuel pathways. When considering the upstream processes, for standard and second order processes, such as material or machinery production, EcoInvent (Ecoinvent, 2013) and the European Commission LCA Database (ELCD) (2014b) are used and selected to represent best available practices in the given country or region of fuel production. For operational emissions the 3rd IMO Greenhouse Gas study is used (Smith et al., 2014), augmented with data from the USEPA Emission Factors for Greenhouse Gas Inventories (USEPA, 2015) and energy content data from Digest of United Kingdom energy statistics (DUKES, 2010). In the base case, operational CO_2 emissions associated with bio-derived fuels are taken to be zero, under the assumption that they are counterbalanced by CO_2 removed from the atmosphere during feedstock growth.

	Net calorific value	SFC	Operational fuel emission factor (g/kWh)					
Fuel	MJ/kg	g/kWh	CO_2	CH_4	N_2O	SO_x	NO_x	PM
LSHFO	40.5	179	541	0.010	0.027	3.23	15.8	0.72
MDO	42.6	170	524	0.010	0.026	0.32	14.8	0.16
LNG	48.6	150	412	3.0	0.016	0.003	1.17	0.027
LH_2	120.0	57	0	0	0	0	0	0
Methanol	20.0	381	522	0	0	0	3.05	0
SVO Soy	37.5	195	-	0.0064	0.013	0.37	17.1	0.19
SVO Rape	37.4	195	-	0.0064	0.013	0.37	17.1	0.19
Biodiesel Soy	37.8	187	-	0.0061	0.013	0.36	17.9	0.18
Biodiesel Rape	37.9	187	-	0.0061	0.013	0.36	17.9	0.18

Table 1: Key characteristics of alternative fuels

Data on bio-derived fuels are taken from Baquero et al. (2011) and ANL (2008). Data on sfc are taken or adapted from Smith et al. (2014), whilst emission per unit of fuel are based on USEPA (2015). Data on fuel carbon content are taken from USEIA (2016). Data on the energy content of hydrogen and methanol are taken from Satyapal et al. (2007) and Stone (2012) respectively. The sfc for refined bio-derived fuels increases relative to MDO due to a lower net calorific value, following Xue et al. (2011).

HFO (low sulphur 1% S)

The production of LSHFO (Low Sulphur HFO) from crude oil is based on average European production data (ELCD, 2014a). The production steps include drilling and extracting of crude oil (offshore and onshore), pre-treatment (for example, solids removal) and refining and catalytic hydrocracking (ELCD, 2014a). Once the crude is refined, the HFO is transported on dedicated tankers to a central hub and stored in a non-pressurised facility. It is combusted in a slow-speed diesel engine. As HFO is a co-product from the refining process, the emissions embodied in these life-cycle stages are allocated between HFO and MDO based on the relative mass of each co-product and the energy content of each fuel. The main life-cycle hot-spots include the efficiency of the refining; fugitive emissions, venting and flaring during crude extraction and refining; and transport distance. However, these are not considered in the sensitivity analysis as the production pathway is considered mature.

MDO (0.1% S)

Similar to HFO, the production of MDO is based on data from ELCD (2014a). MDO is combusted in a slow-speed diesel engine. As it is a co-product this fuel has the same life-cycle hot-spots as HFO and likewise is also not considered in the sensitivity analysis.

LNG

Data for natural gas drilling and extraction is based on Bengtsson, Andersson et al. (2011a), and Skone, Littlefield et al. (2014). Natural gas is extracted both from offshore and onshore sources in Europe. Data for desulphurisation and water removal, dedicated processing, and separation is based on Bengtsson, Andersson et al. (2011a). Data for the range of emissions associated with natural gas liquefaction is based on Jaramillo, Griffin et al. (2005) and includes emissions due to venting and flaring. The CO_2 intensity for liquefaction is 0.2 *(0.2-0.4)* kg CO_2/kg LNG (Jaramillo et al., 2005), the

range reflecting efficient production centres in Europe and less efficient production in the Caribbean and US (Skone et al., 2014). LNG is transported cryogenically 460 km to the central hub and then stored prior to use. It is combusted in a spark-ignition gas engine during ship operation. The main life-cycle hot-spots include liquefaction efficiency; extent of venting and flaring; and methane slip (Jaramillo et al., 2005). Methane slip is taken as the unintended release of methane during ship operation only. These hot-spots are tested in the sensitivity analysis.

Hydrogen (+Carbon Capture and Storage technology (CCS))

The main assumptions and processes are the same as the process steps for LNG production including liquefaction. From here, data for steam reforming of the natural gas and CO_2 shift is based on Cetinkaya, Dincer et al. (2012) and further purification is based on Skone, Littlefield et al. (2014). The natural gas demand for H_2 production is 3.5 kg LNG/kg H_2 (Cetinkaya et al., 2012) and the power demand for liquefaction is 10 *(8-12)* kWh/kg LH_2 (Gardiner, 2009). In the case of H_2 with CCS, the CO_2 is captured and stored during the processing stage. The capture rate for CO_2 is 90% removal *(80-90%)* (Azar et al., 2006); other data for CCS, including the additional power demand associated with CO_2 capture and compression is based on Danny Harvey (2010). Following the production of LH_2, it is transported on a cryogenic truck for 50 km and then stored prior to use. It is combusted in a fuel cell. The main life-cycle hot-spots include the choice of liquefied or compressed H_2, the grid intensity of electricity, the natural gas requirement and the carbon capture efficiency (Gardiner, 2009). These hot-spots are tested in the sensitivity analysis.

Methanol

The main processes are the same as the process steps for LNG production up until liquefaction. From here, the main processing steps are steam reforming, methanol synthesis and purification/distillation (NREL, 2014, Maréchal et al., 1997, Kim et al., 2011). The storage is assumed the same as refined petroleum (Brynolf et al., 2014) and in the base case no long distance transportation is assumed, as the processing is located next to the point of use. It is combusted in a medium- to fast-speed diesel engine, converted to a dual fuel engine. The main life-cycle hot-spots include the methane conversion efficiency; and the use of liquid or gaseous natural gas feedstock. However, these are not considered in the sensitivity analysis.

Renewable hydrogen

Renewable liquid hydrogen (Re LH_2) is taken to mean wind-powered electrolysis. The wind farm is located in Europe and the main process step is the electrolysis of water; data is based on (Bhandari et al., 2014, Patterson et al., 2014). The electrolysis efficiency is based on the higher heating value of Hydrogen at 75% *(65-75%)* MJ/MJ (Bhandari et al., 2014). The embodied emissions of the electricity generation from wind are 14 *(14-25)* g CO_2/kWh (Tremeac and Meunier, 2009, Ecoinvent, 2013), with the lower value used here, which assumes 4 MW wind turbines with a long functional life. Storage requirements are assumed the same as with conventional H_2 production. The renewable hydrogen is assumed to be produced in a large-scale industrial electrolysis facility with the estimates of the material embodied in the production of hydrogen taken from Maack (2008). It is used in a fuel cell. The main life-cycle hot-spots include the efficiency of the electrolysis process; choice of liquefied or compressed H_2; and the construction material embodied in fuel production (Bhandari et

al., 2014, Patterson et al., 2014, Maack, 2008). However, the latter is not considered in the sensitivity analysis.

Soy SVO

The feedstock for SVO production is Argentinian soybean. The upstream processing includes conversion of forestry land for soy production, cultivation of soybean and harvesting, drying and extraction and pressing of soybean, followed by conventional storage. Fertiliser data incorporates specific Argentina fertiliser application rate for soybean cultivation (Hilbert. J.A et al., 2010, Garraín et al., 2014, Panichelli et al., 2009). The Nitrogen and P_2O_5 fertiliser is assumed to be 5.47 and 20.8 kg/ha respectively (Panichelli et al., 2009, Garraín et al., 2014). No K fertiliser is applied in soybean production in Argentina (FAO, 2004, Panichelli et al., 2009). The soybean grain is assumed to be transported by ship to Europe where it is processed and refined to SVO. The data for the extraction and refining is based on average EU production output for SVO extraction (Esteban et al., 2011, Jungbluth, 2007, Malça et al., 2014, Stephenson et al., 2008). The main life-cycle hot-spots include the impact of land use change; and emissions from fertilisers. The land-use change hot-spot is tested in the sensitivity analysis.

Rape SVO

The feedstock for SVO production is European rapeseed. The upstream processing includes preparation of previously arable land, cultivation of rapeseed and harvesting, drying and extraction and pressing of rapeseed, followed by conventional storage. The fertiliser input for rapeseed cultivation is based on the UK average adapted from DEFRA (2013). The data for extraction and refining is based on (Jungbluth, 2007, Malça et al., 2014). The SVO is transported to the port by pipeline and subsequently transported by a tanker a short distance from bunkering facility within a European port to a ship, where it is combusted in a slow-speed diesel engine. The main life-cycle hot-spots include the impact of land use change; and emissions from fertilisers. The land-use change hot-spot is tested in the sensitivity analysis.

Soy and Rape Biodiesel

Biodiesel is produced from further processing of SVO via transesterification using an average EU production output for rape biodiesel and soy biodiesel respectively (Jungbluth, 2007, Malça et al., 2014). The transesterification plant is assumed to be located at the central hub in Europe with the rapeseed feedstock material transported from cultivation site to processing site by lorry while the soybean feedstock is transported via shipping and processed in Europe. Once produced, the biodiesel is stored in a non-pressurised facility and transported 50 km on board a products tanker. It is combusted in a slow-speed diesel engine. The main life-cycle hot-spots include the impact of land use change; emissions from fertilisers; and transesterification steam demand. The land-use change hot-spot is tested in the sensitivity analysis.

Bio-LNG

Bio-LNG production is assumed to take place in Europe and the process steps are based on data from Jungbluth et al., Ebner et al., and Hijazi et al. (Ebner et al., 2015, Hijazi et al., 2016, Jungbluth, 2007). Agricultural and animal waste is collected locally, where the waste feed undergoes pre-treatment and is fed into an anaerobic digestor. The biogas yield is 1 kg per 9 kg solid waste.

Following anaerobic digestion the biogas is collected and liquefied for further transport. The bio-LNG is transported 20 km on a bunker ship and stored cryogenically prior to use. The methane slip assumed during digestor operation is 0.007 kg CH_4/kg biogas (Evangelisti et al., 2014). It is combusted in a spark-ignition gas engine during ship operation. The main life-cycle hot-spots include liquefaction efficiency; methane yield; extent of flaring; and methane slip. These hot-spots are tested in the sensitivity analysis.

2.4 Sensitivity analysis and temporal emission factors

Sensitivity analysis

A sensitivity analysis in key parameters and inventory data is conducted for several of the fuel pathways. Table 2 presents the fuel pathways examined, what part of the inventory is tested for sensitivity, and the specific assumptions modified. It should be noted that, with the exception of SA1, the sensitivity analysis refers to upstream emissions only.

No	Fuel	Fuel Cycle Sensitivities	Assumptions made
SA1	LNG	1.1 Increase in **operational** emissions due to uncombusted methane (methane slip). Note that the alternative emissions are compared against a baseline for operational emissions (termed 'LNG ops' in Figure 5).	0.02 to 0.05 g CH_4/g fuel (based on emissions on a g/kWh basis and estimated sfc (Soares and Santos, 2014).
SA2	LNG	2.1 Increase in raw to process gas ratio. 2.2 Increase in level of emissions from extraction site (incl. venting and flaring, reflecting technology level and scale). 2.3 Decrease in energy efficiency of liquefaction move from best to worst case. 2.4 Increase level of venting and flaring at liquefaction stage. Note that the alternative emissions are compared against a baseline for upstream emissions (termed 'LNG up' in Figure 5).	1.09 to 1.13 kg Raw gas/kg NG. 0.1 to 0.2 kg CO_2/kg NG (Bengtsson et al., 2011a, Skone et al., 2014). 0.2 to 0.4 kg CO_2/kg NG (Jaramillo et al., 2005). 10x increase in methane emissions due to leakage, venting and flaring (Bengtsson et al., 2011a, Jaramillo et al., 2005).
SA3	LNG	3.1 Increase in LNG shipping distance to reflect Qatar to Europe.	550 to 11,000 nautical miles.

SA4	LH$_2$	4.1 Increase in capture rate of carbon emissions.	From 90% to 95%.
		4.2 Change of source of Electricity.	2010 UK grid to large-scale wind only.
		4.3 Change of feedstock source.	From LNG to natural gas feedstock (Spath and Mann, 2000).
SA5	LH$_2$	5.1 Changed state of product fuel.	From liquefied to compressed H$_2$.
SA6	Bio-diesel	6.1 Inclusion of emissions due to land use change (LUC).	Including LUC emissions for soy (Panichelli et al., 2009) and rape (Malça et al., 2014).
SA7	Bio-LNG	7.1 Decreased release of un-combusted methane.	From 2% to 1% of product gas.
		7.2 Decreased energy requirement of biogas upgrading.	From 0.5 to 0.25 kWh/Nm^3 (Uusitalo et al., 2014).

Table 2: Summary of sensitivity analyses – denoted here as SA#.

Temporal emission factors under a low carbon future

To capture potential temporal improvements to grid carbon intensity and process efficiency, associated emission factors are calculated as a function of time, out to 2050. The average grid emission factor is based on the global electricity fuel mix taken from a 2°C energy scenario (GCAM 450) developed for the IPCC Fifth Assessment report (AR5) (IPCC, 2015, IIASA, 2014); and on life-cycle greenhouse gas emission factors for each fuel in the mix, selecting the median values from the respective ranges found in the literature (Bruckner et al., 2014, Moomaw et al., 2011). The average grid CO$_2$ intensity reduces from 560-600 g CO$_2$/kWh (depending on location) in 2010, to 90 g CO$_2$/kWh in 2050, as shown in Table 3. Furthermore, the fuels are assumed to benefit from process efficiency gains. The main assumptions for each fuel subjected to temporal change are summarised below. Within systemic decarbonisation, the life-cycle emissions associated with established and mature conventional fuels are assumed to remain static.

- *LNG:* the replacement of the use of electricity generated in a gas turbine (Bengtsson et al., 2011b) by decarbonised grid electricity as a source of energy for liquefaction.
- *LH$_2$:* the replacement of liquefied feedstock by gaseous feedstock, use of decarbonised grid electricity, increased energy efficiency of hydrogen liquefaction (from 10 kWh/kg to 7 kWh/kg by 2050) (Gardiner, 2009).
- *Methanol:* increase in natural gas conversion efficiency, replacement of natural gas by decarbonising electricity as a heat source (Brynolf et al., 2014).

Variable	Unit	2020	2030	2040	2050
Total Electricity	*EJ/yr*	*97*	*129*	*172*	*227*

Of which:					
Biomass with CCS	EJ/yr	0	1	5	15
Biomass without CCS	EJ/yr	1	2	2	2
Coal with CCS	EJ/yr	0	5	18	32
Coal without CCS	EJ/yr	37	37	23	7
Gas with CCS	EJ/yr	0	3	11	21
Gas without CCS	EJ/yr	27	32	33	30
Geothermal	EJ/yr	1	2	3	4
Hydro	EJ/yr	12	13	15	16
Nuclear	EJ/yr	11	19	36	62
Oil with CCS	EJ/yr	0	0	1	1
Oil without CCS	EJ/yr	2	2	1	1
Solar	EJ/yr	1	2	5	10
Wind	EJ/yr	4	10	19	26
Estimated CO_2 average grid emission factor	g CO_2/kWh	0.53	0.43	0.24	0.09

Table 3: Grid fuel mix taken from GCAM 450 (IPCC, 2015); derived CO_2 life-cycle emission factor in final row.

3. Results from the life cycle assessment

3.1 ALCA base case results

Impact on greenhouse gas emissions

Figures 2 to 4 present the life-cycle emissions for each fuel. Figure 2 presents results in terms of carbon dioxide equivalents (IPCC, 2015), distinguishing between upstream and operational emissions. Figure 3 presents the same results, but distinguishes between the contributions to overall CO_2e of different emissions species. Figure 4 presents emissions of non-greenhouse gas species.

The two conventional fossil fuels and LNG produce comparable baseline greenhouse gas emissions. Their upstream CO_2 emissions range from 0.32 to 0.34 kg CO_2/kg fuel, in line with the literature (Bengtsson et al., 2011a, Corbett and Winebrake, 2008). Among all analysed fuel options, LH_2 without CCS has the highest greenhouse gas emissions; with CCS, LH_2 emissions are about equal to the conventional fuels; and only for the electrolysis pathway using renewable energy input there is a substantial reduction. Methanol increases life-cycle greenhouse gas emissions by 12-15% compared to the conventional fuels. For the range of bio-derived fuels (from soy and rape), compared to the conventional fuels life-cycle greenhouse gas emissions are reduced by 57-79%; bio-derived LNG reduces emissions by 40-41%.

Figure 3 illustrates the significant proportion of non-CO_2 greenhouse gases for all bio-derived fuels. Emissions of N_2O can account for up to nearly half of the greenhouse gas emissions of the bio-derived fuels (42-46% for the fuels derived from rape), due to the production and application of nitrogen based fertiliser during feedstock growth. For bio-LNG, the release of un-combusted methane during reactor operation constitutes the dominant contribution to life-cycle greenhouse gas emissions here.

Comparing the results for the alternative fuels with the literature, the baseline results for hydrogen production (LH$_2$noCCS, excluding the impact of liquefaction) are comparable to those published in Cetinkaya et al. (2012) (at 11.9 and 11.25 kg CO$_2$e/kg H$_2$ respectively). The effect of liquefaction is seen to significantly increase fuel cycle emissions to 17.5 kg CO$_2$e/kg LH$_2$, comparable to 17.3 kg LH$_2$, as estimated by Elgowainy (2013) for US produced hydrogen. However, the result estimated for renewable hydrogen (Re LH$_2$) generally exceeds those estimated in the literature by 40-50% (Cetinkaya et al., 2012, Spath and Mann, 2001). This is likely due to the use of embodied material estimates (in kg/kg H$_2$) taken from Maack (2008), which describes a large-scale hydrogen production plant with a filling station. When expressed in terms of the energy content of fuel, the upstream greenhouse gas estimate for rapeseed derived biodiesel (incl. LUC) closely matches the value estimated in Chryssakis (2014), whereas Malça et al. (2014) estimate significantly higher GWP emissions (excluding LUC).

Impact on local pollutants

Figure 4 presents emissions of SO$_x$, NO$_x$ and PM per kWh of shaft output, distinguishing between operational and upstream emissions.

Although LSHFO is a low sulphur alternative to standard HFO, its 1% fuel sulphur content is twice the mandated global maximum from 2020 onwards. SO$_x$ emissions from all other options are significantly lower (<33%) indicating straightforward compliance with the global maximum. Considering the more stringent 0.1% limit for ECAs, results for all options but LSHFO also indicate straightforward compliance, as upstream emissions do not fall under the regulation.

With respect to NO$_x$ emissions, the results show a clear distinction between the conventional liquid fuels (15-17 g/kWh) and the bio-derived fuels (18-19 g/kWh) on one side, and (bio-)LNG (1-2 g/kWh), hydrogen (1 g/kWh) and methanol (3 g/kWh) on the other.

LSHFO has the highest PM emissions at 0.78 g/kWh. Among the conventional fuels, PM emissions from MDO are 23% of those of LSHFO. PM emissions for H$_2$ from steam-reforming methane are 18% of those from LSHFO. Under the electrolysis pathway of hydrogen with renewable energy, PM emissions are 78%, compared to LSHFO. The range for the four bio-derived fuels is 41% (soy BD) to 45% (rape SVO), whereas bio-LNG, like fossil LNG, has much lower PM emissions of around 4%.

3.2 Results of the sensitivity analysis

Results from the sensitivity analyses are shown in Figure 5. Whilst LNG reduces CO$_2$ emissions compared to the conventional fossil fuels, emissions in terms of CO$_2$e are about equal (cf. Figure 3). Assuming a higher rate of methane slip, SA1 shows increases in CO$_2$e due to methane slip nearly twice the size of the reduction from lower CO$_2$ emissions, rendering life-cycle emissions of LNG, in terms of CO$_2$e, significantly higher than for LSHFO and MDO.

The other sensitivity analyses, SA2-SA7, consider upstream emissions – the key findings are outlined below. SA2 moves away from best practice, in terms of maximised liquefaction efficiency and minimal venting and flaring. As shown in Figure 5, the consequential increase in emissions means that overall life-cycle emissions, in terms of CO$_2$e, are larger than for the conventional fuels under

these assumptions (see Figure 3). SA3 highlights that the transport of energy commodities is efficient, and the penalty of long distances between production and bunkering locations is not a major factor in discriminating between the considered fuel options. The base case production pathway for hydrogen requires significant (fossil and electricity) energy input. Examining SA4 indicates that a substantial cut to CO_2 emissions is possible if the electricity from a carbon-intensive grid mix is replaced with electricity from a renewable source. While liquefaction of H_2 takes energy, the penalty in terms of emissions is small if the production pathway is renewably powered, as shown by SA5. Emissions due to land use change are a major, and critical, issue for bio-derived fuels, as shown by the results from SA6. Taking both upstream and operational emissions into account, the CO_2e emissions saving potential of Rape biodiesel, compared to LSHFO, reduces from 58% to 23%, as land use change emissions are included. The difference is even more drastic in the Soy biodiesel pathway; instead of savings of 76%, emissions increase by 25%. Finally, SA7 illustrates the uncertainty in methane slip during the production of LNG from bio-derived sources. Methane accounts for a large share of Bio-LNG life-cycle emissions in terms of CO_2e. Consequently, emissions can be significantly reduced if methane slip can be tightly limited.

3.3 Results of the temporal analysis

Figure 6 shows the results from the temporal analysis for 2050, compared to the 2010 baseline.

For LNG production, major gains are assumed in the liquefaction process, through decarbonisation of electricity input. But the major component of life-cycle emissions is due to the on-board combustion of LNG. In the absence of on-board CCS, which is not considered here, there is limited opportunity to reduce greenhouse gas emissions from LNG. The same applies to methanol produced from natural gas feedstock.

In contrast, LH_2 life-cycle emissions occur upstream, and the reduction potential is significant. The results show that the major share of emissions from LH_2, produced through steam reforming, are comprised of CO_2 from the feedstock and the CO_2 associated with grid electricity input, in roughly equal parts. Adopting CCS reduces the former and, decarbonising of the grid — in accordance with the underlying mitigation scenario — reduces the latter. In combination, this brings life-cycle emissions down to a level close to, but still above, that of LH_2 under the fully renewably powered electrolysis pathway.

4. Discussion and Implications for industry and policy

Fuel candidates for addressing local pollutants

In comparing the performance per unit of engine power it is should be reiterated the results will depend not just on the inherent emissions per unit of fuel, but also the fuel efficiency of specific engine types. The analysis presented here indicates that all alternative fuel options significantly reduce PM emissions, compared to LSHFO. PM emissions from Re LH_2 are still high, but since they are due to embedded emissions from upstream electricity use, they are not an inherent issue for this fuel option. Among the other alternative fuels, PM emissions are highest for the bio-derived fuels (soy SVO and biodiesel, and rape SVO and biodiesel).

SO_x emissions are mainly determined by the fuel sulphur content. For all alternatives, SO_x content is only a fraction of the content in LSHFO (which in turn has much lower fuel sulphur content than the standard HFO currently used), making compliance straightforward.

Beside the amount of nitrogen bound in a fuel, NO_x emissions depend crucially on the combustion process, including temperature and other characteristics. In turn, these characteristics depend on not just the fuel (or fuel mix), but also on the operating point of the engine and other parameters not directly related to the fuel. Still, results indicate that the bio-derived fuels assessed face broadly the same issues for NO_x emissions as the conventional fuels. With this notable exception, all alternative fuels considered can deliver significant cuts to emissions of PM, NO_x and SO_x, reducing local pollution, yielding benefits in terms of impacts on human health, and facilitating compliance with regulation.

Fuel candidates for decarbonisation

Providing reductions in greenhouse gas emissions and progress towards decarbonisation proves more difficult. The results show that fossil LNG is not a low carbon alternative. When taking into account non-CO_2 emissions, any reductions of greenhouse gas emissions in terms of CO_2e are negligible (see Figure 2). Even under idealised conditions, reductions of CO_2 emissions are strictly limited. Bio-LNG is an exception. The results show that it has the potential to cut CO_2 emissions significantly. However, the feedstock is clearly limited and, in terms of CO_2e, exploiting its abatement potential depends on the ability to keep both upstream and operational methane emissions in check.

Among the other alternative fuels considered, there exists no ready solution to significantly reduce greenhouse gas emissions in the short-term. Hydrogen has no operational CO_2 emissions. However, in the baseline case, associated life-cycle CO_2 emissions are significantly higher than for conventional fuels. When taking full life-cycle emissions into account, significant benefits are only realised if CO_2 emissions from its feedstock and from input energy supply are cut or rid of; either by successful application of CCS and decarbonising input electricity (see Figure 6) or by using renewable energy input in production via electrolysis (see Figures 2 and 3). The same or similar issues as for LH_2 hold for other synthetic fuel options not considered in this paper, such as Fischer-Tropsch fuels and gas-to-liquid synthesis fuels (see van der Giesen et al. (2014)).

Methanol, under the production pathway considered here, only has a very narrow potential. The only advantage over LNG may be its applicability as a drop in fuel, but it comes with a significant life-cycle CO_2 emissions penalty. However, methanol derived from biomass could improve the life-cycle emissions (Brynolf et al., 2014), while raising issues also associated with other bio-derived fuels.

The bio-derived fuels considered show the largest reductions of CO_2 emissions (except Re LH_2). Only if the biomass feedstock takes up atmospheric CO_2 that would otherwise not have been taken up are operational emissions counterbalanced. Inclusion of land use change emissions can dramatically alter the greenhouse gas balance, with results subject to large uncertainty, and highly dependent on the feedstock production process, as shown by sensitivity analysis SA6 (see Figure 5) exemplary of the wider literature (Dubreuil et al., 2007). Some emissions, such as those associated with fertiliser application may be difficult to mitigate as depending on soil conditions, they likely represent a necessary component in maintained feedstock provision. Whether, and at what scale sustainable

production pathways can be realised depends on a wide range of factors, including land availability, competition with land use for food production, and demand from other sectors – as most climate change mitigation scenarios foresee a key role for bioenergy in the wider energy system, with scale up of global demand by orders of magnitude (Van Vuuren et al., 2011).

5. Conclusions

The key environmental challenges for any alternative fuel are twofold: deliver a reduction in local pollutants and comply with longer-term reductions in greenhouse gas emissions. To understand the full extent of the environmental implications it is important to consider the emissions released over the full life-cycle and not just during fuel combustion. Otherwise, there is a risk of misleading the industry and policy on the true emission penalties of any alternative fuels. The fuel options selected in this paper are based on the literature and expert opinion, but are not necessarily exhaustive, nor are the pathways to produce these fuels unique or mature. Nonetheless, the following conclusions are considered robust.

There is, at present, no readily available fuel option to deliver significant savings on local pollutants and greenhouse gas emissions in tandem. In particular, LNG is a promising option for meeting existing regulation, but is not a low greenhouse gas emissions fuel. Consequently, effort needs to be directed at overcoming barriers to exploiting the identified low carbon potential of fuels, or finding alternatives not considered here. Bio-derived fuels show potential, but only if they can be ensured that actual savings are realised; land-use change and other upstream emissions, for example from fertiliser use need to be accounted for. The viability of hydrogen, or other synthetic fuels not considered in this paper, crucially depends on decarbonisation of the production process, through either grid decarbonisation or switching to renewable feedstocks. There are also other barriers and issues outside the scope of this paper, for example, regarding transport and storage of hydrogen. As a result, while some unresolved issues relate more directly to shipping technology, others are not directly related to the shipping sector, or immediately amenable to regulation of the sector. Taken together, this has important implications. As the urgent need to curtail greenhouse gas emissions is the more severe challenge, it is therefore important to ensure that any measure in the short-term does not diminish the potential for roll-out of low carbon fuels in the medium-term, in particular when taking into account the long life times of ships and fuel supply infrastructure. To meet the objective of reducing greenhouse gas emissions, whole life-cycle emissions need to be accounted for. For any promising option, significant efforts will be required first to demonstrate applicability in practice and subsequently to be scaled up to industrial level, with bunkering facilities available along major transport hubs.

Aiming to ensure the medium- to long-term sustainability of the sector, action is needed across a range of sectors, and involving both industry and policy. A diverse set of challenges need resolving and any alternative fuel option must fulfil a range of criteria, including proper accounting for full life-cycle emissions. Otherwise, the sector could find itself addressing its near-term local pollutants targets at the expense of setting itself up to address its imminent longer-term carbon targets.

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Caption List

Figure 1: Life-cycle pathways of selected alternative fuels

Figure 2: Greenhouse gas emissions per kWh of shaft output, by life-cycle stage. Ex LUC denotes excluding land use change.

Figure 3: Greenhouse gas emissions per kWh of shaft output, by gas species. Ex LUC denotes excluding land use change.

Figure 4: Non-greenhouse gas emissions per kWh shaft output.

Figure 5: Impact of sensitivity assumptions on emissions (as summarised in Table 2), measured in g CO_2e/kWh shaft output (represented as a light grey bar), compared to baseline estimates presented in Figure 3 (represented as a black bar). Note 'LNG op.' and 'LNG SA1' refer to operational emissions whilst the others refer to upstream emissions.

Figure 6: Impact of temporal assumptions on life-cycle emissions summarised in Table 3, measured in g CO_2e per kWh shaft output.
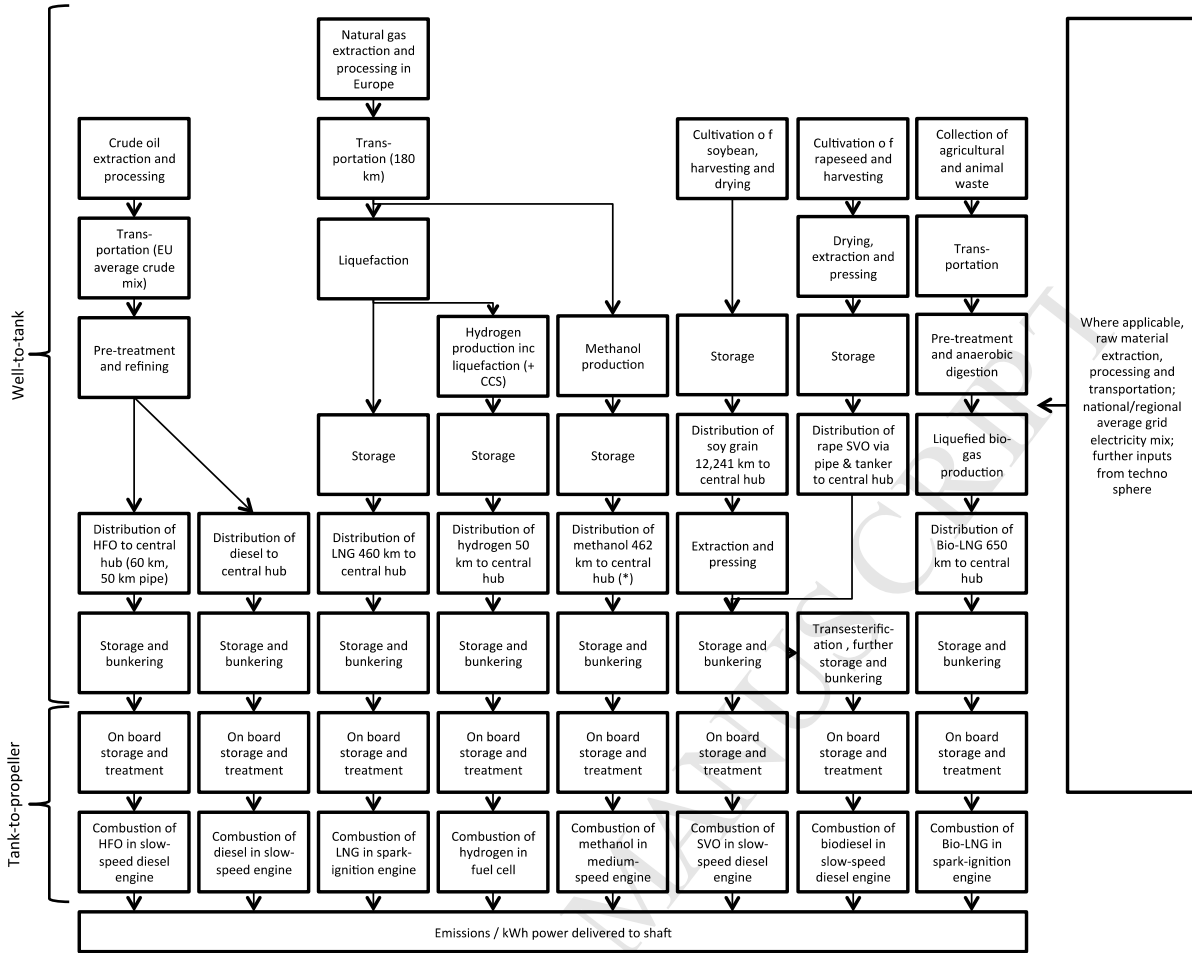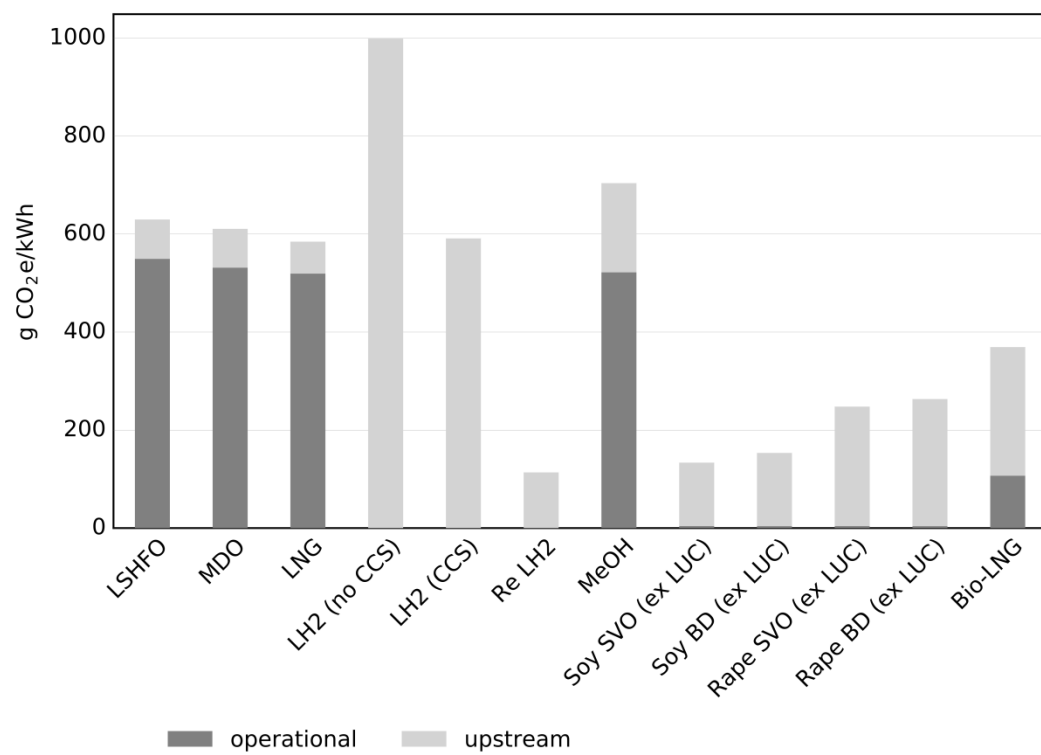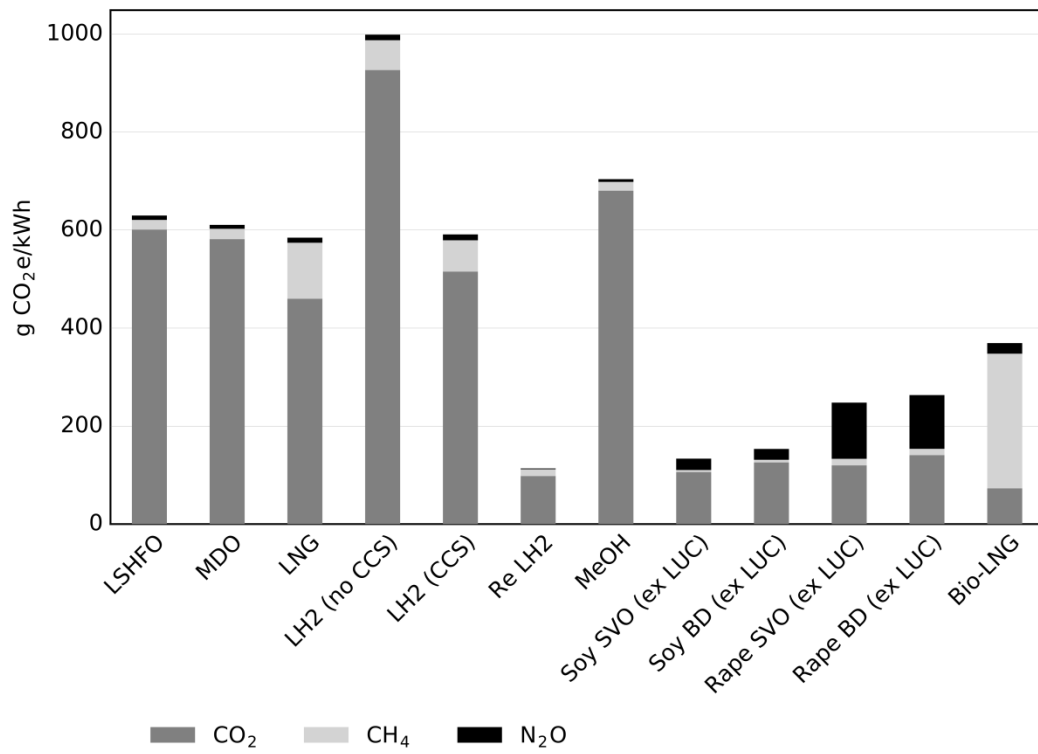
Figure 1

Figure 2

Figure 3

Figure 4

Figure 5