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ORIGINAL RESEARCH

Assessing the impact of EU policies on recycling supply chain: a system dynamics perspective on advancing packaging recycling capacity

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Abstract

Recycling stands as a crucial strategy in mitigating climate change and advancing towards carbon neutrality. Within the European Union (EU), the development of a resilient recycling supply chain is of paramount importance, particularly in response to global disruptions such as the widespread ban on solid waste imports by numerous countries like China, Malaysia, Thailand, and Vietnam. Such disruptions have exposed the vulnerabilities of EU member states, notably their overreliance on waste export and limited domestic recycling capacities. This study integrates primary data from diverse public sources into a system dynamics simulation model to assess the effectiveness of three policy types used to enhance EU domestic recycling capacities: Innovation-focused (IF), Subsidy-focused, and Market-based (MB) policies. Our findings show that IF policies exert the most considerable impact in the short term and continue to play a crucial role in the EU's recycling capacity expansion over the medium and long term. Conversely, MB policies are identified as most effective for immediate capacity enhancement in response to abrupt disruptions. Finally, the result suggests the optimal policy mix where 84% government resources should be allocated to IF policies and 16% to MB policies to ensure the EU achieves the deliberate balance between short-term market stabilisation and long-term transformation of its domestic recycling capacity for economic, environmental, and social sustainability. This research represents a pioneering effort in examining the efficacy of a diverse array of policy types within an optimised mix, thereby encompassing a broader range of policy considerations.

Keywords Government policies · Recycling supply chain · Waste management capacity · Packaging recycling · System dynamics

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1 Introduction

1.1 Research background and motivation

Climate change, characterised by global warming and extreme weather events, poses a significant threat to the environment, economies, and societies worldwide. Mitigating climate change and advancing towards carbon neutrality have become imperative goals for countries globally, with the European Union[1] (EU) at the forefront of this endeavour. In this context, recycling emerges as a critical component in achieving these goals. Recycling not only reduces the need for extracting and processing raw materials, which are energy-intensive processes contributing to greenhouse gas emissions, but also minimises waste generation, thereby reducing landfill use and associated methane emissions.

However, the EU, while being a global leader in recycling and waste management, faces significant challenges due to its reliance on exporting waste to other countries. This dependence has been a practical but vulnerable strategy, especially when nations traditionally receiving waste start imposing bans on imports. It was reported that the total installed mechanical recycling capacity in the European Union (EU) is around 10.4 million tonnes annually (McKinsey, 2020), while its total packaging waste generated was about 9 times higher—more than 89 million tonnes in 2018 (Eurostat, 2021). The severe shortage in recycling capacity was also echoed in the latest report by (European Court of Auditors, 2020a), which affirmed that the EU only has enough facilities to recycle half of its total plastic packaging waste. This issue has been shaped by the EU's decades-long overreliance on recycling capacity in developing countries for economic reasons. However, due to low environmental standard of the recycling industry in these countries, the EU's waste export practice has been unsustainable. The turning point emerged in 2018 when China, the EU's largest importer of recyclable waste, started to impose the waste import ban (World Trade Organization, 2017). The EU, along with several western countries, have been severely hit by the disruption from the China Waste Ban (CWB).

Responding to the waste recycling crisis in the post-CWB, several alternative solutions have been proposed in the EU. A commonly used measure is to reallocate the exporting destination to other third countries in Southeast Asia, India, or the Middle East. In 2020, half of the plastic waste that the UK claimed as "recycled" was actually sent to other countries (Greenpeace, 2021). Even so, China's recycling capacity was simply just too significant to be replaced. The sudden surge of waste import has overwhelmed the recycling system of many countries such as India, Malaysia, Sri Lanka, Thailand, Turkey and Vietnam, so that they have to start banning some imported waste to protect themselves (Greenpeace, 2021).

Longer-term solutions that the EU has imposed or planned to impose are to enhance domestic recycling facilities, reduction in waste generation and increased reuse obligations, as stated in the 2018 revised Packaging Waste Directive. In addition, the Extended Producer Responsibility schemes (EPRs) will become mandatory for all packaging companies by the end of 2024 (European Commission, 2020a). To put more pressure on its members, the EU is also tightening up the rules on what counts as recycling (European Court of Auditors, 2020b). For that, packaging wastes exported outside the EU are under stricter requirements to be counted as recycled (European Commission, 2018a), resulting in considerable drops in recycling rate

[1] The European Union (EU) is a political and economic union of 27 member states that are located primarily in Europe.

across the country members. From 2021, under new international rules, unsorted and contaminated recyclable plastics will not be allowed to be shipped to non-OECD[2] countries, which means more waste would have to be processed domestically. Therefore, it becomes an urgent need for European countries to expand its current domestic recycling capacity (Brooks et al., 2018; European Court of Auditors, 2020a; Wen et al., 2021).

The disruption resulting from the waste bans has revealed the poor functioning of the EU's domestic waste recycling industry with various fundamental underlying issues. Suppliers of recycled packaging materials have insufficiently invested in sorting and recycling capacity due to the limited profitability. Meanwhile, buyers (i.e., manufacturing firms) have low incentives to use recycled materials due to the concerns on availability and quality uncertainty. The resiliency and sustainability of the EU's waste recycling industry could be improved significantly if these issues are addressed (European Commission, 2018b; OECD, 2018).

In response to the disruption, the domestic recycling capacity expansion remains the most mutually agreed solution (Huang et al., 2020; Morita & Hayashi, 2018; Qu et al., 2019). Recently, (Wen et al., 2021) reaffirmed that developed countries should reinforce local management and waste treatment system through policy incentives and financial supports, rather than deliberately and recklessly exporting to other countries. As such, for the EU region, appropriate strategies to enhance the EU's waste recycling capacity are urgently required (European Court of Auditors, 2020a; Huang et al., 2020).

Therefore, it motivates us to examine how different governmental policies can help increase the existing capacity to meet domestic waste management needs in the short, medium, and long term.

According to the Adam Smith's Invisible Hand (The Wealth Nations) by Sterman (2000), profitability is a key driver of supply. For the EU's recycling industry, 'supply' refers to the domestic recycling capacity. Hence, governments can facilitate the expansion of this capacity by enhancing the industry's profitability. This could be achieved by aiding recyclers in reducing recycling cost and/or increase selling price of recycled products/materials. Cost reductions can be realised directly through government subsidies or indirectly by innovations that boost productivity. Meanwhile, selling prices can be elevated through governmental incentives and programmes designed to stimulate demand for recycled materials. For the reasons discussed, we chose three types of policies to be studied in this paper:

- Innovation-focused policies (e.g., direct financial supports for any R&D activities, tax incentives/relieves for innovations on recycling process)
- Subsidy-focused policies (e.g., financial subsidies for recyclers, public funds on separation collection systems, tax incentives for recyclers)
- Market-based policies. (e.g., Extended Producer Responsibility which requires packaging producers to accept and recycle used packaging from consumers, imposing minimum recycled content in a particular material, public awareness campaign to raise consumer demand)

Although comparing the relative effectiveness of different individual types of policies could provide some insights, policy makers cannot merely rely on individual policies but require appropriate policy combinations (Hao et al., 2019; Palmer & Walls, 1997). Identifying the most effective policy mix is therefore crucial for the EU to utilise its available resources productively.

Indeed, there have been several studies on each type of the policies for recycle capacity building: IFP (Aldieri et al., 2019; Huo et al., 2018a; Li et al., 2021; Yu et al., 2021), SFP

[2] The Organisation for Economic Co-operation and Development (OECD) is an intergovernmental economic organisation with 37 member countries.

(Gradus et al., 2017; Joshi et al., 2021; Qiao & Su, 2021; Wang et al., 2014), and MBP (Chang et al., 2016; Hong & Guo, 2019; Huo et al., 2018a; Ma et al., 2013; Rahbar & Abdul Wahid, 2011). However, most of these analyses are empirical based on past data with short-term and static nature and limited to the simplifying assumption of linearity. An alternative approach that can address these shortcomings is using the long-term oriented SD approach; however, its adoption in investigating the influence of different policies in recycle capacity building is scarce.

1.2 Research objective and contribution

To fill the gap above, the primary aim of this study is to offer policy recommendations on how the EU can implement three types of policies to expand recycling capacity, ensuring resilience against disruptions in the global recycling chain. Specifically, our research objectives are: (1) to analyse the dynamic behaviour of each individual policy over immediate-, short-, mid- and long-term period; (2) to optimise the budget allocation across the policy mix for maximising cumulative capacity; (3) to conduct scenario analyses to evaluate the sensitivity of the result under varying conditions; and (4) to validate the findings using real data from three EU member countries.

The system dynamic (SD) modelling approach is chosen in this study due to its capability to capture important dynamic behaviour-through-time phenomena derived between all important variables in the complex, real-work system, thereby providing a more plausible model of reality (Duran-Encalada et al., 2017). In addition, the tool enables what-if scenarios analysis and sensitivity analysis which are suitable for policy evaluation (Mingers & White, 2010). The graphical representations of the system can be easily comprehended by a wider audience, making it more accessible for policy makers, recyclers, and other stakeholders (Sterman, 2000).

The contributions of this research are twofold: theoretical and practical. From a theoretical standpoint, our study presents one of the few models that offer a comprehensive view of the waste recycling system, illustrated through the packaging waste stream. This model is versatile, allowing for adaptations to other types of waste streams and applicable to different nations. Furthermore, while existing literature extensively explores the impact of individual policies on industry capacity expansion, research on the combined effect of policy mixes, as undertaken in this paper, remains limited. Additionally, by employing SD modelling, this work enhances the current theoretical frameworks used for addressing disruptions in reverse logistics.

In terms of practical contributions, this research offers two key benefits to the field. Firstly, it provides practitioners within the EU's packaging waste recycling system with a deeper understanding of how different policies perform dynamically over time. This insight is crucial for adapting to evolving market and environmental conditions. Secondly, the study furnishes strategic recommendations for policymakers, guiding them in the optimal allocation of government budgets for capacity building. This is particularly vital for addressing the challenges posed by disruptions in the global recycling chain, ensuring a more robust and resilient recycling infrastructure.

The remainder of the paper is organised as follows: Section 2 discusses literature review and identifies research gap. Section 3 describes the methodology—the details of how the system dynamics model of EU packaging recycling system is developed. Section 4 discusses the result of simulation, optimisation of EU policy mix, and further scenario analysis. Section 5 is the conclusion.

2 Literature review

2.1 Studies of waste management systems (WMS)

According to the World Bank report, the world generates 2.01 billion tonnes of municipal solid waste each year and expects to rise to 3.4 billion tonnes by 2050. Notably, at least 33% of this waste is not treated in an environmentally responsible manner (Kaza et al., 2018). Therefore, to effectively manage current and future waste streams, a well-designed waste management system (WMS) is essential for improved waste collection, transportation, separation, treatments, and disposal processes. However, designing WMS is a complex task as it inherently involves multifaceted trade-offs among a plethora of local and regional factors such as socioeconomic, technological, ecological, and political (Sandoval-Reyes et al., 2024).

To deal with these complexities, several techniques in the system analysis have been adopted to provide interdisciplinary supports for a wide spectrum of technical and non-technical WMS issues. These can be classified into two core domains: system engineering and system assessment (Chang et al., 2011). First, system engineering models focus on WMS design issues and synergistic interfaces based on cost–benefit analysis (e.g. assessing environmental and economic impacts), optimisation (e.g. selecting facility location, size, and technology portfolio), simulation (e.g. analysing dynamic behaviour of continuous or discrete-event waste flows in complex WMS), forecasting (e.g. time-series forecasting of waste generations with related variables such as population, income level, demographics), and integrated modelling systems (e.g. improving synergy among sub-systems/functionalities such as between waste generation and shipping or optimal capacity expansion for waste-to-energy and landfill facilities).

The second domain includes system assessment tools to evaluate WMS performance and seek for improvements and adaptations in response to the increasing challenges posed by regulations and the public. Most WMS assessment tools used in literature are Life Cycle Analysis (LCA), environmental impact assessment, risk assessment, strategic environmental assessment, sustainable assessment, socioeconomic assessment, material flow analysis, scenario development, and management information/expert system/ decision support system (Allesch & Brunner, 2014; Chang et al., 2011; Sandoval-Reyes et al., 2024).

We refer readers to Pires et al. (2011) for a more in-depth analysis of how these five engineering modelling approaches and nine assessment tools are used in the European WMS literature.

2.2 Studies of packaging WMS in response to the recycling crisis

WMS are inherently complex, intertwining with numerous other systems. To effectively analyse the impact of policies, this paper narrows its focus to packaging WMS. The assessment of the impact stemming from the escalating waste recycling crisis, provoked by a growing number of global disruptions, has been addressed in existing literature through both qualitative discussions and quantitative examinations.

Regarding qualitative discussions, Qu et al. (2019) study the impact of the waste ban on the global circular economy of solid waste, and suggest that for developed countries, their recycling industries with limited capacity and historic dependence on exporting would encounter challenges in the short run. In the long run, however, this could provide opportunities for the global circular economy, given that appropriate policy frameworks (e.g. Extended Producer Responsibility) are properly designed. Similarly, Morita and Hayashi (2018) recommend the policy makers in Japan to have suitable measures for more accurate data collection from recycling and processing routes of all plastics waste, along with the volume in each route. This type of data is critical to create strategies aiming to expand the domestic recycling capacity for plastic scrap within Japan. Reviewing the waste management situation in China before and after the CWB promulgation, Song et al. (2023) posit that the ban might stimulate some short-term negative impacts on local environments in both China and overseas such as increased landfills and fly-tipping behaviours.

Adopting a quantitative approach, Wen et al. (2021) use LCA to quantify the environmental impacts of changes in movements and treatment methods for 6 types of plastic waste across 18 countries in the aftermath of the CWB. They found that the ban has vastly improved four of the environmental impact indicators (i.e., fine particulate matter formation, freshwater ecotoxicity, human carcinogenic toxicity, and water consumption) in the short term. In the long run, to achieve global environmental sustainability, countries are advised to prioritise the gradual transition from export to domestic waste processing, and from landfill to recycling, which could save them an estimated eco-cost of about 1.5–3.2 billion euros. Likewise, Bourtsalas et al. (2023) and Bourtsalas (2024) also observe the environmental and public health benefits to both importing and exporting countries when reducing plastic waste exports and increasing domestic recycling, despite of higher capital costs required. Investigating the plastic waste flows from a combined production and consumption-based perspective, Huang et al. (2020) employ a set of environmental-economic models to analyse the impact of the ban on China and numerous countries. The research find that (1) China is one of the dominant controllers within the global trade networks of plastic waste, (2) the ban causes only low economic loss to China, (3) the ban results in a shortage in recycled materials in China, and (4) waste treatment facilities need to be ramped up in developed countries. Analysing the city-level local air quality in China after the execution of the import ban, Li and Takeuchi (2023) stress that the environmental impact of the ban get weaker in the long run, hence it is vital that policy makers support the transformation of the plastic waste recycling industry by adopting cutting-edge technologies.

2.3 Policies and recycling capacity

2.3.1 Innovation-focused policies (IFP)

Innovation is the use of new techniques, new methods, and new organisational forms (Kemp et al., 2000). From an economic perspective, innovation can drive down cost through better productivity (Thatcher & Oliver, 2001).

a. The current EU's practice.

In the EU Action Plan for the Circular Economy, innovation is acknowledged as a key driver for the transition from linear to circular economy, including the transformation of waste to high value-added products (European Commission, 2020b). Particularly, the EU's Eco-innovation Action Plan (EcoAP) has listed out 7 types of actions for sustainable innovations, which are regulation integration, supporting ideas commercialisation, setting standard and targets, funding, international cooperation, addressing skills gap, and promoting partnerships between public and private sector (European Commission, 2011). Since its adoption, the EcoAP has been targeting innovative SMEs, offering funding opportunities under COSME, Horizon 2020, and the LIFE programme, along with building the Enterprise Europe Network (EEN) for business matchmaking (European Commission, 2020b).

Following the EcoAP, the EU members have developed many initiatives and policies to support the innovation advancement in both direct and indirect ways. In terms of direct support, Germany, for example, provides more direct support in form of grant, innovation vouchers, loan and credit (Eco-innovation Observatory, 2019a). In contrast, Belgium is well-known for embedding eco-innovation and sustainability goals into industrial and economic policies by offering the provision of tax incentives/relieves for eco-innovation (businesses, R&D activity), and subsidies to allow companies to use expert services in the eco-conception of sustainable business models and processes (Eco-Innovation Observatory, 2019b).

b. Academic research.

Government policies targeting innovation advancements within the recycling industry has attracted many interests in the literature. These can be in the form of government financial subsidies specifically for research, development and deployment of green technologies (Li et al., 2021; Yu et al., 2021), a mix of financial and strict penalties (Huo et al., 2018b; Yalabik & Fairchild, 2011), and public campaigns to raise awareness towards green innovations (Huang et al., 2016; Li et al., 2021). Another approach to improve waste recycling innovation is through incentives supporting the integration and knowledge transfer between industries (Aldieri et al., 2019). However, the knowledge exchange initiatives often involve risks related to intellectual property which would demotivate firms to innovate. For that reason, policy makers were recommended to provide strong intellectual property rights such as patents to inventors (Bloom et al., 2019). To ensure the green innovation progress, it is noteworthy for policy makers to understand that economic policy uncertainties could significantly reduce the performance of green technology innovation, especially among non-state-owned and low-tech enterprises (Zhou et al., 2024).

2.3.2 Subsidy-focused policies (SFP)

a. The current EU's practice.

There are different forms of SFP, for example:

- Subsidy for the industry—forcing waste producers to partly contribute as a form of subsidy. One of the most popular policies in this regard is the Extended Producer Responsibility, where producers are obliged to bear some of the environmental costs associated with the treatment or disposing of a product. It can take out some burdens from recyclers, which has been recognised as the best practice among some of the most successful waste management economies, including Western Europe and Japan (D'ambrières, 2019).
- Public funds on separation collection systems—a large portion of recycling cost goes to the preparation phase, where the costly process of waste sorting and separation are required (Velzen et al., 2013). Most of these costs have been subsidised by local authorities in EU since 2008 when the Waste Framework Directive came into effect. Under this Directive, member states are obliged to invest and set up separation collection systems for household waste.
- Tax incentives—under the EU's New Circular Economy Action Plan released in 2020, Member States would be supported to provide subsidy in form of tax incentives for recyclers (European Commission, 2020b).

b. Academic research.

Compared to other waste management methods such as incineration or landfill, the cost of recycling is relatively high. Therefore, there were several attempts to drive down recycling cost by offering subsidies to the management of household plastic waste (Gradus et al., 2017), auto parts waste (Wang et al., 2014), lead-acid battery waste (Joshi et al., 2021), and general waste (Liu et al., 2021; Qiao and Su, 2021; Xu et al., 2019). Among the subsidy approaches, initial subsidy for new joiners was evidenced to increase the number of remanufacturers, hence, to be the most suitable to be used at the initial stage of industry development. But when the industry develops to a certain extent, combining this with other subsidy policies aiming at waste collection and production activities are proved to be more effective (Wang et al., 2014). Separation is a costly stage within remanufacturing process for plastic packaging (Schyns & Shaver, 2021). To minimise this cost, policies to subsidise industrial-scale post-separation were proposed to replace source-separation by householders (Gradus et al., 2017). Reducing tax is another form of subsidy which has demonstrated its usefulness in helping remanufacturers reduce cost (Joshi et al., 2021). Even though it is widely believed that remanufacturers should be the sole recipient of government subsidy in order to increase remanufacturing activities, (Mitra & Webster, 2008) found that sharing certain fraction of that subsidy to the manufacturers would yield the most benefits. In particular, subsidy sharing encourages manufacturers to come up with more suitable product design for remanufacturing, as well as be more willing to accept the return of end-of-life products.

2.3.3 Market-based policies (MBP)

a. The current EU's practice.

The sustainability of remanufacturing industry heavily relies on the market demand. Many countries have adopted regulatory schemes to stimulate the demand of secondary materials. For example, one of the longest-serving and most successful one is the EPR regulation, which requires retailers and packaging producers to accept and recycle used packaging from consumers (Retail Council of Canada, 2020). Another MBP example is the tradable recycling credit scheme, which aims to boost the market demand by imposing a minimum share of recycled content in a particular material (Söderholm & Ekvall, 2020). For instance, under the EU's single-use plastics Directive released in 2019, plastic bottles will have to contain at least 25% of recycled content by 2025 and 30% by 2030 (European Commission, 2019). Apart from imposing regulations, governments can also initiate public awareness campaigns to shift consumers demand towards sustainable products, which would in turn pressure the packaging manufacturers to utilise more recycled materials in production (KfW, 2019).

b. Academic research.

In the literature, MBP has also been explored (Conrad, 2005; Costa et al., 2019; Ling & Xu, 2021). It is argued that tightening emission regulations could force retailers to undertake their green marketing efforts, which in turn boost market demand (Hong & Guo, 2019; Rahbar & Abdul Wahid, 2011). Direct government support for supply chain members is also recommended to increase their capitals to promote green products (Huo et al., 2018b). Consumption subsidy is another way which could encourage consumers to purchase recycled products (Ma et al., 2013). In China, the Remanufacturing Product Pilot Program which subsidies consumers to purchase remanufactured auto part has proved to be effective (Chang et al., 2016).

2.4 System dynamic (SD) modelling of WMS

SD modelling has been widely adopted in the field of reverse logistics and closed-loop supply chains (CLSC). For example, Zhou et al. (2017) develop a SD model to investigate the impact of product return and remanufacturing uncertainty on the dynamic performance of the CLSC system. Ulli-Beer et al. (2007) and Joh and Adolph (2006) use SD approach to reveal the dynamic interactions between recycling behaviours to different contextual and human factors. Besiou et al. (2012) develop a SD model to explore the impact of scavenging activities on the WEEE (Waste Electrical and Electronic Equipment) product recovery system in Greece under three regulatory scenarios: (1) environmental (natural resource availability, pollution from illegal scavenging activities), (2) economical (profitability of the whole system), and (3) social (sum of unemployed scavengers).

SD models of packaging WMS can also be found in the literature. For instance, Dace et al. (2014) is one of few studies using this approach to investigate the influence of certain policies and eco-design advancement on the volume of used packaging materials, and the amount of waste being generated, recycled and landfilled. Adopting the same approach, a more recent paper, Dhanshyam and Srivastava (2021) evaluate the effectiveness of different policy mix (among developing kerbside facilities, charging disposal fee, and providing recycling subsidy) in mitigating the plastic waste issue in India.

2.5 Research gap

In summary, our literature review shows that although previous studies have focused on investigating the global and local impact of waste import bans and revealing the opportunities and challenges of expanding domestic recycling capacity to respond to the disruptions, actionable recommendations to support policy making remain limited. In addition, there is a lack of studies that investigate the design and implementation of different recycling capacity building strategies (i.e. IFP, SFP, and MBP) in a holistic dynamic point of view.

Therefore, to fill the gaps, our study uses SD modelling approach to build a dynamic EU recycling system for packaging waste. Based on this model, different simulations are conducted to assess the effectiveness of individual policies, and hence suggesting the optimal policy mix for the domestic recycling expansion.

3 Methodology

3.1 Conceptual model

To better capture the interconnections between different components within recycling system, and the impacts of the three types of policies on capacity expansion from the discussion above, a conceptual model (causal loop diagram) is developed (Fig. 1). Causal loop diagram is the representation of the causal relationships between different variables in the system. The causality and its direction are shown by the directed arrow starting from the independent variable to the dependent variable. The polarity (+) or (−) on the arrow embodies the sign of the effect. The (+) sign implies that the variables change in the same direction; otherwise, they change in the opposite way.

The main components of this causal loop diagram are adapted from the simple representation of the feedback structure of Adam Smith's Invisible Hand (The Wealth Nations) by

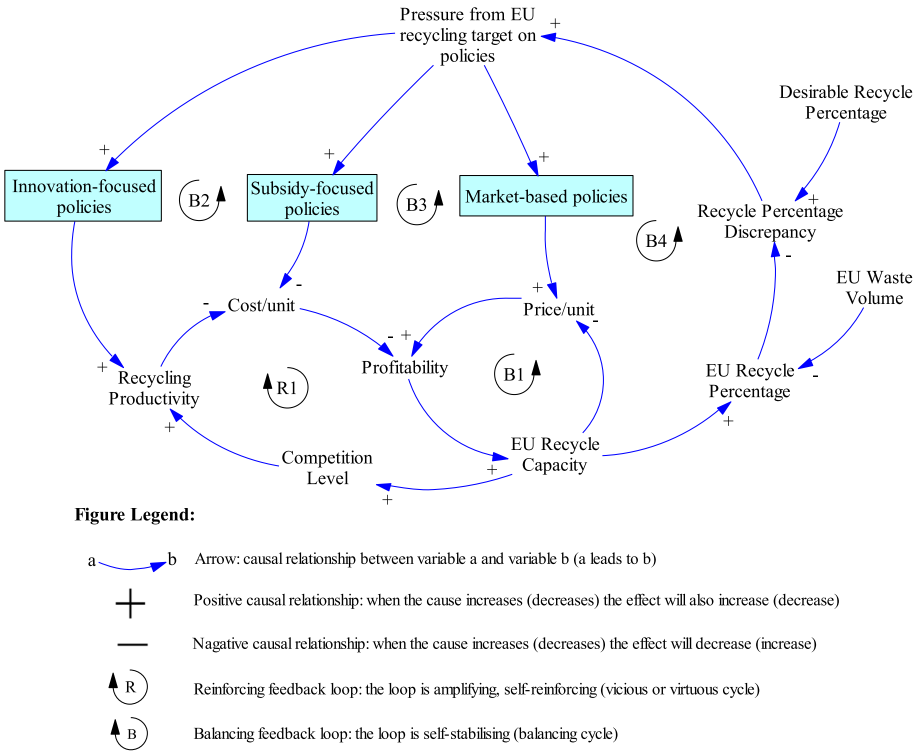


Fig. 1 The proposed conceptual model—causal loop diagram (*Source*: Authors)

Sterman (2000). These include the causal effects between cost/unit, price/unit, profitability, and supply. Among these, the EU supply of recycled materials/products (or recycle rate) is only constrained by the recycling capacity of the whole industry. Therefore, "*EU Recycle Capacity*" in this diagram, within the context of this paper, is the representation of supply in Sterman's diagram. Here is the detailed explanation of the conceptual model in Fig. 1.

- *B1–Balancing Loop*: EU Recycle Capacity increases → Price/unit decreases → Profitability drops → EU Recycle Capacity decreases.

Profitability is the main driver for the supply of the secondary material market. When profitability increases, new entrants are attracted while existing producers are encouraged to expand its recycling capacity. With more producers in the market, the competition becomes tougher, which could eventually drive down the selling price of recycled materials/products. As the price shrinks, so does the profitability, thus forming a balancing loop (**B1**) in Fig. 1.

- *R1–Reinforcing Loop*: EU Recycle Capacity increases → Competition Level increases → Recycling Productivity increases → Cost/unit drops → Profitability rises → EU Recycle Capacity increases.

At the same time, when recycle capacity increases as a result of the increased profitability, the competition level in the market also rises. According to the economic theory of "the escape-competition effect" (Thatcher & Oliver, 2001), the pressure from rising competitions forces firms to invest more in innovation to improve productivity. Cost is driven down when productivity increases, which in turn increases profitability. This forms a reinforcing loop (**R1**).

- *B2–Balancing Loop***:** EU Recycle Capacity decreases → EU Recycle Percentage decreases → Recycle Percentage Discrepancy increases → Pressure from EU recycling target on policies increases → Policies promote Demand for Recycled Materials increases → Price/unit rises → Profitability improves → EU Recycle Capacity improved.

As the recycling capacity in EU shrinks, given that the annual waste volume generated in the EU remains constant, the recycle percentage also drops. The lower the recycle percentage, the further it is from the EU's desirable recycling target (70% of EU's packaging waste from all streams to be recycled by 2030—(Eurostat, 2021)), hence the larger the recycle percentage discrepancy. When the recycle percentage discrepancy widens, pressure will mount for the authorities to intervene the market with more aggressive policies to improve profitability, with the objective to close the gap between the actual recycle percentage and the desirable target. When these policies are aimed at boosting innovation, leading to a rise in productivity, the profitability would be improved because of a cost reduction, forming a balancing loop (**B2**).

- *B3 – Balancing Loop*: EU Recycle Capacity reduces → EU Recycle Percentage decreases → Recycle Percentage Discrepancy increases → Pressure from EU recycling target on policies increases → Policies provide Subsidy for Recyclers rises → Cost/unit drops → Profitability improves → EU Recycle Capacity increases.

When the policies aim to provide more subsidies for recyclers, the profitability would also be improved, thanks to a drop in recycling cost. This forms another balancing loop (**B3**).

- *B4–Balancing Loop***:** EU Recycle Capacity reduces → EU Recycle Percentage decreases → Recycle Percentage Discrepancy increases → Pressure from EU recycling target on policies increases → Policies improve Recycling Productivity via Innovation rises → Recycling Productivity improves → Cost/unit drops → Profitability improves → EU Recycle Capacity improves.

Finally, when the policies are aimed at promoting market demand for recycled materials, the profitability would be increased accordingly through growing selling price. This forms a final balancing loop (**B4**) of the conceptual model.

3.2 SD model of EU packaging recycle industry in the CWB context

The software used for developing the stock and flow diagram (SFD), simulating the policy effect, as well as optimising the policy mix is Vensim® DSS (Version 6.1c).

The CWB targets mainly unsorted mixed papers and post-consumer plastics which counts for a large portion of the packaging recyclable waste export in the EU. Hence, the SD model in this work will focus on the EU's domestic recycling industry for packaging waste to showcase the impact of the CWB on the whole WMS in the EU.

The SD modelling approach is adopted, which enables us to build computer simulations to represent the complex, real-world EU packaging recycling systems under CWB context. The what-if scenario-based simulations and optimisation will then be performed to analyse the dynamic behaviour and determine the optimal implementation of policy instruments for the capacity expansion plan.

The SD model including the SFD that we developed in this section is based on the conceptual model in Fig. 1 with the input from the data we gathered through secondary sources

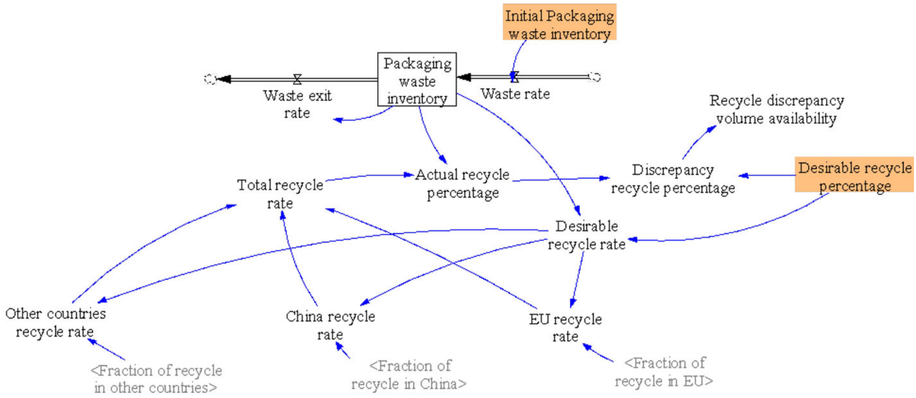


Fig. 2 The proposed EU recycling target sub-system (*Source*: Authors)

and interviews with stakeholders and key experts in SD, which will be explained in detail in Sect. 3.3.

While the CLD (Fig. 1) helps us understand the causal relationships between variables in the system, the SFD can capture their dynamic behaviours derived from the mathematical properties of the stock accumulation over time (Sterman, 2000). The variables used in the SFD can be classified into three categories: stock, flow, and auxiliary. The stock variable, represented by rectangular box, captures the accumulated level of inventory of a variable over time. The flow variable, represented by the valve icon, describes the changing rate of quantities from or to a stock and is the only variable which changes the stock level. Auxiliary variables are drawn without any icon. Like in the CLD, the arrows in SFD also represent the causality between variables. Finally, the clouds show a source of flows coming from outside of the model boundary.

To improve the visualisation, the full simulation model is divided into three SFDs representing three sub-systems within the EU recycling industry for packaging waste, namely "The EU recycling sub-system" (Fig. 2), "Total recycling capacity sub-system" (Fig. 3), and "EU recycling capacity sub-system" (Fig. 4).

3.2.1 Data collection

The data used as input for the SFD includes:

- Data related to the packaging waste generation and recycling activities across 28 country members of the EU were obtained from the EU's official statistics database (Eurostat, 2021).
- Data related to the waste ban (for example: which year the ban took into effect, starting from, then which year the waste ban extended to other countries, etc.) were accessed via numerous official government sources such as (World Trade Organization, 2017), and (European Court of Auditors, 2020a).
- Data related to the EU recycling industry (for instance: recycling cost per unit, price per unit of recycled materials, effect of EU recycle capacity on price per unit of recycled materials, etc.) were directly extracted or indirectly estimated from highly reliable sources such as official government websites, peer-reviewed academic papers, and industry reports.

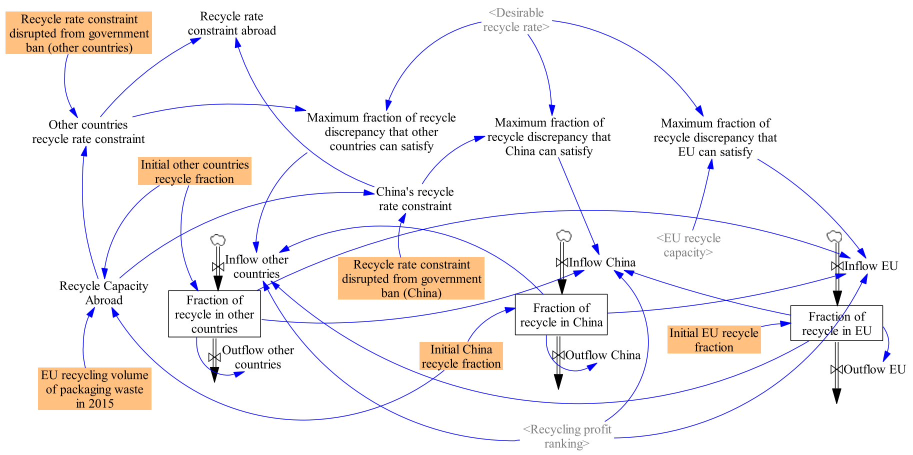


Fig. 3 The proposed recycling rate by region sub-system (*Source*: Authors)

For other data used in the model but not publicly available, assumptions are rigorously made. The detailed explanation of the model and its data used is discussed below.

3.2.2 The EU recycling target sub-system

Figure 2 represents high-level overview of the packaging waste recycling sector in the EU. The *packaging waste inventory* is the annual amount of packaging waste that are generated across the European members. The *initial packaging waste inventory* is set at 84,850 thousand tonnes, corresponding to the total volume of packaging waste generated in the EU in 2015 (Eurostat, 2021). The *total recycle rate* is assumed to be the accumulation of three sources: the rate comes from domestic recycle facilities in EU (*EU recycle rate*); the rate of waste being exported and processed in China (*China recycle rate*); and the rate of waste being exported and processed in other countries (*Other countries recycle rate*). All the recycle rates across three regions are controlled by their respective fraction of *total recycle rate* and the *desirable recycle rate*, which is governed by the *desirable recycle percentage* targeted by the European Commission at 70% (European Commission, 2020a). Please refer to Table 7 for the full list of data explanation for this sub-system. Equation 1–14 are mathematical expressions associated with variables within this sub-system in Fig. 2.

$$Actual\ recycle\ percentage = \frac{Total\ recycle\ rate}{Packaging\ waste\ inventory}(Units: dimensionless) \tag{1}$$

$$China\ recycle\ rate = ACTIVE\ INITIAL\ (Desirable\ recycle\ rate \times Fraction\ of\ recycle\ in\ China, 0)\ (Units: thousand\ tonnes) \tag{2}$$

$$Desirable\ recycle\ rate = Desirable\ recycle\ percentage \times Packaging\ waste\ inventory\ (Units: thousand\ tonnes) \tag{3}$$

$$Discrepancy\ recycle\ percentage = Desirable\ recycle\ percentage - Actual\ recycle\ percentage\ (Units: \mathrm{dim}\,ensionless) \tag{4}$$

$$EU\ recycle\ rate = ACTIVE\ INITIAL\ (Desirable\ recycle\ rate \times Fraction\ of\ recycle\ in\ EU, 0)\ (Units: thousand\ tonnes) \tag{5}$$

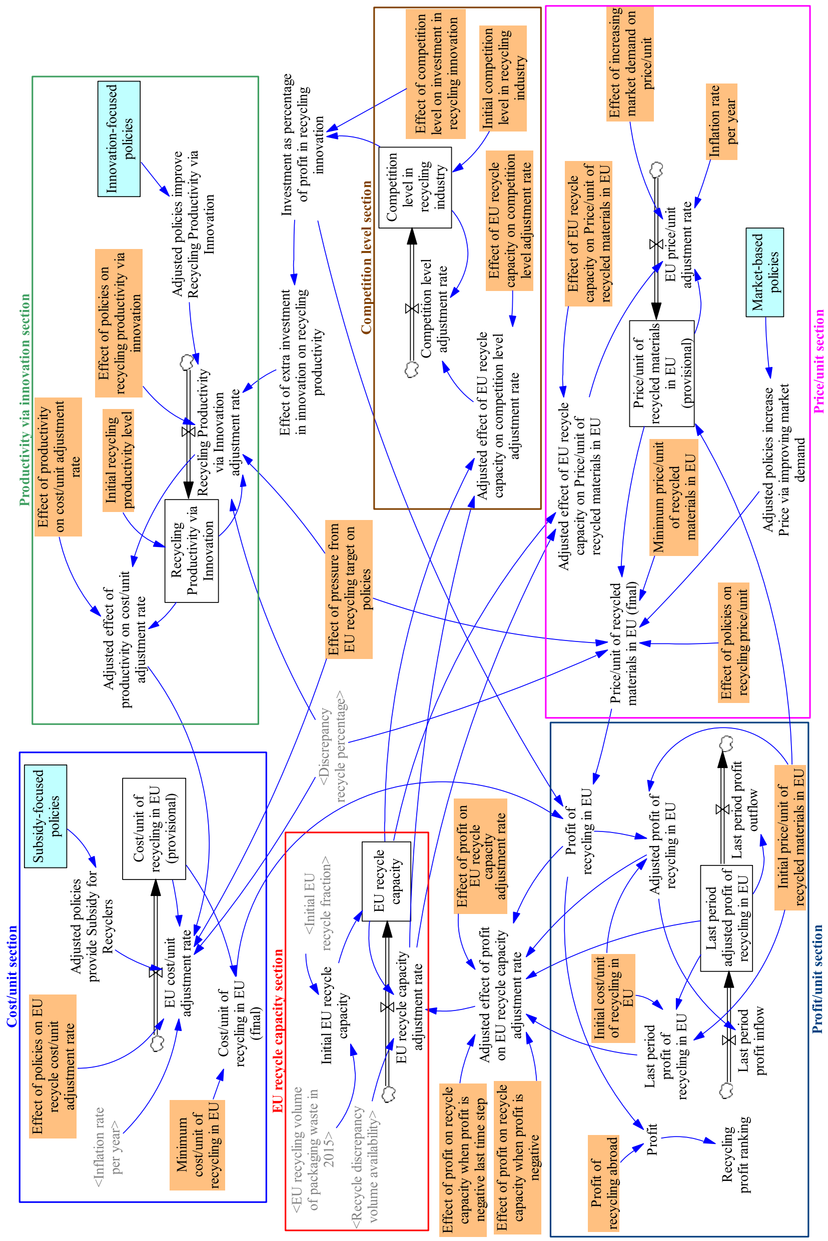


Fig. 4 The proposed EU recycling capacity sub-system (*Source*: Authors)

$$Fraction\ of\ recycle\ in\ China = Initial\ China\ recycle\ fraction + \int[Inflow\ China - Outflow\ China]dt \quad (Unit : \text{dim}\,ensionless) \tag{6}$$

$$Fraction\ of\ recycle\ in\ EU = Initial\ EU\ recyclefraction + \int[Inflow\ EU - Outflow\ EU]dt \quad (Units : dimensionless) \tag{7}$$

$$Fraction\ of\ recycle\ in\ other\ countries = Initial\ other\ countries\ recycle\ fraction + \int[Inflow\ other\ countries - Outflow\ other\ countries]dt \quad (Units : \text{dim}\,ensionless) \tag{8}$$

$$Other\ countries\ recyle\ rate = ACTIVE\ INITIAL\ (Desirable\ recycle\ rate \times Fraction\ of\ recycle\ in\ other\ countries, 0) \quad (Units : thousand\ tonne) \tag{9}$$

$$Packaging\ waste\ inventory = Waste\ rate + \int[Waste\ rate - Waste\ exit\ rate]dt \quad (Units : thousand\ tonnes) \tag{10}$$

$$\text{Re}\,cycle\ discrepancy\ volume\ availability = IF\ THEN\ ELSE\ (Discrepancy\ recycle\ percentage > 1e - 005, 1, 0) \quad (Units : \text{dim}\,ensionless) \tag{11}$$

$$Total\ recycle\ rate = China\ recycle\ rate + Other\ countries\ recyle\ rate + EU\ recycle\ rate (Units : thousand\ tonnes) \tag{12}$$

$$Waste\ exit\ rate = Packaging\ waste\ inventory (Units : thousand\ tonnes) \tag{13}$$

$$Waste\ rate = Initial\ Packaging\ waste\ inventory\ (Units : thousand\ tonnes) \tag{14}$$

3.2.3 Recycling rate by region sub-system

The SD model describing the fraction of recycle rate across three regions (the EU, China, and other countries) can be seen in Fig. 3. For cohesion and clarity purpose, the full list of equations of this sub-system is moved to Table 5.

As can be seen in Fig. 3, the fraction of recycle in each region is subject to its profitability ranking, government restrictions and recycle capacity constraint. Particularly, China, which is ranked with the highest recycling profitability, has taken the most fraction of recycling, whereas in contrast, EU and other countries are only responsible for much lower fraction of recycling due to limited recycle capacity and/or government waste ban.

The initial recycle fraction of each region is set (see Table 1) as the starting point for dynamic interaction during the simulation period.

3.2.4 EU recycling capacity sub-system

Figure 4 represents the stock and flow diagram of the system of the recycling capacity and profitability in China, other countries, and EU region. For clarity purpose, the full list of equations of this sub-system is moved to Table 6. The list of input data for this sub-system can be found in Table 2.

- EU recycle capacity section

The magnitude of the *EU recycle capacity adjustment rate* depends on profit of recycling in EU. As the profit increase, there is more incentive for the existing players within the industry to expand their capacities, leading to a higher *EU recycle capacity adjustment rate*.

Table 1 Values of exogenous variables (constants) in the EU recycling rate by region sub-system (Full data explanation can be seen in Table 8)

Parameter	Value	Data source
Initial other countries recycle fraction	%1.%2 (dimensionless)	Eurostat (2021)
Initial China recycle fraction	0.85 (dimensionless)	European Commission (2018b)
Initial EU recycle fraction	0.06 (dimensionless)	
EU recycling volume of packaging waste in 2015	55,810 (thousand tonnes)	Eurostat (2021)
Recycle rate constraint disrupted from government ban (China)	DELAY FIXED (1, 3, 0)	World Trade Organization (2017)
Recycle rate constraint disrupted from government ban (other countries)	DELAY FIXED (1, 6, 0)	European Court of Auditors (2020a)

At the same time, this makes the market more attractive for new entrants, which subsequently causing a larger recycle capacity adjustment rate in a longer run.

As the *EU recycle capacity* increase, so does the overall supply of the market which drags down the overall *Price/unit of recycling in EU (provisional)* via a negative effect on the *EU price/unit adjustment rate*. This creates a balancing loop (B1) in which the increase in *EU recycle capacity*, as a result of the discrepancy between the *actual recycle percentage* and the *desirable recycle percentage*, leads to the deterioration of the *Price/unit of recycling in EU (final)*, and eventually push the *EU recycle capacity* to drop.

- Profit/unit section

The *Profit of recycling in EU* is the difference between the *Price/unit of recycled materials in EU (final)* and the *Cost/unit of recycling in EU (final)*.

- Price/unit section

Apart from the *EU recycle capacity*, the price/unit of recycling in EU is also directly impacted by the market demand for recycled products via the *Effect of increasing market demand on price/unit*. This can be put simply as if the supply of recycled materials increases, the competition from the market would drive down the price of selling one unit of recycled packaging materials. Additionally, government can have certain influence on the increase of the price/unit through *market-based policies* aim at improving market demand for recycled materials. *Inflation rate per year* is considered here to reflect the annual currency depreciation. While the price/unit can decrease, there is a *minimum price/unit of recycled materials in EU* to prevent it from reaching unrealistic value of 0.

- Competition level section and recycling productivity via innovation level section

There is a direct causal effect between the *EU recycle capacity* and *Competition level in recycling industry*. The changes in the latter are proportional to the changes in the previous stock. The *competition level in recycling industry* in turn encourages the investment in innovation on recycling productivity, hence the actual productivity adjustment rate. As accumulated over time, this would result in higher recycling productivity. Apart from the mentioned, this stock also benefits from the *innovation-focused policies* aiming to improve recycling productivity through innovation.

- Cost/unit section

Table 2 List of exogenous variables in the EU recycling capacity sub-system (Full data explanation can be seen in Table 10)

Parameter	Value	Source
Inflation rate per year	0.048 (dimensionless)	The World Bank (2019)
Minimum price/unit of recycled materials in EU	0.0001 (USD)	
Effect of policies on price/unit of recycled materials	$y = \frac{x}{20}$ (dimensionless) where policy point as x and price/unit of recycled materials as y	
Initial price/unit of recycled materials in EU	234 (USD)	Da Cruz et al. (2014)
Initial cost/unit of recycling in EU	308 (USD)	Da Cruz et al. (2014)
Profit of recycling abroad	China: 100 (USD); Others: 70 (USD)	
Effect of increasing market demand on price/unit	0.07 (dimensionless)	Exal and BCG (2019)
Effect of EU recycle capacity on price/unit of recycled materials in EU	0.06 (dimensionless)	Busso and Galiani (2019)
Effect of profit on EU recycle capacity adjustment rate	0.25 (dimensionless)	Mansikkasalo et al., (2014)
Initial competition level in recycling industry	1 (dimensionless)	

Table 2 (continued)

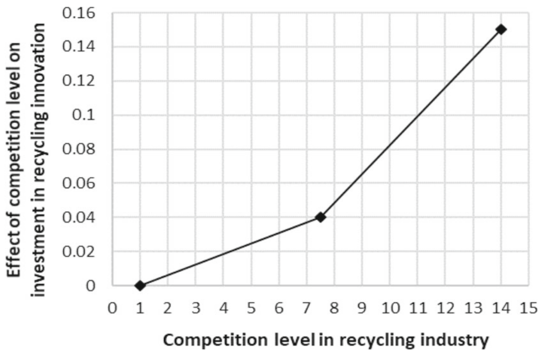
Parameter	Value	Source
Effect of competition level on investment in recycling innovation		Aghion et al. (2018)
Effect of EU recycle capacity on competition level adjustment rate	1 (dimensionless)	

Table 2 (continued)

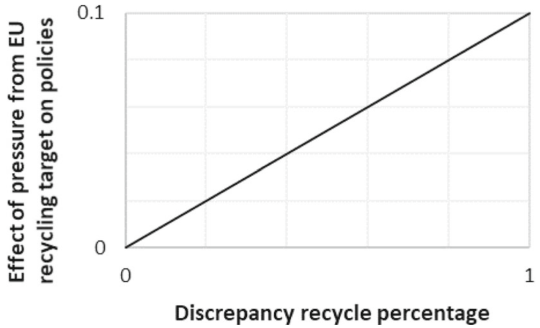
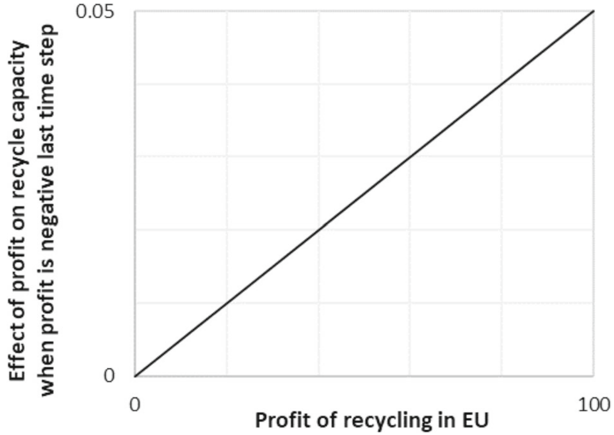
Parameter	Value	Source
Effect of pressure from EU recycling target on policies		
Minimum cost/unit of recycling in EU	0.0001 (USD)	
Effect of policies on recycling productivity via innovation	$y = \frac{x}{20}$ (dimensionless) where policy point as x and price/unit of recycled materials as y	
Effect of productivity on cost/unit adjustment rate	0.26 (dimensionless)[(a)]	Rogers (2006)
Effect of policies on EU recycle cost/unit adjustment rate	$y = \frac{x}{20}$ (dimensionless) where policy point as x and price/unit of recycled materials as y	
Initial recycling productivity level	1 (dimensionless)	

Table 2 (continued)

Parameter	Value	Source
Effect of profit on recycle capacity when profit is negative	− 0.01 (dimensionless)	Sterman (2000)
Effect of profit on recycle capacity when profit is negative last time step		

(a) Assumes that the growth rate of productivity is proportional to the reduction in cost/unit of production. According to Rogers (2006), using UK's ONS data from 1996 to 2003, for all manufacturing firms the estimated rate of return on productivity growth to R&D is between 19 and 33%. We take the average of these two numbers to get 26%

The EU cost level adjustment rate is not only being influenced by the changes in recycling productivity but also by the inflation rate (which reflects the depreciation in currency value), and by the *subsidy-focused policies*—which are the policies aiming to reduce the recycling cost/unit. The value of the *EU cost/unit adjustment rate* is the aggregation of the effects from all the listed above.

All of the policies that influence cost/unit, price/unit and productivity via innovation development are also amplified by the pressure that the local authorities face from meeting the EU recycle target on packaging waste (*Effect of pressure from EU recycling target on policies*).

3.3 Model validation

In order to ensure reliability of the model, validation must be carried out before simulation (Forrester & Senge, 1980). Number of tests were carried out, including (1) *Structure assessment*—checking the realistic nature of the interconnection between variables, and between variables and levels; (2) *Boundary adequacy*—the suitability of the selection of endogenous variables, or the boundary of the system built; (3) *Dimensional consistency*—checking whether the units of the models make sense, especially when many equations exist; (4) *Parameter assessment*—checking whether every parameter have real life meaning; and finally, (5) *Behavioural reproduction*—using the 2006–2018 data of recycling rate for packaging waste across the 28 EU members, obtained from (Eurostat, 2021), to verify the model's behaviours.

For both *structure assessment* and *boundary adequacy* test, feedbacks and opinions have been obtained in the Circular Economy workshop organised by Bexley council, UK, and "The Spectrum of Systems Approaches to Problem Solving: from Systems Engineering to System Dynamics to Systems Thinking" workshop organised by the System Dynamics Society. Remaining tests are run using built-in functions on Vensim. The result shows that the developed simulation model is stable and does not have any validation issues.

4 Result analysis

4.1 Simulation

Assuming the government has a limited and fixed budget over the simulation time, firstly, we need to understand the impact of each of the policies on capacity building; secondly, how to allocate this budget across the three policy types to maximise the performance of the model. Within this simulation, the fixed budget is represented by 10 points. Table 3 explains each case setting.

Apart from the governmental budgets being set based on Table 3, other parameters for the simulation are set as in Tables 1 and 2 above. The simulation results can be seen in Fig. 5. We focus particularly on the simulated periods between 2015 and 2040 as there is not much change in the trend line patterns across all 4 scenarios after year 2040.

Unlike SFP and MBP, of which their impact can be seen quickly after implementation, IFP takes much longer time to influence productivity level (Cooper & Perez, 2003; Gross et al., 2018; Grübler, 1998). Hence, we assume that there is an additional 3-year delay after the IFP are adopted. This reflects that any creation of innovations usually takes time, not in days or weeks but years.

Table 3 Summary of the scenario settings

Scenario	Description
Base	No points are awarded to any policy type, implying that the government does not have policies in response to the CWB. The performance of the system in this scenario is used as a benchmark for comparing the effectiveness of other policy scenarios
Innovation-focused	All 10 points of the governmental budgets are allocated towards IFP, while none is allocated to the other two policies
Subsidy-focused	All 10 points of the governmental budgets are allocated towards SFP, while none is allocated to the other two policies
Market-based	All 10 points of the governmental budgets are allocated towards MBP, while none is allocated to the other two policies

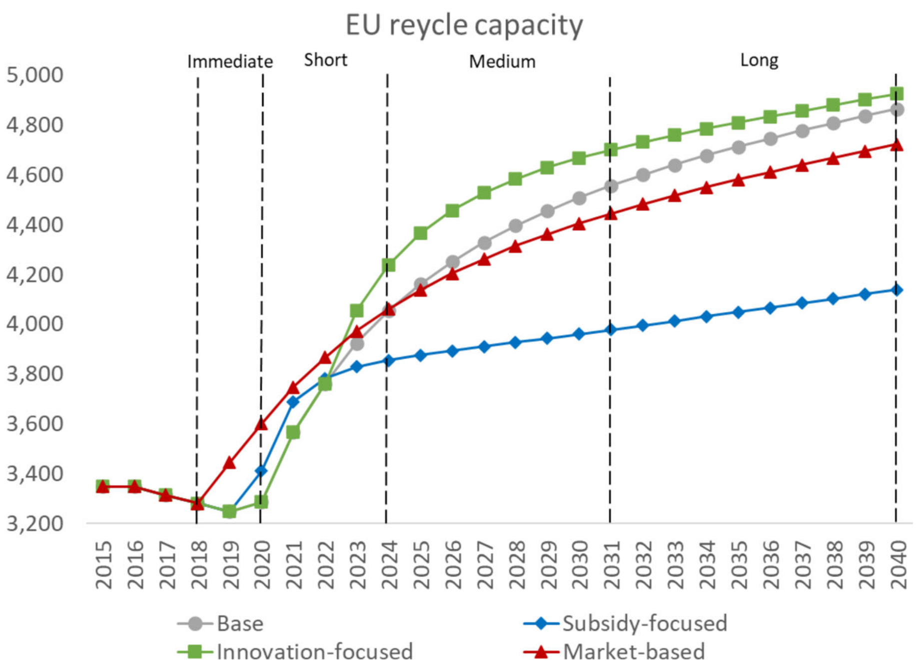


Fig. 5 Simulation results for the EU recycle capacity across all scenarios

4.1.1 The immediate term between 2018 and 2020

As can be seen in Fig. 5, the EU recycle capacity in the base scenario remains unchanged in the first 2 years since the CWB in 2018, which reaffirmed the urgency of having the policy incentives supporting the domestic capacity building to make up for the sudden capacity loss from China.

Among three types of governmental policies, the MBP provide the fastest response to the CWB disruption by accelerating the expansion of the EU recycle capacity instantly from

2018. The capacity building supported by the SFP also quickly take into effect from 2019. As expected, the IFP have not had any impacts yet due to the 3-year delay in effect.

There is plenty of empirical evidence showing the high performance of SFP and MBP in the capacity building of WMS over the short term. SFP (eg. Tax incentives under the EU's 2020 New Circular Economy Action Plan, public funds on separation collection systems under the EU 2018 Waste Framework Directive, and Belgium's Green Dot fee scheme) can provide direct financial supports that help drive down the cost and increase the profit margins of recyclers instantly, thereby encourage them to expand their recycling operation for higher capacity. Likewise, through MBP, the growing pressure from the compliance of law enforcement (eg. EPR and tradable recycling credit scheme) and the public awareness campaign (eg. German's KfW Dossier campaign—Why we need circular economy) can also force the company to act responsibly and sustainably by consuming more recycled materials/products, thus lifting the recycling capacity to meet the increased demand.

4.1.2 The short term between 2020 and 2024

In the next 4 years, the MBP continues to play the pivotal role in the EU recycle capacity expansion plan, whilst the effectiveness of the SFP is levelled off. In 2022, the capacity level in SFP is at the same level as in the base scenario whereby there are no specific policy incentives in use. From 2022 onwards, the SFP is totally outperformed by the rest of the scenarios. This further confirms that the recycling industry is a demand-driven business; therefore, to sustain its viability over the longer run, the government should rely on the MBP to enhance public green awareness and create real demands in the secondary market, rather than over rely on the direct monetary subsidy.

As opposed to the slow response in the immediate term, the impact of IFP seems to be much more noticeable in the short term, as its capacity level quickly exceeds the SFP, the base scenario and the MBP in 2023. This can be explained by the indirect causal relationship that innovation level has with the profitability. Unlike the other two policy types, it would take sometimes (about 2 years) before the benefit the IFP can be well-observed. However, after that, the innovation advancement would significantly increase productivity rate, hence profitability, which eventually lead to the fast and prolonged growth in capacity level, as can be seen in Fig. 5 for the period between 2020 and 2024.

4.1.3 The medium term between 2024 and 2031

Not much have changed in the trend lines between 2024 and 2031 apart from the fact that MBP loses its momentum and is overtaken by the base scenario from 2024. As compared to the previous term, the pace of capacity growth due to the IFP is much slower over the mid-term, though it remained the most effective policy type for recycle capacity building, followed closely by the base scenario. The SFP continues to experience the sluggish growth in the capacity, as compared to the base scenario and the other two policies.

The slowdown in the IFP-based capacity growth could be explained as follows. When the productivity grows exponentially, thanks to the innovation advancement, the recycling cost decreases and gets close to 0 very quickly. When the innovation reaches a certain level of maturity, its perceived benefit towards cost reduction and profit increase is weaken over time, thereby flattening the capacity growth driven by the IFP.

4.1.4 The long term between 2031 and 2040

Following the same trend in the medium term, the IFP-led capacity growth continues to be the highest over the long term, and then gradually faded away when its capacity level gets closer to that of the baseline scenario. However, it is noteworthy that the IFP scenario in this model is simulated based on the perceived benefits of innovation over the increasing productivity of recyclers. Therefore, it is still possible for the government to encourage the capacity building in the recycling industry through IFP after 2040 if the focus is shifted to other valued-added benefits of innovation (e.g., eco-design of new products) rather than just productivity improvement.

4.2 Optimisation of EU policy mix

After understanding the effectiveness of each policy type in the expansion of the EU recycling capacity, our next attempt is to find the best course of governmental actions in response to the disruptive event of the CWB. Like other industries, the EU policy makers in the recycling industry also operate under limited budget and resources, therefore, the budget allocated for each type of policy incentives is subject to be optimised.

Assumingly, the EU governmental budget and resources available for expanding the domestic recycling capacity is limited to 10 points, our aim is to find the optimal proportion of the governmental budget allocated to each of the three studied policy types (IFP, MBP, and SFP) in order to maximise the total EU recycle capacity accumulated over the 25-year simulated period between 2015 and 2040. The optimisation problem is solved by Powell hill climbing algorithm integrated in the built-in solver in Vensim® DSS for Windows Version 6.1c. The values of parameter setting for the optimisation is the same as in the simulation as discussed earlier.

Figure 6 shows the dynamic behaviour of the EU recycle capacity growth in different policy scenarios. The optimal solution was found with the budget mix of 84% government resources dedicating to IFP, 16% to MBP, and 0% to SFP. As can be easily seen, the EU capacity level in the scenario using the suggested optimal policy design significantly outperforms the other scenarios across the short, medium and long term.

This finding affirms that the most effective policy design for the EU packaging recycling capacity expansion is the one that can support both the supply side and demand side. It further highlights the paramount importance of innovation as the key enablers in the quest to achieve the EU's recycling target in the aftermath of the CWB. This also reflects the best practices across the world's leading countries with the highest recycling rate such as Japan, Netherland, and Germany. All of which have been the pioneers in adopting cutting-edge technological innovations in recycling operations.

4.3 Sensitivity analysis

This section aims to examine how the optimal solution of the policy mix varies according to changes in the ratio of initial unit price and initial unit cost (initial P/C ratio) which represents different recycling situations in the EU with regard to the industry's profitability. This also validates the reliability of the developed model to see if it responds in a reasonable way to parameter changes.

Particularly, changes to the initial P/C ratio can be done in two ways. The first way is we incrementally change the initial unit price while keeping the initial unit cost at the EU average

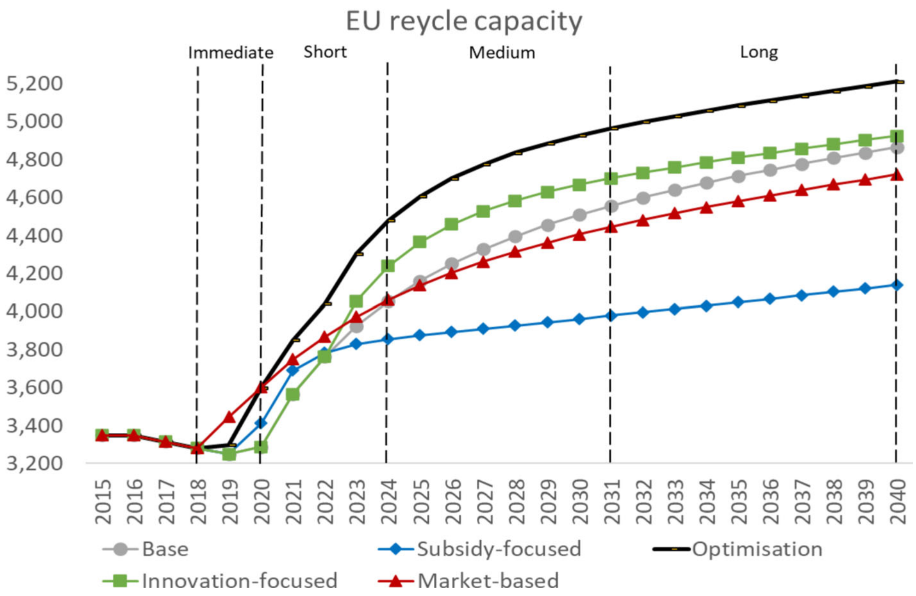


Fig. 6 Optimisation results compared to other scenarios

value of €308. Likewise, the second way is to incrementally change the initial unit cost while keeping the initial unit price at the EU average value of €234. For other parameters, we keep the value as they are in the optimisation setting in Sect. 4.2. The result of the optimal policy mix and the cumulative capacity achieved from two approaches can be seen in Figs. 7 and 8, respectively.

From the results, it is worth mentioning that even though the government has a budget of 10 points to allocate into the three policies, the maximum cumulative capacity in each scenario is not always being achieved by spending all government budget. This can be demonstrated at the initial P/C ratio level of 0.2, 0.3, 0.5, and 4.5 in Fig. 7, as well as 0.2 in Fig. 8.

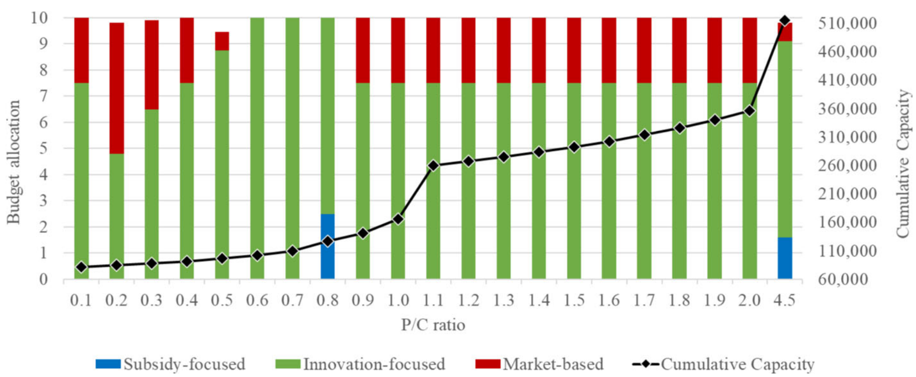


Fig. 7 Analysis 1-Changes in optimal policy mix and cumulative capacity when initial unit price varies, and initial unit cost is fixed at the EU average value (€308)

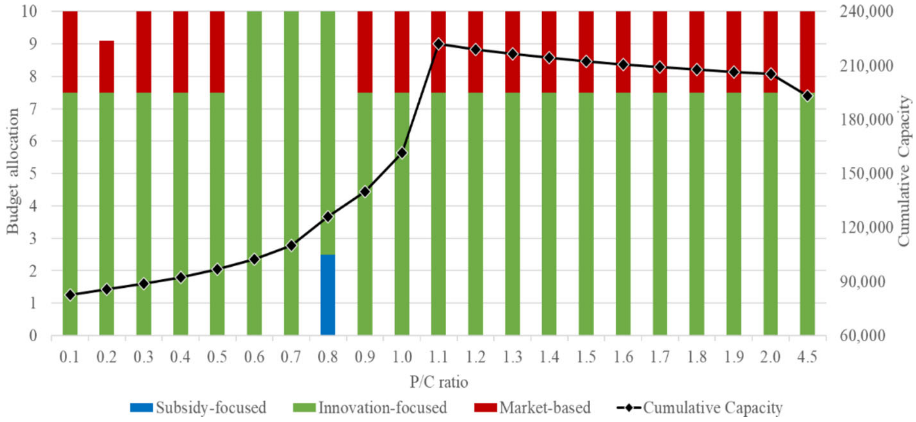


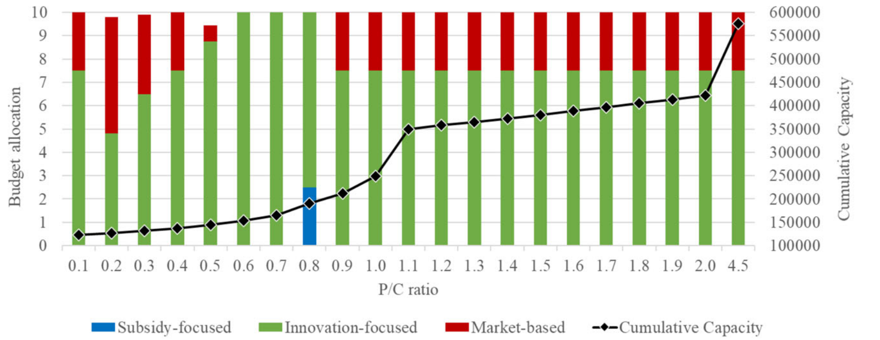
Fig. 8 Analysis 2-Changes in optimal policy mix and cumulative capacity when initial unit cost varies, and initial unit price is fixed at the EU average value (€234)

As can be seen in Fig. 7, for countries with loss-making recycle industries (the initial P/C ratio lower than 1.0), the optimal solution for the policy mix is relatively sensitive to the change of initial unit price. Particularly, looking at cases with the ratio level between 0.2 and 0.8, it can be observed that countries with higher initial unit price are suggested to invest more on IFP and SFP than MBP in order to reduce unit cost that elevates the recycle profitability and capacity. Nevertheless, the optimal solution becomes insensitive to the initial unit price changes when the recycle industry starts making profits (see P/C ratio between 0.9 and 2.0). Interestingly, for countries enjoying highly lucrative recycle industries with high initial unit price (e.g., the initial P/C ratio at 4.5), the mix of all three policies is recommended and the huge uplift in the cumulative recycle capacity can be achieved accordingly.

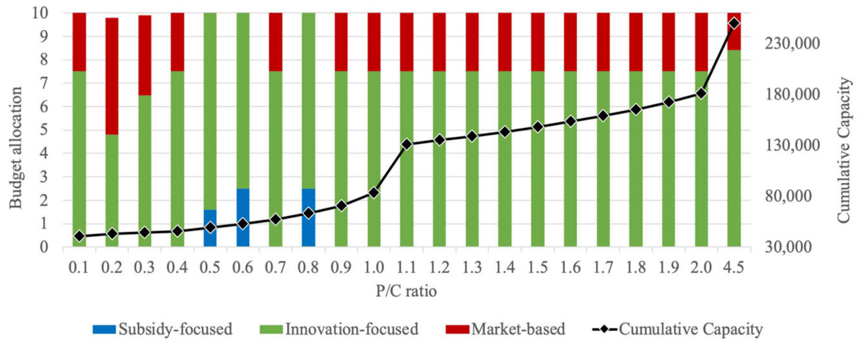
Compared to Fig. 7, we can see from Fig. 8 that the optimised policy mix seems less sensitive to changes in initial unit cost than changes in initial unit price. In addition, for those countries suffer from substantial losses due to extremely high recycling unit cost (the initial P/C ratio between 0.1 and 0.5), the deployment of the optimal policy mix only has minor impacts on capacity building. On the contrary, for countries with reduced recycle cost but limited profitability (P/C ratio ranging from 0.6 to 1.1), the benefit of using the optimal policy mix is much more obvious as the cumulative capacity rises significantly. However, when the P/C ratio is higher than 1.1 implying countries having low-cost and high-profit recycling industries, the effectiveness of the optimal policy mix in capacity building is levelled off or even causes an opposed effect.

Altogether, the analyses in Figs. 7 and 8 emphasise the pivotal role of innovation in recycling capacity building regardless of the profitability situation in each EU countries. The impact of MBP is also more definite than that of SFB in many cases.

In general, it is essential to know how the optimial results senstive to the initial value setting. When re-conducting Analysis 1 (Fig. 7) with different initial EU recycle capacity levels (Fig. 9), and different volume of generated waste levels (Fig. 10), the optimal policy mix across different P/C ratios stay relatively similar to that of the original analyses. The only variations are the policy mixes for P/C ratios ranging from 0.5 to 0.8 out of 21 ratios. This indicates that optimial policy mixes are robust against the initial values of EU recycle capacity and the volume of generated waste.



a. Sensitivity analysis: when initial EU recycle capacity increases by 50% to 5,025 thousand tonnes



b. Sensitivity analysis: when initial EU recycle capacity decreases by 50% to 1,675 thousand tonnes

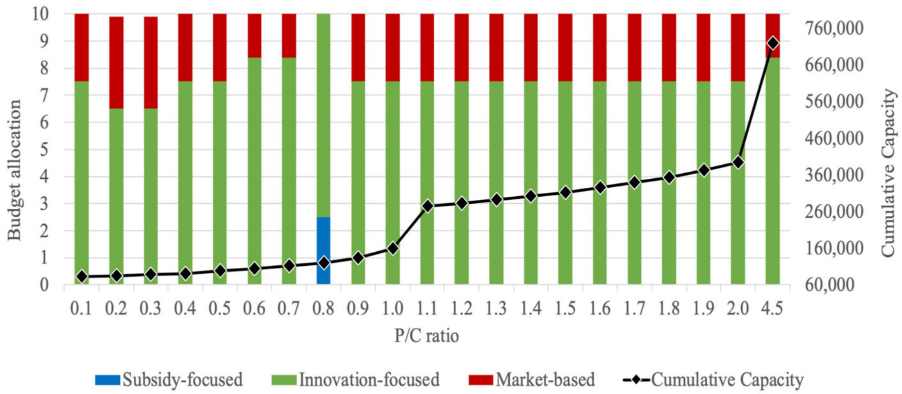
Fig. 9 Changes in optimal policy mix and cumulative capacity with different levels of initial the EU recycle capacity

Altogether, the optimal policy mixes corresponding to changes in unit price, unit cost, initial EU recycle capacity, and volume of generated packaging waste as shown in Figs. 7, 8, 9 and 10, respectively, provide a potential guidance for the EU member countries to build domestic recycling capacity taking into consideration unique conditions of each country.

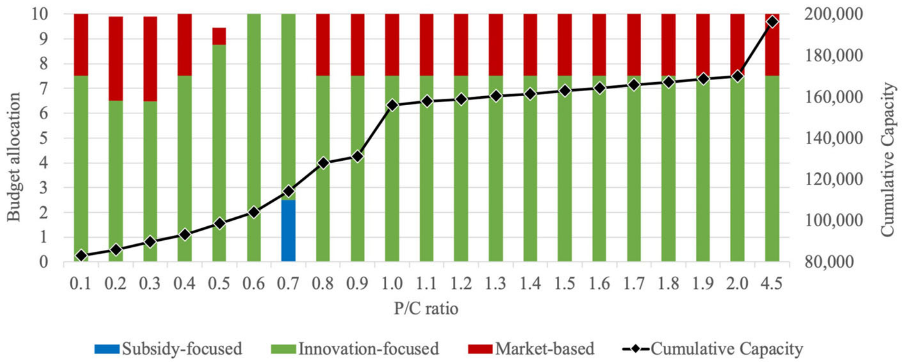
4.4 Verification of the results

To test the EU's guideline we proposed above, three EU member countries were chosen based on the availability of comparable data to run policy mix optimisations—France, Romania and Portugal. The data for *initial cost/unit* and *initial price/unit* for each country were obtained from Fig. 3 in Da Cruz et al. (2014), while the *packaging waste generated volume* and i*nitial capacity* were obtained from (Eurostat, 2021) for year 2015 in thousand tonnes.

As shown in Table 4, the optimal policy mix for France perfectly matches the EU's guideline for P/C ratio at 1.0. Meanwhile, at P/C ratio of 0.8, the optimal policy mix for Romania matches the scope of the EU's guideline when the volume of generated packaging waste decreases by 50% (Fig. 10b). Finally, for P/C ratio at 0.5 in Portugal case, although does not perfectly match (i.e. IFP + MBP as proposed by the EU's guideline), the optimal



a. Sensitivity analysis: when volume of generated waste increases by 50% to 127,275 thousand tonnes



b. Sensitivity analysis: when volume of generated waste decreases by 50% to 42,425 thousand tonnes

Fig. 10 Changes in optimal policy mix and cumulative capacity with different levels of generated waste

policy mix for this country still reflects the EU's guideline in a sense where IFP accounts for the majority of government budget. This shows that in reality, the best mix of policy does not only rely on the P/C ratio, but also could be influenced by other factors. Therefore, there would be no one-fit-all solution. Each member country should take into account their respective unique conditions in deciding the most effective policy mix.

Table 4 Optimal policy mix for France, Romania, and Portugal

Scenario	P/C ratio	Packaging waste generated volume	Initial capacity	Subsidy	Innovation	Market	Cumulative capacity	In line with proposed EU guidance
France	1.0	12,469	490	0	7.5	2.5	22,474	Yes
Romania	0.8	1397	47	0	7.5	2.5	1533	Yes
Portugal	0.5	1585	54	1.6	8.4	0	1618	Partly

5 Discussion of implications

Based on the result analysis above, our findings suggest the EU to allocate the majority of their governmental budget (up to 84%) on IFP and a smaller, but still significant portion (up to 16%) to MBP. This budget allocation framework is proposed to ensure the EU achieves the deliberate balance between the short-term market stabilisation in response to the waste bans and the long-term transformation of its domestic recycling capacity for environmental sustainability and economic growth. Our innovation-heavy budget can be economically, environmentally and socially justified.

From economic perspective, increasing IFP budgets may be appealing. Studies show that compared to high-carbon innovations, low-carbon innovations tend to generate higher knowledge spillovers which lead to broader applications across the entire economy (Dechezleprêtre et al., 2013). Therefore, they have greater economic benefits and higher social values to partly or even fully offset the cost of policy changes. To the EU, innovation is particularly crucial for enhancing its global leadership in recycling technologies, driving long-term economic growth through increased productivity and creating new opportunities for exports. On the other hand, MBP should not be neglected as policies like subsidies, ERP scheme or carbon credit help stabilise the sector in the short-term after the CWB shocks by boosting immediate demand and strengthening market mechanism for recycled materials. However, overreliance on those market-based instruments alone without sufficient investment on innovation may limit potentials for long-term economic growth and competitiveness as markets often demand for innovative, cost-effective solutions to truly thrive. In fact, economists found that MBP provides greater incentives for innovation than command-and-control policies (e.g., technology standards or performance requirements) by rewarding firms for the continuous improvement in their decarbonisation efforts (Dechezleprêtre et al., 2016).

From the environmental rationale, our proposal reflects the urgent need for the EU to handle its own waste in the new global recycling landscape set by the waste bans. Indeed, without developing cutting-edge recycling technologies such as automatic sorting system or chemical recycling, the EU will struggle to meet its recycling and landfill target. Additionally, empirical research has implied that effective implementation of technological innovations is a driving force in transitioning towards a climate-neutral, circular economy which is the EU goal by 2050 (Tanveer et al., 2022).

Fostering innovation can also generate significant social advantages by creating new job opportunities in research and development (R&D) and advanced manufacturing in waste management sector, thus aligning with the EU's broader goals for promoting technological leadership and social cohesion. Furthermore, advancements in recycling technologies can also help improve public health by reducing waste incineration which is a well-known source of air pollution and health risks (Kurniawan et al., 2021). On the contrary, the MBP or SFP-heavy budget framework may carry risks for market failure and job losses, especially in sectors like waste management where demand for recycled materials is largely fluctuated and heavily rely on the quality and quantity uncertainties of the collected waste and returned products (Nguyen et al., 2019).

The practical implications of our policy recommendation to policymakers and economic agents in the EU recycling industries can be discussion as follow:

- Implications for governments and policymakers

By gearing the majority of the budget toward innovation, governments must prioritise R&D investments, support public and private partnerships (PPPs), and ensure a regulatory environment that encourages technological advancement. They will need to work closely with research institutes, universities and private sectors to maximise the impact of IFP, including creating initiatives for knowledge sharing, technology transferring and innovation hubs.

Indeed, the EU's current regulatory framework is heavily aligned with our recommendations. In terms of IFP, programmes like Horizon Europe running from 2021 to 2027 with a budget of €95.5 billion are the key funding mechanism to support projects with eco-innovation, advanced material recovery, and automation in recycling (e.g. the CIRCULARISE Plastic project). The EU commitment to a net-zero circular economy, as seen in the Green Deal and the Circular Economy Action Plan (CEAP), also reflects the importance of driving long-tern sustainability through innovation.

Additionally, the shift towards innovation in recycling could foster job creations in high-tech sectors, leading to growing demands for new skill sets related to advanced materials, waste sorting technologies, and digital solutions for recycling flow tracking. Under this circumstance, governments need strategic investments in education and re-training programmes to manage the transition of workers from conventional, labour-intensive recycling jobs into the modern, higher-skilled recycling industry.

- Implications for firms in recycling industries

Firms that invest and adopt early innovative waste management technologies are better positioned to gain competitive advantages, capture market share and improve profitability over time, thereby offsetting the heavy initial costs of investment. In this regard, large recycling firms will likely align well with our IFP recommendation since they have capabilities and resource to invest heavily on R&D of new technologies like AI and machine learning (eg. Veolia's automated waste sorting system) or chemical recycling (eg. the breakthrough depolimerisation process of waste plastic developed by CARBIOS), thus enjoying economic benefits of being early adopters (Zhao et al., 2023). Conversely, small and medium enterprises (SMEs) face barriers to innovation due to capital constraints and workforce challenges caused by the skill mismatch of new recycling technologies. Therefore, they may struggle to benefit from IFP unless they receive more targeted support and public funding (e.g. EIC's Accelerator Programme, Seed fundings) to help them fully align with the IFP. For instance, the European Innovation Council (EIC) plays an active role in scaling up breakthrough innovations through its Accelerator Programme which is particularly relevant to deep-tech, SME recycling firms.

6 Conclusion

Major waste-importing countries like China and Malaysia have imposed waste bans which cause major disruptions to the waste supply chain and unprecedent challenges to the recycling industry. In response to these disruptive events, it is imperative for countries that are over-reliant on waste exporting like the EU to develop and execute expansion strategies for their domestic recycling capacities. Hence, this study aims to develop a SD-based simulation optimisation model to evaluate the effectiveness of three distinct policy types—innovation advancement, subsidies, and market promotion—in supporting the expansion of the EU's domestic recycling capacity for packaging wastes. Additionally, it proposes a guideline for implementing an optimal policy mix, tailored to the unique price-to-cost ratios of each EU member country.

The result shows that IFP can help accelerate the capacity at the fastest pace in the short term and become the main driver of capacity building in the medium to long term, although its effectiveness may not be perceived immediately as compared to SFP and MBP. By contrast, the MBP can provide the fastest response to the disruptive event by boosting up the capacity instantly in the immediate term. However, their effectiveness is faded away during the medium and long term. Finally, the capacity driven by the SFP also shows immediate improvement compared to the capacity under innovation-focused and no policy (baseline scenario) in the immediate and the first half of short term but was quickly overshadowed by all three other scenarios afterwards. The optimisation results suggested that the maximum capacity level can be achieved if policy makers could allocate most of its budget and resources (up to 84%) on IFP, and the rest 16% on MBP. In other words, our findings affirm that the EU's recycling sector is an innovation-led and demand-driven industry. Further scenario analyses also conducted under various conditions reveal that our optimisation results are robust against any changes, which was verified by the cases of Romania, Portugal, and France.

For theoretical contributions, our proposed model is amongst the few models offering the holistic picture of the waste recycling system. The model is versatile, allowing for adaptations to other types of waste streams and applicable to different nations. In addition, although the effectiveness of individual policies on recycling capacity expansions has widely studied, research on the combined effect of policy mixes, as examined in this paper, remains limited. Finally, our SD modelling approach enhances the current theoretical frameworks used for addressing disruptions in reverse logistics.

From the political perspective, our findings are vital as they give policymakers a steer on how to strategically allocate the government budgets to ensure the EU not only mitigates the immediate aftermath of the waste ban shocks but also reinforces its domestic recycling industry to support economic, environmental and social sustainability.

For practical contributions, this research provides the waste recycling practitioners with a deeper understanding of how different governmental policies perform dynamically in the immediate-, short-, middle-, and long-term. Considering the heavy capital investment required for recycling capacity expansions, our insights are crucial for both large firms and SMEs to be aware and adjust their business strategies accordingly.

Our study has some limitations which can be addressed in future research. Firstly, while this research provides evidences of how each type of policies impacts on EU domestic packaging recycling capacity development, the model itself inherits the limitation of SD methodology, for example, some causal relationships are hard to quantify and verify, hence empirical evidence and expert opinions are used. In future, data-driven policy design would be a research direction for more informed decision makings. Secondly, although our results show that the optimal policy mix outperform individual policies in addressing the shortage of EU's domestic recycling capacity, its effectiveness needs to be further assessed through industry feedback, survey, and case studies.

Appendix

See Tables 5, 6, 7, 8, 9, 10, 11 and 12.

Table 5 System dynamics model equations for recycling rate by region sub-system

Recycling rate by region sub-system (Fig. 3)
China's recycle rate constraint =
IF THEN ELSE ("Recycle rate constraint disrupted from government ban (China)" > 0, MIN ('Recycle rate constraint disrupted from government ban (China)', Recycle Capacity Abroad[China]), Recycle Capacity Abroad[China])
Units: thousand tonnes
Desirable recycle rate =
Desirable recycle percentage * Packaging waste inventory
Units: thousand tonnes
EU recycle capacity =
INTEG(IF THEN ELSE ((EU recycle capacity + EU recycle capacity adjustment rate) < 0, 0, EU recycle capacity adjustment rate), Initial EU recycle capacity)
Units: thousand tonnes
EU recycling volume of packaging waste in 2015 = 55,810
Units: thousand tonnes
Fraction of recycle in China =
INTEG(Inflow China•Outflow China, Initial China recycle fraction)
Units: dimensionless
Fraction of recycle in EU =
INTEG(Inflow EU•Outflow EU, Initial EU recycle fraction)
Units: dimensionless
Fraction of recycle in other countries =
INTEG(Inflow other countries•Outflow other countries, Initial other countries recycle fraction)
Units: dimensionless
Inflow China =
IF THEN ELSE (Rank Profit[China] = 3, Maximum fraction of recycle discrepancy that China can satisfy, IF THEN ELSE (Rank Profit[China] = 2:AND: Rank Profit[EU] = 3, MIN (Maximum fraction of recycle discrepancy that China can satisfy, 1•Fraction of recycle in EU), IF THEN ELSE (Rank Profit[China] = 2:AND: Rank Profit[Other] = 3, MIN (Maximum fraction of recycle discrepancy that China can satisfy, 1•Fraction of recycle in other countries), MIN (Maximum fraction of recycle discrepancy that China can satisfy, 1•Fraction of recycle in other countries•Fraction of recycle in EU))))
Units: dimensionless
Inflow EU =
IF THEN ELSE (Rank Profit[EU] = 3, Maximum fraction of recycle discrepancy that EU can satisfy, IF THEN ELSE (Rank Profit[EU] = 2:AND: Rank Profit[China] = 3, MIN (Maximum fraction of recycle discrepancy that EU can satisfy, 1•Fraction of recycle in China), IF THEN ELSE (Rank Profit[EU] = 2:AND: Rank Profit[Other] = 3, MIN (Maximum fraction of recycle discrepancy that EU can satisfy, 1•Fraction of recycle in other countries), MIN (Maximum fraction of recycle discrepancy that EU can satisfy, 1•Fraction of recycle in China•Fraction of recycle in other countries))))
Units: dimensionless
Inflow other countries =
IF THEN ELSE (Rank Profit[Other] = 3, Maximum fraction of recycle discrepancy that other countries can satisfy, IF THEN ELSE (Rank Profit[Other] = 2:AND: Rank Profit[China] = 3, MIN (Maximum fraction of recycle discrepancy that other countries can satisfy, 1•Fraction of recycle in China), IF THEN ELSE (Rank Profit[Other] = 2:AND: Rank Profit[EU] = 3, MIN (Maximum fraction of recycle discrepancy that other countries can satisfy, 1•Fraction of recycle in EU), MIN (Maximum fraction of recycle discrepancy that other countries can satisfy, 1•Fraction of recycle in China•Fraction of recycle in EU))))

Table 5 (continued)

Recycling rate by region sub-system (Fig. 3)
Units: dimensionless
Initial China recycle fraction = 0.85
Units: dimensionless
Initial EU recycle fraction = 0.06
Units: dimensionless
Initial other countries recycle fraction = 0.09
Units: dimensionless
Maximum fraction of recycle discrepancy that China can satisfy =
MIN (1, China's recycle rate constraint/Desirable recycle rate)
Units: dimensionless
Maximum fraction of recycle discrepancy that EU can satisfy =
MIN (1, EU recycle capacity/Desirable recycle rate)
Units: dimensionless
Maximum fraction of recycle discrepancy that other countries can satisfy =
MIN (1, Other countries recycle rate constraint/Desirable recycle rate)
Units: dimensionless
Other countries recycle rate constraint =
IF THEN ELSE ("Recycle rate constraint disrupted from government ban (other countries)" > 0, MIN ("Recycle rate constraint disrupted from government ban (other countries)", Recycle Capacity Abroad[Other]), Recycle Capacity Abroad[Other])
Units: thousand tonnes
Outflow China =
Fraction of recycle in China
Units: dimensionless
Outflow EU =
Fraction of recycle in EU
Units: dimensionless
Outflow other countries =
Fraction of recycle in other countries
Units: dimensionless
Profit[China] = Profit of recycling abroad[China]
Profit[Other] = Profit of recycling abroad[Other]
Profit[EU] = Profit of recycling in EU
Units: USD
Rank Profit[Recycle location] =
VECTOR RANK (Profit[Recycle location], 1)
Units: dimensionless
Recycle Capacity Abroad[China] =
Initial China recycle fraction * EU recycling volume of packaging waste in 2015
Recycle Capacity Abroad[Other] =
Initial other countries recycle fraction * EU recycling volume of packaging waste in 2015
Units: thousand tonnes

Table 5 (continued)

Recycling rate by region sub-system (Fig. 3)
Recycle rate constraint abroad[China] = China's recycle rate constraint
Recycle rate constraint abroad[Other] = Other countries recycle rate constraint
Units: thousand tonnes
"Recycle rate constraint disrupted from government ban (China)" =
DELAY FIXED (1,3, 0)
Units: thousand tonnes
"Recycle rate constraint disrupted from government ban (other countries)" =
DELAY FIXED (1,6, 0)
Units: thousand tonnes

Table 6 System dynamics model equations for EU recycling capacity sub-system

EU recycling capacity sub-system (Fig. 4)
Adjusted effect of EU recycle capacity on competition level adjustment rate =
(EU recycle capacity adjustment rate/EU recycle capacity) * Effect of EU recycle capacity on competition level adjustment rate
Units: dimensionless
Adjusted effect of EU recycle capacity on Price/unit of recycled materials in EU =
EU recycle capacity adjustment rate/EU recycle capacity * "Effect of EU recycle capacity on Price/unit of recycled materials in EU"
Units: dimensionless
Adjusted effect of productivity on cost/unit adjustment rate =
(Recycling Productivity via Innovation adjustment rate / Recycling Productivity via Innovation) * "Effect of productivity on cost/unit adjustment rate"
Units: dimensionless
Adjusted effect of profit on EU recycle capacity adjustment rate =
IF THEN ELSE (Profit of recycling in EU < = 0, Effect of profit on recycle capacity when profit is negative, IF THEN ELSE (Last period profit of recycling in EU < = 0, Effect of profit on recycle capacity when profit is negative last time step (Profit of recycling in EU), (Adjusted profit of recycling in EU•Last period adjusted profit of recycling in EU)/Last period adjusted profit of recycling in EU * Effect of profit on EU recycle capacity adjustment rate))
Units: dimensionless
Adjusted policies improve Recycling Productivity via Innovation =
DELAY FIXED (Policies improve Recycling Productivity via Innovation,6, 0)
Units: dimensionless
Adjusted policies increase Price via improving market demand =
DELAY FIXED (Policies promote Demand for Recycled Materials,3, 0)
Units: dimensionless
Adjusted policies provide Subsidy for Recyclers =
DELAY FIXED (Policies provide Subsidy for Recyclers,3, 0)
Units: dimensionless
Adjusted profit of recycling in EU =
Profit of recycling in EU•("Initial price/unit of recycled materials in EU"•"Initial cost/unit of recycling in EU") + 10
Units: USD
Competition level adjustment rate =
Competition level in recycling industry * Adjusted effect of EU recycle capacity on competition level adjustment rate
Units: dimensionless
Competition level in recycling industry =
INTEG(Competition level adjustment rate, Initial competition level in recycling industry)
Units: dimensionless
"Cost/unit of recycling in EU (final)" =
"Cost/unit of recycling in EU (provisional)" + "Minimum cost/unit of recycling in EU"Units: USD
"Cost/unit of recycling in EU (provisional)" =
INTEG("EU cost/unit adjustment rate", ("Initial cost/unit of recycling in EU"•"Minimum cost/unit of recycling in EU"))
Units: USD

Table 6 (continued)

EU recycling capacity sub-system (Fig. 4)
Discrepancy recycle percentage = Desirable recycle percentage•Actual recycle percentage
Units: dimensionless
Effect of competition level on investment in recycling innovation
([(0,0)-(16,0.11)],(0,0),(7.5,0.04),(14,0.11))
Units: dimensionless
Effect of EU recycle capacity on competition level adjustment rate = 1
Units: dimensionless
“Effect of EU recycle capacity on Price/unit of recycled materials in EU” = 0.06
Units: dimensionless
Effect of extra investment in innovation on recycling productivity =
Investment as percentage of profit in recycling innovation
Units: dimensionless
"Effect of increasing market demand on price/unit" = 0.07
Units: dimensionless
"Effect of policies on EU recycle cost/unit"
([(0,0)-(10,0.5)],(0,0),(10,0.5))
Units: dimensionless
"Effect of policies on price/unit of recycled materials"
([(0,0)-(10,0.5)],(0,0),(10,0.5))
Units: dimensionless
Effect of policies on recycling productivity via innovation
([(0,0)-(10,0.5)],(0,0),(10,0.5))
Units: dimensionless
Effect of pressure from EU recycling target on policies
([(0,0)-(1,0.3)],(0,0),(1,0.1))
Units: dimensionless
"Effect of productivity on cost/unit adjustment rate" = 0.26
Units: dimensionless
Effect of profit on EU recycle capacity adjustment rate = 0.25
Units: dimensionless
Effect of profit on recycle capacity when profit is negative = -0.01
Units: dimensionless
Effect of profit on recycle capacity when profit is negative last time step
([(0,0)-(100,0.1)],(0,0),(100,0.05))
Units: dimensionless
"EU cost/unit adjustment rate" =
IF THEN ELSE(Discrepancy recycle percentage > 0, "Cost/unit of recycling in EU (provisional)"*(-"Adjusted effect of productivity on cost/unit adjustment rate"-Inflation rate per year-"Effect of policies on EU recycle cost/unit adjustment rate" (Adjusted policies provide Subsidy for Recyclers) • Effect of pressure from EU recycling target on policies(Discrepancy recycle percentage)), "Cost/unit of recycling in EU (provisional)" * (-"Adjusted effect of productivity on cost/unit adjustment rate" • Inflation rate per year • Effect of pressure from EU recycling target on policies(Discrepancy recycle percentage)))

Table 6 (continued)

EU recycling capacity sub-system (Fig. 4)
Units: USD
"EU price/unit adjustment rate" =
"Price/unit of recycled materials in EU (provisional)" * (•"Adjusted effect of EU recycle capacity on Price/unit of recycled materials in EU" + "Effect of increasing market demand on price/unit"•Inflation rate per year)
Units: USD
EU recycle capacity =
INTEG(IF THEN ELSE ((EU recycle capacity + EU recycle capacity adjustment rate) < 0, 0, EU recycle capacity adjustment rate), Initial EU recycle capacity)
Units: thousand tonnes
EU recycle capacity adjustment rate =
EU recycle capacity * Adjusted effect of profit on EU recycle capacity adjustment rate * Recycle discrepancy volume availability
Units: thousand tonnes
EU recycling volume of packaging waste in 2015 = 55,810
Units: thousand tonnes
Inflation rate per year = 0.048
Units: dimensionless
Initial competition level in recycling industry = 1
Units: **undefined**
"Initial cost/unit of recycling in EU" = 308
Units: USD
Initial EU recycle capacity =
Initial EU recycle fraction * EU recycling volume of packaging waste in 2015
Units: thousand tonnes
Initial EU recycle fraction = 0.06
Units: dimensionless
"Initial price/unit of recycled materials in EU" = 234
Units: USD
Initial recycling productivity level = 1
Units: dimensionless
Investment as percentage of profit in recycling innovation =
Effect of competition level on investment in recycling innovation (Competition level in recycling industry)
Units: dimensionless
Last period adjusted profit of recycling in EU =
INTEG(Last period profit inflow•Last period profit outflow, 10)
Units: USD
Last period profit inflow =
Adjusted profit of recycling in EU
Units: USD
Last period profit of recycling in EU =
Last period adjusted profit of recycling in EU + ("Initial price/unit of recycled materials in EU"•"Initial cost/unit of recycling in EU")•10
Units: USD

Table 6 (continued)

EU recycling capacity sub-system (Fig. 4)
Last period profit outflow =
Last period adjusted profit of recycling in EU
Units: USD
"Minimum cost/unit of recycling in EU" = 0.0001
Units: USD
"Minimum price/unit of recycled materials in EU" = 0.0001
Units: USD
Policies improve Recycling Productivity via Innovation = 0
Units: dimensionless [0,10]
Policies promote Demand for Recycled Materials = 0
Units: dimensionless [0,10]
Policies provide Subsidy for Recyclers = 0
Units: dimensionless [0,10]
"Price/unit of recycled materials in EU (final)" =
IF THEN ELSE (Discrepancy recycle percentage > 0, ("Price/unit of recycled materials in EU (provisional)" * (1 + "Effect of policies on price/unit of recycled materials" (Adjusted policies increase Price via improving market demand) + Effect of pressure from EU recycling target on policies (Discrepancy recycle percentage))) + "Minimum price/unit of recycled materials in EU", "Price/unit of recycled materials in EU (provisional)")
Units: USD
"Price/unit of recycled materials in EU (provisional)" =
INTEG("EU price/unit adjustment rate", "Initial price/unit of recycled materials in EU"•"Minimum price/unit of recycled materials in EU")
Units: USD
Profit[China] = Profit of recycling abroad[China]
Profit[Other] = Profit of recycling abroad[Other]
Profit[EU] = Profit of recycling in EU
Units: USD
Profit of recycling abroad[China] = 100
Profit of recycling abroad[Other] = 70
Units: USD
Profit of recycling in EU =
("Price/unit of recycled materials in EU (final)"•"Cost/unit of recycling in EU (final)") * (1•Investment as percentage of profit in recycling innovation)
Units: USD
Rank Profit[Recycle location] =
VECTOR RANK (Profit[Recycle location], 1)
Units: dimensionless
Recycle discrepancy volume availability =
IF THEN ELSE (Discrepancy recycle percentage > 1e-005, 1, 0)
Units: dimensionless
Recycle rate constraint abroad[China] = China's recycle rate constraint
Recycle rate constraint abroad[Other] = Other countries recycle rate constraint

Table 6 (continued)

EU recycling capacity sub-system (Fig. 4)
Units: thousand tonnes
Recycling Productivity via Innovation =
INTEG(Recycling Productivity via Innovation adjustment rate, Initial recycling productivity level)
Units: dimensionless
Recycling Productivity via Innovation adjustment rate =
Recycling Productivity via Innovation * (Effect of extra investment in innovation on recycling productivity + IF THEN ELSE (Discrepancy recycle percentage > 0, Effect of policies on recycling productivity via innovation (Adjusted policies improve Recycling Productivity via Innovation) + Effect of pressure from EU recycling target on policies (Discrepancy recycle percentage), 0))
Units: dimensionless

Table 7 Full explanations of values of exogenous variables (constants) in the EU recycling target sub-system

Parameter	Value	Source
The EU recycling target sub-system		
Initial Packaging waste inventory	84,850 (thousand tonnes) Total volume of packaging waste generated in EU in 2015	Eurostat (2021)
Desirable recycle percentage	0.7 (dimensionless) By 31 December 2030, the European Commission target at least 70% by weight of all packaging waste must be recycled	European Commission, (2020a)

Table 8 Full explanations of values of exogenous variables (constants) in recycling rate by region sub-system

Parameter	Value	Source
Recycling rate by region sub-system		
Initial other countries recycle fraction	%1.%2 (dimensionless) Taking average value of available data (Eurostat, 2020), the EU recycling percentage outside the EU for packaging waste is around 9% in 2018 (Table 9). Since the CWB had been in effect from 1st January 2018, this can be interpreted as the EU recycling percentage outside the EU except China	Eurostat (2021)
Initial China recycle fraction	0.85 (dimensionless) This is the estimation for all packaging waste based on the statistics that more than 85% of the exported plastic waste from EU was shipped to China in 2018	European Commission, (2018b)
Initial EU recycle fraction	0.06 (dimensionless) On a scale from 0 to 1, given that initial China recycle fraction is 0.85, the "Initial other countries recycle fraction" is 0.09, then the "Initial EU recycle fraction" can be estimated as 1–0.85–0.09 = 0.06	
EU recycling volume of packaging waste in 2015	55,810 (thousand tonnes) Total volume of packaging waste being recycled across European Union – 28 countries in 2015	Eurostat (2021)
Recycle rate constraint disrupted from government ban (China)	DELAY FIXED (1, 3, 0) where 1 is the input, 3 is the delay time step, 0 is the initial value The function would return the value of the input delayed by the delay time step of 3 (3 years from initial time step of 2015, in 2018 the waste ban took into effect). The initial value is the value of the variable at the start of the simulation	World Trade Organization, (2017)
Recycle rate constraint disrupted from government ban (other countries)	DELAY FIXED (1, 6, 0) where 1 is the input, 6 is the delay time step, 0 is the initial value The function would return the value of the input delayed by the delay time step of 6. This is translated as 6 years from initial time step of 2015, in 2021 the waste ban took into effect in other countries following the China ban in 2018 (ECA, 2020). The initial value is the value of the variable at the start of the simulation	European Court of Auditors, (2020a)

Table 9 The EU recycling percentage outside the EU for packaging waste in 2018

Country	Recycling Percentage
Bulgaria	0
Denmark	0
Estonia	14.4
Ireland	21.5
France	2.5
Croatia	0
Italy	0.2
Cyprus	42.3
Lithuania	0.1
Luxembourg	0
Hungary	1.8
Austria	0
Poland	0
Romania	3.2
Slovakia	1.2
Finland	0
Sweden	0
Liechtenstein	68
Norway	0
United Kingdom	23.2
Average	9

Table 10 Full explanations of values for exogenous variables in the EU recycling capacity sub-system

Parameter	Value	Source
EU recycling capacity sub-system		
Inflation rate per year	0.048 (dimensionless) Equivalent to 4.8% per year. Take inflation rate average of each country within Europe & Central Asia from 1999 to 2019, then again estimate the average of these (excel calculation available)	The World Bank, (2019)
Minimum price/unit of recycled materials in EU	50 (USD) Assumed a reasonable lowest price that recycled material should be sold at (around 20% of initial price/unit) to avoid the price reaching unrealistic value of 0	
Effect of policies on price/unit of recycled materials	$y = \frac{x}{20}$(dimensionless)|with policy point as x and price/unit of recycled materials as y [(a)]	
Initial price/unit of recycled materials in EU	234 (USD) The average of (benefits–Government grants–Financial support) across three countries Portugal, France, and Romania in Fig. 3. Cost coverage considering (PPP-adjusted) international dollars per ton (Da Cruz, 2014)	Da Cruz et al. (2014)
Initial cost/unit of recycling in EU	308 (USD) The average of costs across three countries Portugal, France, and Romania in Fig. 3. Cost coverage considering (PPP-adjusted) international dollars per ton (Da Cruz, 2014)	Da Cruz et al. (2014)
Profit of recycling abroad	China–100 (USD)/Others–70 (USD) Assumed a positive healthy profit of recycling industry outside Europe (China and other countries). Since China received a majority of packaging waste for recycling from EU before the 2018's waste ban, profit in China is higher than "Others". The values assigned here have no impact on the overall performance of the model due to the ban from 2018	

Table 10 (continued)

Parameter	Value	Source
Effect of increasing market demand on price/unit	0.07 (dimensionless) (Table 11)	Exal and BCG (2019)
Effect of EU recycle capacity on price/unit of recycled materials in EU	0.06 (dimensionless) Based on Busso (2019)'s estimation that when competition (measured by the number of participating stores in the district) rose by 1 percent, prices for eligible goods decreased by 0.06 percent	Busso and Galiani (2019)
Effect of profit on EU recycle capacity adjustment rate	0.25 (dimensionless) The average of the price elasticity of recycle paper supply of around 0.20–0.30	Mansikkasalo et al. (2014)
Initial competition level in recycling industry	1 (dimensionless) Assigned value of 1 corresponding to the initial supply of the market or "Initial EU recycle capacity" (2791 thousand tonnes), which in turn corresponding to "Initial EU recycle fraction" (0.05)	

Table 10 (continued)

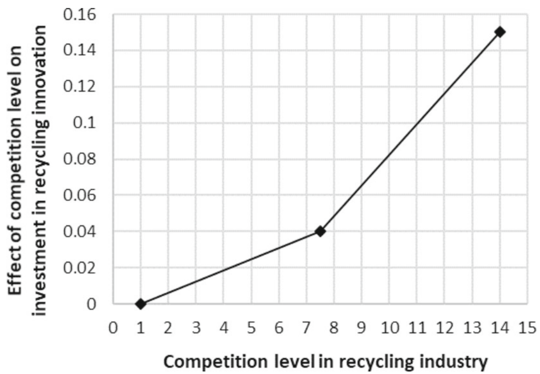
Parameter	Value	Source
Effect of competition level on investment in recycling innovation	 See (Table 12)	Aghion et al. (2018)
Effect of EU recycle capacity on competition level adjustment rate	1 (dimensionless) Within the context of this paper, it is assumed that any rise in supply/EU recycle capacity would lead to proportional increase of competition level	

Table 10 (continued)

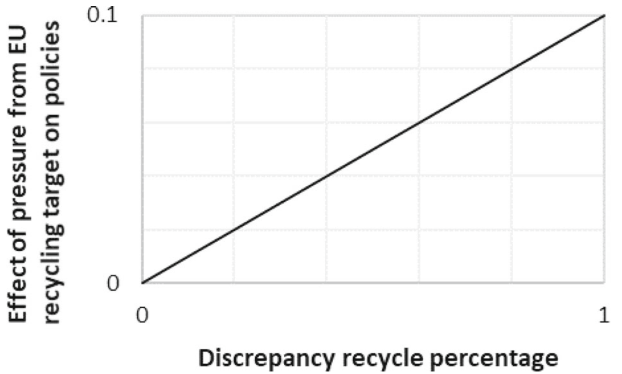
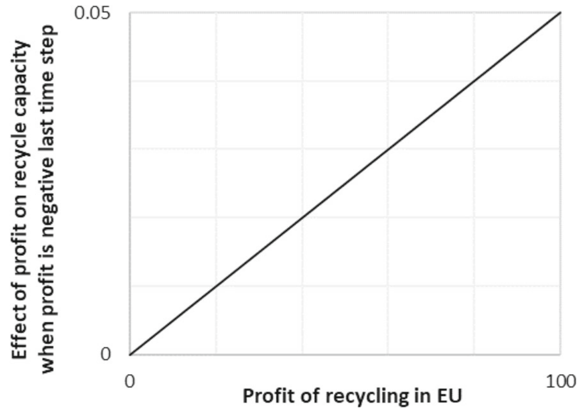
Parameter	Value	Source
Effect of pressure from EU recycling target on policies	 The larger the discrepancy recycle percentage, the more pressure for governments to be more aggressive in its policies. Within the context of this paper, it is assumed that when the discrepancy recycle percentage reach 1, the effect of pressure on policies would be 0.1	
Minimum cost/unit of recycling in EU	50 (USD) Assumed a reasonable lowest cost that recycled material should be produced at to avoid the cost/unit of reaching unrealistic value of 0	
Effect of policies on recycling productivity via innovation	$y = \frac{x}{20}$(dimensionless)|with policy point as x and recycling productivity level as $y^{(a)}$	

Table 10 (continued)

Parameter	Value	Source
Effect of productivity on cost/unit adjustment rate	0.26 (dimensionless) [b]	Rogers (2006)
Effect of policies on EU recycle cost/unit adjustment rate	$y = \frac{x}{20}$(dimensionless)|with policy point as x and recycling cost/unit as y [a]	
Initial recycling productivity level	1 (dimensionless) Assumed a value of 1 corresponding to the "Initial competition level in recycling industry" at 1	

Table 10 (continued)

Parameter	Value	Source
Effect of profit on recycle capacity when profit is negative	− 0.01 (dimensionless) When the industry is making a loss, regardless of the amount, there is no incentives to expand the capacity (Sterman, 2004). Here we assume a 1% decrease in capacity anytime the industry makes a loss or negative profit	Sterman (2000)
Effect of profit on recycle capacity when profit is negative last time step	 To eliminate the inaccuracy in estimating the percentage change from a negative profit to a positive profit, we assume the effect of profit on recycle capacity follows the linear regression line of y = 0.0005 × whenever there is negative profit during the preceding time step and a positive profit during the current time step	

[a]The effect of "Market-based policies", "Subsidy-focused policies", and "Innovation-focused policies" on cost/unit, price/unit, and recycling productivity respectively are set using the same equation. This is to ensure no bias and ensure fair comparability of the effectiveness of each policy on the EU recycle capacity. Within the context of this paper, it is assumed to follow the function $y = \frac{x}{20}$

[b]Assumes that the growth rate of productivity is proportional to the reduction in cost/unit of production. According to Rogers (2006), using UK's ONS data from 1996 to 2003, for all manufacturing firms the estimated rate of return on productivity growth to R&D is between 19 and 33%. We take the average of these two numbers to get 26%

Table 11 Effect of increasing market demand on price/unit - using percentage of price increase customers are willing to pay for beverage and beauty/personal care products

		Based on a USD 10 product (Exal and BCG, 2019)			
		Beverage product		Beauty/personal care product	
Pay more range	Average	Percentage of responses	Expected pay more amount	Percentage of responses	Expected pay more amount
0	0	26%	0	28%	0
2	2	6%	0.12	7%	0.14
1–2	1.5	14%	0.21	16%	0.24
0.5–1	0.75	35%	0.2625	24%	0.18
025–0.5	0.37	22%	0.0814	25%	0.0925
		Sum	0.6739		0.6525
		Average	0.6632		
		As percentage	7%		

Table 12 Effect of competition level on investment in recycling innovation

Competition level [(a)]	Average R&D investments [(a)]	EU recycle fraction [(b)]	Competition level in recycling industry [(c)]	Effect of competition level on investment in recycling innovation [(d)]
No competition	11.7	5	1	0.00
Intermediate competition	12.2	37.5	7.5	0.04
Full competition	13.5	70	14	0.15

[(a)]Adapted from Fig. 4 in Aghion et al. (2018)
[(b)]Assume no competition at "Initial EU recycle fraction" and full competition at "Desirable recycle percentage"
[(c)]Since the "Effect of EU recycle capacity on competition level adjustment rate" is 1, change in "Competition level in recycling industry" (starting at 1) is proportionate to the change in "EU recycle fraction"
[(d)]Change percentage of Average R&D investments from no competition

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Declarations

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