MSc Thesis Report

Positive tipping points in the adoption of sustainable energy technologies

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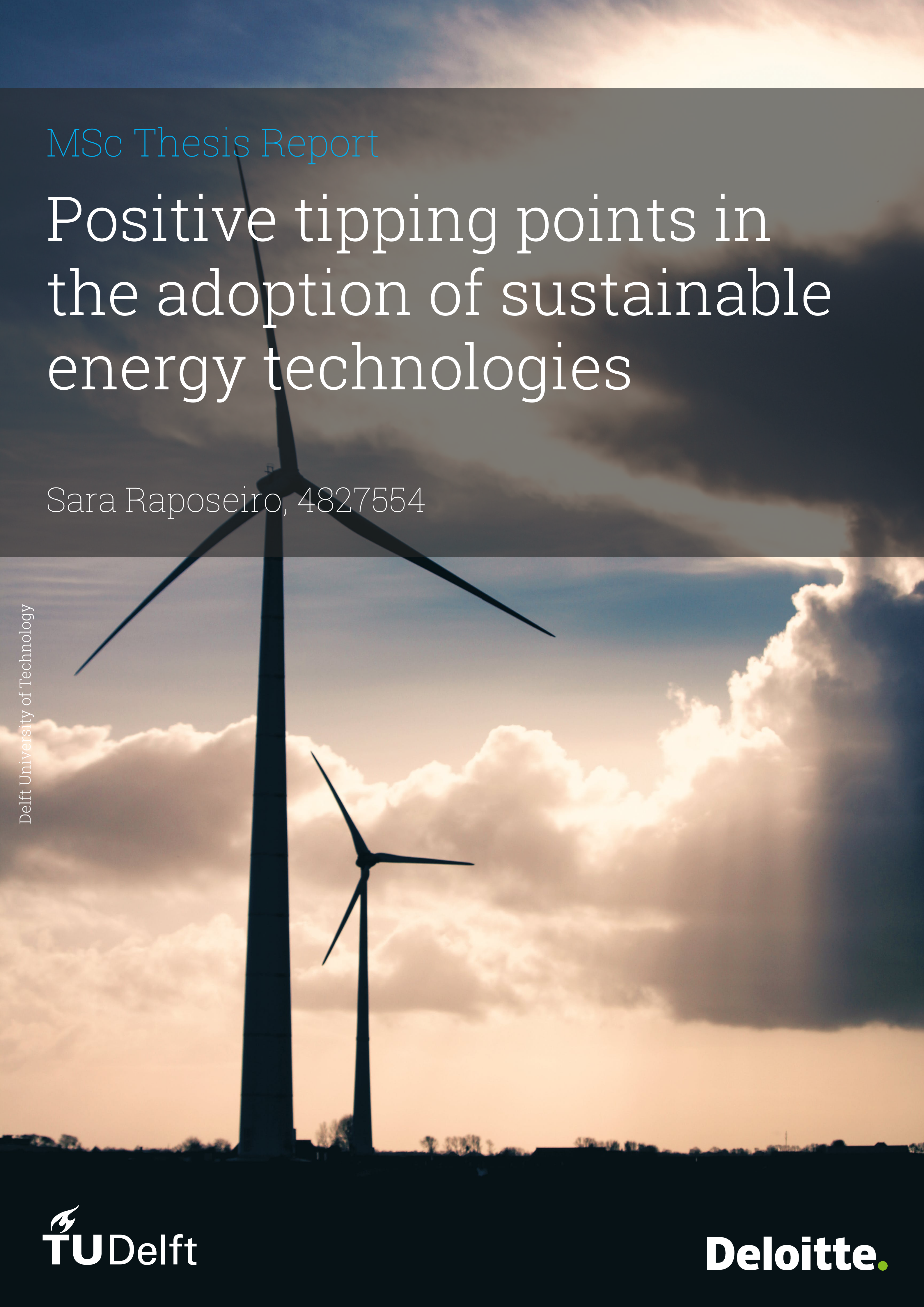

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Preface

Since a young age I have been passionately driven to contribute to fighting climate change and to safeguarding a better future for us and for the next generations. I felt like the best way to do so was to work on the energy field, which is full of tangible options to rapidly reduce anthropogenic emissions. This ambition led to me to pursue the MSc Sustainable Energy Technologies. This inter-faculty programme has provided me with an overview of different sustainable energy technologies as well as how they fit in the broader scope of a country's energy needs.

This thesis is a culmination of this systems perspective, and I am grateful for the help of several people during the process of completing it. I would like to thank my first supervisor, Linda M. Kamp, for her constant guidance and feedback over the last months, which allowed the work done to have a higher quality than it would otherwise have had. The critical attitude of my second supervisor, Aad Correljé, was also essential to have a fresh perspective on the topics analysed, such that relevant aspects were not overseen. I am also thankful for all the interviewees who agreed to speak to me, who sparked my creativity and helped me validate my work.

I want to thank Deloitte for this thesis opportunity and for the people it led me to meet. I received a warm welcome from the Sustainability Team, who is always willing to lend a helping hand. In particular, I am very grateful for my Deloitte supervisor, Jelle van den Berk, who was present for my thesis colleagues and I, always having an advice or comforting words to give. I would also like to thank my fellow thesis interns, Isabel Klennert and Rosita Tombari, whose companionship and help made these last nine months more enjoyable.

Writing a thesis is full of challenges and overcoming them is made easier by finding support and comfort in your friends and family. A thank you note goes to my close university friends, my second family, who were by my side in every step of these last six years. I would also like to thank my boyfriend, António, in specific, who has been a major source of support. Finally, I am grateful for my family and the support they have always given me. The TU Delft experience would not have been possible without them.

This Master's thesis concludes my six-year journey at TU Delft. It has been a truly enriching chapter of my life, full of challenges but also of many rewarding moments.

Sara Raposeiro
Delft, May 2024

Summary

The Earth is at a critical juncture due to anthropogenic greenhouse gas (GHG) emissions and ecosystem degradation, which may lead to irreversible shifts in its climate system. Crossing climate tipping points could trigger catastrophic ecosystem changes. *Tipping points* represent critical thresholds in complex systems where small changes can lead to significant and irreversible shifts. Feedback loops play a crucial role, where reinforcing loops amplify change, and dampening loops resist it. *Positive tipping points*, unlike climate tipping points, are intentional and can be leveraged for transformative change. They involve deliberate actions to strengthen reinforcing feedback loops and weaken dampening ones, leading to rapid shifts toward desirable states, such as sustainability and decarbonisation.

The energy sector is one of the biggest contributors to GHG emissions. To reform it, *sustainable energy technologies* (SETs) are crucial. Sustainable energy technologies include, among others, renewable energy sources, energy storage, clean transportation, and smart grids. Positive tipping points in the uptake of SETs are identified by a marked acceleration in their rate of adoption. Triggering positive tipping points requires coordinated actions across technological, regulatory, economic, and social domains.

Geels and Ayoub (2023) analyse positive tipping points in the context of socio-technical transitions, which depend both on social and technological developments. The authors elaborate a feedback loop model comprising of seven feedback loops between four actor groups and the technology being deployed. The framework is tested by the authors through two case studies: the uptake of offshore wind and electric vehicles (EVs) in the United Kingdom (UK). Geels and Ayoub's model was used as a starting point for this thesis, which aimed to refine and expand it.

The main research question reads as ***"How can the feedback loop model of Geels and Ayoub be refined and expanded to understand how positive tipping points can be triggered in the adoption of sustainable energy technologies?"***. In this quest, the focus was on understanding which actors and interactions among these (referred to as actor roles) were the most relevant to trigger positive tipping points in the adoption of clean technologies. Special attention was given to the role of policymakers since several authors, including Geels and Ayoub, have acknowledged that policies play an essential role in enabling transitions.

As for the method used, first, the model of Geels and Ayoub was refined, before making any additions to it. Second, literature related to SETs and positive tipping points in general was examined to understand how the model could potentially be expanded. Third, four case studies where a positive tipping point had been reached were analysed, testing the hypotheses derived from the literature. The case studies were offshore wind energy in the UK, wind energy in Portugal, EVs in the UK, and EVs in the Netherlands. Fourth, the insights from the case studies were used to derive the final feedback loop model. Finally, all findings were validated through four semi-structured interviews with experts.

In terms of findings, both additional actors and actor roles were identified. On the one hand, Geels and Ayoub included policymakers, technology firms, adopters, and the wider public in their model. However, based on the literature initially analysed, academic and research institutes, trade associations, non-

governmental organisations, and financial institutions were also foreseen to have had a key role. All eight actor groups were identified in the wind energy case studies. However, financial institutions did not appear relevant in the EV case studies.

On the other hand, the interactions in the model of Geels and Ayoub can be aggregated into seven overarching actor roles. These are 1) technology development, 2) technology adoption, 3) legitimising technology, 4) providing financing incentives/options, 5) investing in infrastructure, 6) establishing legislation, and 7) lobbying. Based on the literature initially examined, six other actor roles were identified, them being 8) raising awareness, 9) fostering collaboration, 10) transferring knowledge, 11) giving and receiving feedback, 12) establishing market-based mechanisms, and 13) promoting education. In the wind energy case studies, all these actor roles appeared relevant except for actor role 13. Actor roles 12 and 13 were not found to be relevant in the EV case studies.

As for the role of policymakers, Geels and Ayoub only included economic and regulatory policy instruments in their framework. Economic instruments affect financial decisions, while regulatory instruments are tools that affect the addressees' behaviour. On the one hand, the literature analysed suggested that additional economic and regulatory instruments could be relevant. Indeed, market-based mechanisms were not included in Geels and Ayoub's model but played an essential role in the wind energy case studies. Similarly, strategic planning was an important regulatory instrument in all four case studies. On the other hand, it was also found that information instruments - which relate to fostering collaboration, knowledge exchange, and public awareness - can be important. While the two former were found in all case studies, policymakers did not appear to be involved in raising public awareness. The results thus suggest that policy mixes combining economic, regulatory, and information instruments are effective.

Due to the differences found in the case studies, two final feedback loop models were created. Figure 1 relates to the wind energy case studies, while Figure 2 was based on the EV case studies. The grey blocks and black labels were already included in Geels and Ayoub's model. The green and yellow blocks and labels correspond to the additions made. In green the actors and interactions that overlap between Figure 1 and Figure 2 are shown. Yellow is used to illustrate the additions that are specific of only one of the final feedback loop models.

The findings provide a conceptual framework to understand the actors and actor roles involved in enabling positive tipping points in the adoption of SETs. In particular, Figure 1 could be used as a reference for the deployment of business-to-business (B2B) technologies, typically adopted in large numbers by businesses. Figure 2 could be used as a baseline for the uptake of business-to-consumer (B2C) technologies, mainly adopted in small numbers by individual buyers.

This research addressed knowledge gaps regarding positive tipping points in the adoption of SETs. By enhancing, expanding and validating the feedback loop model proposed by Geels and Ayoub (2023), this MSc thesis contributed to the development of a pertinent theoretical framework in the field. Additionally, the four case studies provide empirical knowledge on the dynamics of socio-technical tipping points. The results of this study allow to better understand the actors and actor roles involved in triggering a positive tipping point in the adoption of B2B and B2C sustainable energy technologies. This was enabled by the use of feedback loop models, which allow to explore the interaction between the technologies and the socio-technical system. Furthermore, this thesis contributed to understanding how policies can effect technological and behavioural changes, as well as how policy mixes affect socio-technical transformation and vice-versa. Overall, this research's findings may provide insights on how to intentionally trigger future technological transitions.

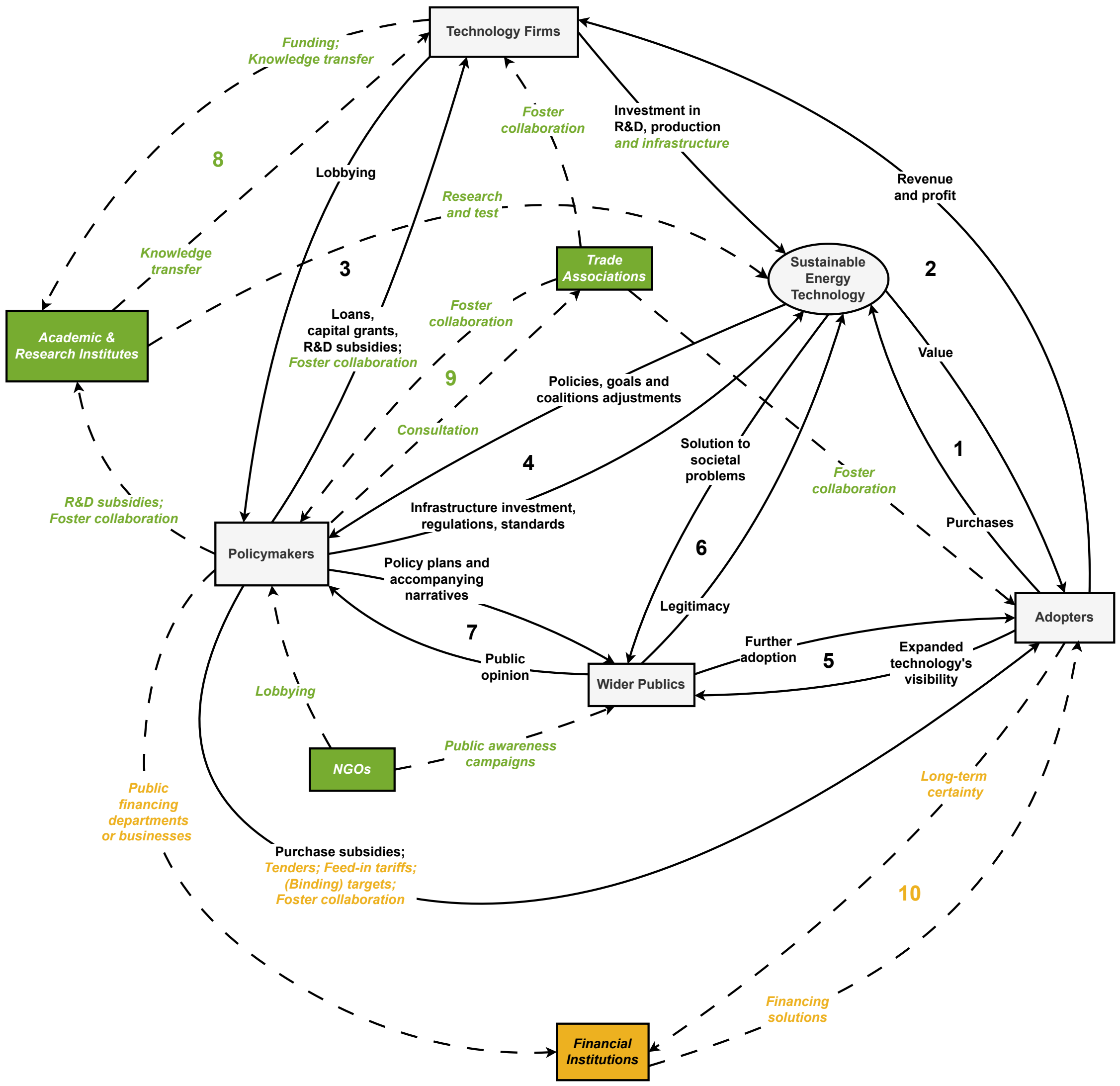

Figure 1: Feedback loop model showing the relevant actors and respective roles in triggering a tipping point in the adoption of wind energy. This model might be used as a reference for the uptake of other B2B sustainable energy technologies

The research has several limitations, including a limited number of case studies focusing on two technologies and European countries, which limits the generalisability of the findings. More case studies could provide a broader empirical understanding. Additionally, some actor groups currently encompass a wide range of actors, and could be expanded further. The research also focused on the tipping point enablers and less on its barriers, which are typically more prominent at an initial stage. Future studies could analyse more years prior to the tipping point, and dampening feedback loops could be included in future models. The latter could be facilitated by using causal loop diagrams (CLDs), which also allow to more easily incorporate feedback loops involving multiple actors and create a numerical model of the system. Furthermore, the operationalisation of positive tipping points remains challenging, and future studies could define metrics that reliably indicate a tipping point and analyse whether multiple positive tipping points exist. Quantitative methods could help understand the relative importance of different interactions. Besides, the sequence of events could be compared between case studies through temporal dynamics analysis. Finally, future research could study the initiation of feedback loops.

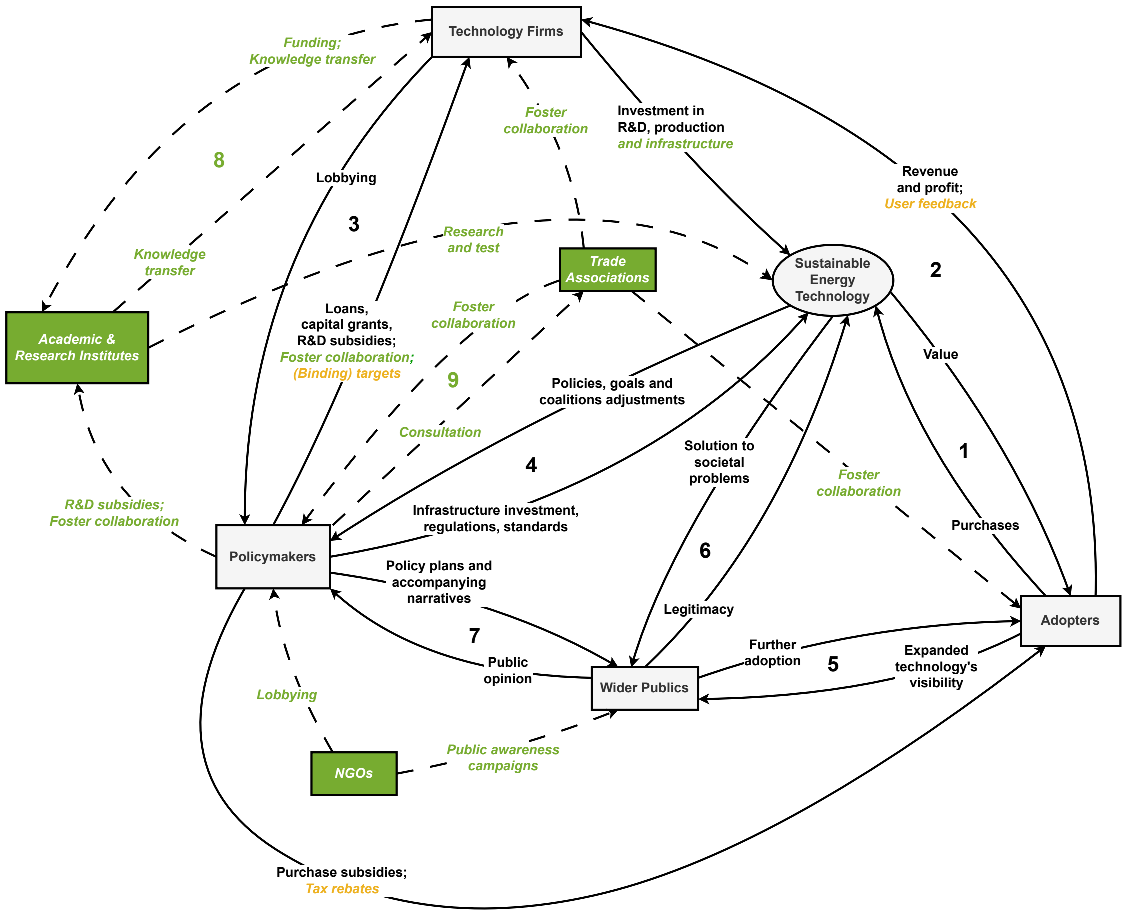

Figure 2: Feedback loop model showing the relevant actors and respective roles in triggering a tipping point in the adoption of electric vehicles. This model might be used as a reference for the uptake of other B2C sustainable energy technologies

Despite this study's limitations and avenues for future research, it holds political and practical significance. In terms of its political relevance, this thesis emphasises the importance of integrating knowledge from socio-technical transitions and political science, rather than examining policies in isolation. The study highlights the value of using policy mixes and understanding the roles and interventions of policymakers in successful case studies. This helps government agencies design and implement effective policies, especially in wind energy and EVs. Concerning its practical applicability, industry players and investors can benefit from understanding the policy landscape and its impact on adoption, contributing to strategic decision-making. The research underscores the importance of considering the interactions among the actors in the system. Analysing interactions between actors and identifying which roles are not being successfully fulfilled can ensure all relevant actor roles are covered, potentially leading to a positive tipping point in the technology's adoption.

This research provides insights on how to deliberately trigger positive tipping points in the uptake of sustainable energy technologies. The possibility of doing so gives hope for realising a successful energy transition and securing a sustainable future for future generations.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
B2B	Business-to-business
B2C	Business-to-consumer
BEV	Battery electric vehicle
CLD	Causal loop diagram
EU	European Union
EV	Electric vehicle
GDP	Gross domestic product
GHG	Greenhouse gas
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
IEA	Internation Energy Agency
LEZ	Low-emission zone
NGO	Non-governmental organisation
PHEV	Plug-in hybrid electric vehicle
R&D	Research and development
RD&D	Research, development, and demonstration
SET	Sustainable energy technology
SMEs	Small and medium enterprises
TSO	Transmission System Operator
UK	United Kingdom
WWF	World Wildlife Fund
Specific to UK case studies (Section 6.1 and Section 6.3)	
CfD	Contracts for Difference
CE	Crown Estate
DECC	Department of Energy & Climate Change
ETI	Energy Technologies Institute
EU ETS	European Emissions Trading System
FED	Fuel Excise Duty
FiDeR	Final Investment Decision Enabling for Renewables
FoE	Friends of the Earth
NAREC	National Renewable Energy Centre
RO	Renewable Obligation
ROCs	Renewable Obligation Certificates
RSPB	Royal Society for the Protection of Birds
SMMT	Society of Motor Manufacturers and Traders

Continued on next page

Table 1 – continued from previous page

Abbreviation	Definition
TSB	Technology Strategy Board
ULEV	Ultra Low Emission Vehicle
ULEZ	Ultra Low Emission Zone
VED	Vehicle Excise Duty
Specific to wind in Portugal case study (Section 6.2)	
APREN	Portuguese Association for Renewable Energies (*Associação Portuguesa de Energias Renováveis*)
FEUP	Engineering Faculty of the Porto University (*Faculdade de Engenharia da Universidade do Porto*)
INESC	Mechanics Engineering and Industrial Management Institute (*Instituto de Engenharia de Sistemas e Computadores*)
INETI	National Institute of Engineering, Technology and Innovationm (*Instituto Nacional de Engenharia, Tecnologia e Inovação*)
ISEP	Porto Higher Engineering Institute (*Instituto Superior de Engenharia do Porto*)
IST	Higher Technical Institute (*Instituto Superior Técnico*)
Specific to EV in the Netherlands case study (Section 6.4)	
ANWB	General Dutch Cyclists' Union (*Algemene Nederlandse Wielrijdersbond*)
BOVAG	Association of Automobile Dealers and Garage Owners (*BOnd Van Automobielhandelaren en Garagehouders*)
EVO	Own Carrier Organization (*Eigen Vervoerders Organisatie*)
HBO	University (*Hogeschool*)
MBO	Secondary vocational education (*Middelbaar beroepsonderwijs*)
NKL	National Charging Infrastructure Knowledge Platform Foundation (*Nationaal Kennisplatform Laadinfrastructuur*)
RAI	Bicycle and Automotive Industry (*Rijwiel en Automobiel Industrie*)
TLN	Transport and Logistics Netherlands (*Transport en Logistiek Nederland*)
TU	University of Technology (*Technische Universiteit*)
VNA	Association of Dutch Car Leasing Companies (*Vereniging Nederlandse Autoleasemaatschappijen*)
VNO	Association of Dutch Enterprises (*Verbond van Nederlandse Ondernemingen*)
VZR	Business Drivers Association (*Vereniging Zakelijke Rijders*)

Key Definitions

Term	Definition
Climate Tipping Points	Crucial thresholds that when crossed trigger rapid and potentially irreversible changes to a stable state in the Earth's climate system (Lenton et al., 2008)
Positive Tipping Points	Intentional interventions causing large-scale systemic changes through small actions, leading to transformative shifts toward low-carbon systems (Lenton et al., 2022)
Feedback Loops	When a change in one parameter leads to subsequent changes, which amplify (positive feedback) or oppose (negative feedback) the initial change (Geels & Ayoub, 2023)
Sustainable Energy Technologies	Technologies designed to reduce environmental impact, particularly in the context of energy production and consumption (Shahbaz, Siddiqui, Siddiqui, Jiao, & Kautish, 2023)

1 | Introduction

As evidenced by a plethora of scientific literature, there is no doubt of the effects of anthropogenic climate change. In 2023, six of the nine planetary boundaries - important metrics for climate-related thresholds - had been crossed (Richardson et al., 2023). This increases the risk of crossing climate tipping points, defined as critical thresholds in the Earth climate system that when crossed can lead to irreversible changes to ecosystems (Lenton et al., 2008). To avoid such a scenario, current research has focused on triggering positive tipping points to convert high-carbon systems into low-carbon ones (Lenton et al., 2022), for which sustainable energy technologies are essential (Shahbaz et al., 2023).

Positive tipping points are deliberate and depend on reinforcing feedback loops to trigger swift changes. Tipping points in the adoption of sustainable energy technologies occur in a socio-technical context, involving both technological and societal factors. Due to the complexity involved, research on how to trigger socio-technical tipping points is still limited, even though the interest is rapidly growing (Lenton et al., 2022, 2023). With their model Geels and Ayoub (2023) took a step towards understanding which reinforcing feedback loops between actors were involved in the deployment of a new technology.

This thesis aimed to *understand how the model developed by Geels and Ayoub (2023) could be refined and expanded to understand how positive tipping points can be triggered in the adoption of sustainable energy technologies*. To do so, it was investigated which other actors and actor roles were relevant in the uptake of sustainable energy technologies. The findings were supported by four case studies: wind energy in the United Kingdom (UK) and in Portugal, and electric vehicles in the UK and the Netherlands.

This report is structured in the following manner. Firstly, in Chapter 2 the necessary background is provided. Secondly, the research design is covered in Chapter 3, which touches upon aspects such as the literature review conducted and the knowledge gap found, the research aim and questions, and the significance of this study. In Chapter 4 the conceptual framework is described. Then, Chapter 5 describes the methodology utilised to analyse the case studies. This chapter should provide the reader with the tools for replicating the work performed in this research, if desired. This is followed by the four case studies, in Chapter 6. A subsequent discussion of the results is then provided in Chapter 7. Here, the main insights and generalisations are presented, as well as the final feedback loop models. To close, Chapter 8 provides the answers to the research questions, clarifies the scientific contribution, policy relevance, and practical insights of this thesis, and highlights limitations and recommendations.

2 | Background

In this chapter, the necessary background about key concepts is provided. Section 2.1 puts the problem of climate change into perspective, highlighting the need for an energy transition. In this context, climate and positive tipping points have been the focus of much research. Section 2.2 therefore explains the concept of tipping points. Then, Section 2.3 clarifies what are climate tipping points, while Section 2.4 does so for positive tipping points. At last, Section 2.5 delves into socio-technical tipping points, relevant to promote energy-related shifts.

2.1. Climate Crisis & Energy Transition

Human activities, particularly greenhouse gas (GHG) emissions are to blame for global warming. The energy sector is one of the biggest contributors, having accounted for 34% of net global GHG emissions in 2019. Another 21% came from transportation and buildings (IPCC, 2023a), which cannot be sustainable if the energy sector itself is not. There is therefore an increasing effort to realise a transition towards sustainable energy technologies.

Sustainable energy technologies (SETs) are the focus of this Master's thesis. These refer to adapted or innovative environmentally responsible solutions, products, and systems designed to meet current energy needs while minimising negative environmental impacts, reducing GHG emissions and promoting the sustainable use of natural resources. Therefore, SETs relate to producing, gathering, converting, storing, transporting, and operating electrical power. Consequently, they encompass not only renewable energy sources but also technologies related to energy storage, carbon capture, and clean transportation. In addition, smart grid systems and sustainable building technologies can also be considered SETs (Bossink, Blankesteijn, & Hasanefendic, 2023; Shahbaz et al., 2023).

Although the trend towards sustainability has been accelerating (Geels, Sovacool, Schwanen, & Sorrell, 2017), out of the fifty sustainable technologies monitored by the IEA (2023c), only three - solar photovoltaics, electric vehicles, and lighting - are considered to be fully on track with the net zero by 2050 scenario. Upon the slow progress of SETs, global GHG emissions have kept rising. As a consequence, extreme weather and climate events have been negatively affecting Earth's atmosphere, ocean, cryosphere, and biosphere, as well as people's health and safety (IPCC, 2023b).

If decarbonisation does not occur at a higher pace, there is the risk of triggering several climate tipping points, in which case life on Earth might become very different from what is known (Lenton et al., 2008; Roberts et al., 2018). Triggering instead positive tipping points can have the power to prevent such a catastrophic future (Fesenfeld, Schmid, Finger, Mathys, & Schmidt, 2022). Before delving into these concepts, Section 2.2 explains the characteristics and dynamics of tipping points in a broader sense.

2.2. Tipping Points

Tipping points act as crucial thresholds in complex systems, where even a small change in one parameter can have non-linear consequences and trigger a significant, abrupt, and potentially irreversible change to a stable state (Geels & Ayoub, 2023). Irreversibility is tightly linked to hysteresis, meaning that returning to the initial stable state involves more effort than the one needed to cross the tipping point. For example, should the Greenland Ice Sheet completely melt due to global warming, it would not be enough to stop emissions and have global warming under control for the ice sheet to form again. Instead, global cooling would be necessary. This assumes, however, that it is still possible (even if hard) to revert back to the initial state, which might not be true (Lenton et al., 2022, 2023).

Underlying the dynamics of tipping points there are feedback loops. In positive or reinforcing feedback loops an initial change is amplified, leading to either vicious or virtuous cycles. Conversely, negative or dampening feedback loops are characteristic of a stable system, where an initial change is opposed[1] (Sterman, 2000). The latter often pose as the barriers for crossing a tipping point and the former as the enablers. Indeed, a tipping point is crossed because reinforcing feedback loops overshadow dampening feedbacks, making the process self-perpetuating. Once in the new stable state, dampening feedback loops contribute to an (almost) irreversible process (Lenton et al., 2022).

2.3. Climate Tipping Points

A specific type of tipping points are climate tipping points, which hold a negative connotation. Climate tipping points are pivotal thresholds within the Earth's climate system. Crossing them can result in substantial and irreversible shifts in the planet's climate and ecosystems and in life as is known. Additionally, triggering one tipping point can potentially cause another to activate, and so on, due to the possibility of upward scaling tipping cascades (Lenton et al., 2022, 2023).

For instance, the tipping of the Greenland Ice Sheet would lead to a substantially different Earth climate system, with higher temperatures due to a lower Earth albedo, as well as major biodiversity impacts (Lenton et al., 2008)[2]. At the same time, triggering this tipping point could lead to a critical transition in one of the major components responsible for regulating Earth's temperature and supporting the marine ecosystems. These disruptions together cause sea-level rise and Southern Ocean heat accumulation, which could in turn accelerate ice loss from the west Antarctic Ice Sheet (Steffen et al., 2018).

Lenton et al. (2008) pioneered the research on tipping points by identifying policy-relevant climate tipping points at the risk of being triggered this century. According to Lenton et al. (2023), five climate tipping points are already at the imminent danger of being crossed.

2.4. Positive Tipping Points

To mitigate the possibility of crossing climate tipping points, the tipping point dynamics can be used in favour of society (Lenton et al., 2023). Enabling *positive* tipping points offers a glimmer of hope (Fesenfeld et al., 2022) as it might be the only way to avoid the worst consequences of climate change (Alkemade & de Coninck, 2021) or, in other words, propel climate action (Winkelmann et al., 2022).

[1]'Positive' and 'negative' are not meant to transmit a sense of good or a bad. Rather, this is the commonly used terminology for reinforcing/amplifying and dampening/balancing feedback loops, respectively (Sterman, 2000).
[2]For other examples of climate tipping points, consult Lenton et al. (2008) or Lenton et al. (2023) (page 21).

Positive tipping points relate to causing large-scale systemic changes through small and smart interventions aiming at converting high-carbon into low-carbon systems (Lenton et al., 2022). Crossing a positive tipping point can also have a cascading effect. For example, a tipping point electric vehicles' adoption might be associated with a reduction in battery costs. This would allow to upscale storage capacity, facilitating a tipping point in green ammonia production (Lenton et al., 2023).

Positive tipping points have all the characteristics explained under Section 2.2. Nevertheless, unlike climate tipping points, positive tipping points are intentional, requiring deliberate forcing to strengthen reinforcing feedback loops and weaken dampening ones (Roberts et al., 2018). By understanding and triggering positive tipping points, there is the potential to induce rapid and transformative shifts towards desirable states that promote global decarbonisation and sustainability (Fesenfeld et al., 2022).

Geels and Ayoub (2023) consider that a positive tipping point occurs when innovation dynamics change from a fragile state to a self-sustaining one, i.e. when the technology has reached a stable design and its adoption picks up momentum[3]. Moreover, Lenton et al. (2022) identify a positive tipping point as going up the typical S-curve of adoption. These definitions are in agreement with the one provided in Lenton et al. (2023) and illustrated in Figure 2.1. According to the authors, after a tipping point is crossed an accelerating phase, characterised by non-linear changes and reinforcing feedbacks, is entered, after which the system stabilises at a more sustainable state.

Figure 2.1: Concept of a positive tipping point, with the system (circle) moving through three different phases (Lenton et al., 2023)

[3]Explained in more detail under Section 4.1.1.

Figure 2.1 shows the system evolving through three phases: enabling, accelerating, and stabilising. During the *enabling phase*, initially dominated by dampening feedback loops, agents can strategically intervene to trigger a positive tipping point. This is done by creating enabling conditions to weaken dampening feedbacks and enhance reinforcing ones. The *acceleration phase* is entered once the tipping point is crossed, being characterised by non-linear and self-perpetuating changes driven by strong reinforcing feedbacks. This is followed by the *stabilising phase*, during which the system stabilises at a qualitatively different state. If a positive tipping point is successfully triggered, the end result is a more sustainable, safe, and just world. Nevertheless, as demonstrated in Figure 2.1, this attempt might not be well succeeded, resulting in shallower outcomes or, in the worst case, unintended consequences.

This thesis focused, for one, on the enabling phase to understand the interventions that enable reinforcing feedback loops to dominate and a positive tipping point to be crossed. For another, it studied how these attempts resulted in a successful tipping point by analysing the beginning of the acceleration phase. Identifying the interventions, conditions, and mechanisms that lead to a positive tipping point in a particular context is especially relevant to understand how to foster such a self-perpetuating change.

2.5. Socio-Technical Tipping Points

Positive tipping points can be observed in a diverse set of systems, with energy transitions developing in socio-technical systems. These are characterised by complex environments involving socio-economic and techno-economic developments as well as actor reorientations. Social factors include changes to cultural norms, values, public perception and acceptance, while technological aspects refer to innovation, R&D, infrastructure expansion, and interoperability. Economic factors involve the market dynamics, the technology's affordability, funding and investment. The political domain often plays an important role through the policies, incentives, and governance in place. Thus, to understand how to trigger tipping points in the adoption of SETs it is vital to take a systems-thinking approach, understanding the actor dynamics involved (Alkemade & de Coninck, 2021; Geels & Ayoub, 2023; Geels et al., 2017; Lenton et al., 2022, 2023; Sovacool, 2016; Stadelmann-Steffen, Eder, Harring, Spilker, & Katsanidou, 2021).

Specific interventions can promote socio-technical tipping points, such as technological and social innovations, behavioural nudges, spreading public information, private and public investments, and policy intervention (Brescia, 2019; Kekäle & Helo, 2014; Lenton et al., 2022; Newell, Twena, & Daley, 2021). Concerning the latter, efficient economic, regulatory, and information instruments can create synergies between technological and behavioural changes, leading to virtuous feedback loops (Fesenfeld et al., 2022; Roberts et al., 2018; Rogge & Reichardt, 2016). Some of these are shown in Table 2.1.

Table 2.1: Examples of economic, regulatory and information policy instruments (Rogge & Reichardt, 2016)

	Primary purpose		
Primary type	*Technology push*	*Demand pull*	*Systemic*
Economic instruments	RD&D grants and loans, tax incentives, state equity assistance	Subsidies, feed-in tariffs, trading systems, taxes, levies	Tax and subsidy reforms, infrastructure provision, cooperative RD&D grants
Regulation instruments	Patent law, intellectual property rights	Technology/performance standards, prohibition of products/practices, application constraints	Market design, grid access guarantee, priority feed-in, environmental liability law
Information instruments	Professional training and qualification, entrepreneurship training, scientific workshops	Training on new technologies, rating and labelling programs, public information campaigns	Education system, thematic meetings, public debates, cooperatives RD&D programs, clusters

Interventions such as the ones described above can create the necessary enabling conditions to trigger strong, self-perpetuating reinforcing feedback loops and, subsequently, positive tipping points. Enabling conditions might involve a technology's performance, price, symbolism and accessibility. At the same time, they might also relate to the population size, the tightness of the social network, the information available, and the technology's complementarity with other products. In the energy and transportation sectors, the technology's performance, cost, and associated infrastructure were found to have the largest impact. Furthermore, strategic interventions might strengthen reinforcing feedback loops. Economies of sale, learning-by-doing, social contagion, and technological reinforcement were found to be the most relevant reinforcing feedbacks in the energy and transportation sectors (Kekäle & Helo, 2014; Lenton et al., 2022, 2023; Otto et al., 2020; Sharpe & Lenton, 2021).

This chapter provided background on the topic of sustainable energy transitions and tipping points. Climate tipping points, positive tipping points, and socio-technical tipping points were covered. Comprehending socio-technical tipping points is a pressing necessity to support governance and decision-making processes, aimed at minimising climate damage and fostering transitions towards sustainability (Lenton et al., 2023). Chapter 3 explains how this Master's thesis aimed at contributing to this goal.

3 | Research Design

This chapter outlines the research design. Section 3.1 presents a literature review, while Section 3.2 covers the identified knowledge gaps. The research aim is explained in Section 3.3, followed by the research questions in Section 3.4. At last, the significance of the study is detailed in Section 3.5.

3.1. Literature Review

There is plenty of research on enabling either technological (Mercure et al., 2021; Rogge & Reichardt, 2016; Sharpe & Lenton, 2021) or social (Eder & Stadelmann-Steffen, 2023; Newell et al., 2021; Otto et al., 2020; Stadelmann-Steffen et al., 2021; Winkelmann et al., 2022) tipping points. Nevertheless, studies that integrate these two perspectives and look at socio-technical tipping points are still scarce (Geels & Ayoub, 2023; Lenton et al., 2022). An overview of important work on the field is given below.

"Sociotechnical transitions for deep decarbonisation"

Geels et al. (2017) addressed the complexity of deep decarbonisation by developing a socio-technical framework and demonstrating how co-evolutionary interactions between technology and socio-cultural groupings might accelerate low-carbon transitions. First, they point to aligning innovations and systems so that several innovations are linked. Second, they highlight the relevance of building societal and business support for fast technological transitions. Third, they claim that the phase-out of polluting technologies and supply chains can remove barriers for niche innovations.

For future research, the authors advise exploring the interaction between innovations and socio-technical systems, emphasising that consumer acceptance, business models, and socio-political factors are often overlooked. They also highlight the need to align innovation policy with sector-specific policy in polycentric efforts. Lastly, they suggest combining model-based analysis with socio-technical research to develop cost-effective and socio-politically feasible policy approaches for deep decarbonisation.

"The politics of accelerating low-carbon transitions: towards a new research agenda"

Even though Roberts et al. (2018) do not develop any framework on the field, they examine the politics of deliberate acceleration by combining insights from political science, policy analysis, and socio-technical transition studies. Their research sets the stage for prospective investigations within this domain. For one, they stress the importance of increased collaboration between socio-technical transition and political science scholars for a deeper understanding of acceleration policies.

Identified areas for further research include the sustainability of positive feedback loops generated by transition policies, crafting policies that are both popular and self-expanding, distinguishing between policy feedback effects and mechanisms, and exploring the deliberate cultivation of reinforcing feedbacks by policymakers. Additionally, they highlight research opportunities in understanding the dynamics of power, agency, and politics, as well as considering the broader context of low-carbon transitions.

"The co-evolution of policy mixes and socio-technical systems: Towards a conceptual framework of policy mix feedback in sustainability transitions"

Edmondson, Kern, and Rogge (2019) advocate for policy mixes in socio-technical transformations and feedback mechanisms, arguing that individual policy instruments are not adequate in this context. Therefore, they develop a framework aiming to clarify how policy mixes affect socio-technical transformation (via resource, interpretive, and institutional effects) and how modifications to the socio-technical system in turn influence the evolution of the policy mix (through socio-political, administrative, and fiscal feedbacks). At the same time, their framework, illustrated in Figure 3.1, also includes the influence of exogenous factors. Their concept emphasises the need to overcome obstacles that could eventually erode political support while establishing incentives for beneficiaries to mobilise support.

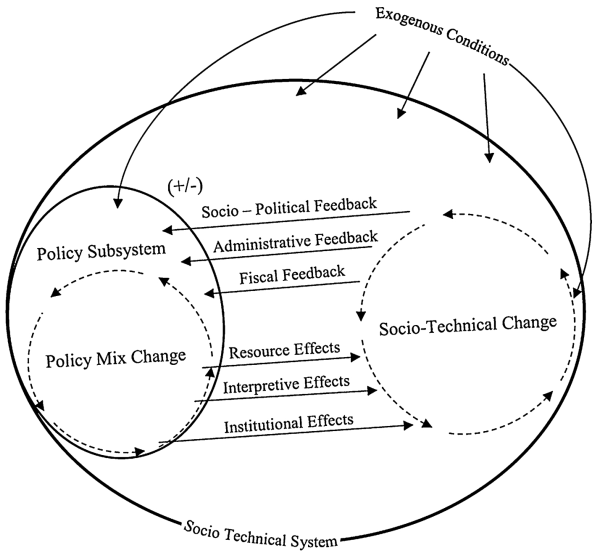

Figure 3.1: Interactions between policy mixes and socio-technical systems by Edmondson et al. (2019)

Even though Edmondson et al. (2019), Geels et al. (2017), and Roberts et al. (2018) focus on sustainable transitions in socio-technical systems and their insights can be used to deliberately trigger tipping points, they do not revolve around positive tipping points. In contrast, the studies presented below do so, offering clear insights into the dynamics of socio-technical tipping points.

"Operationalising positive tipping points towards global sustainability"

Lenton et al. (2022) focus on social-technical-ecological systems, presenting enabling conditions for positive tipping, how these influence reinforcing feedbacks, and which actions can trigger positive tipping in the adoption of sustainable technologies and behaviours, as summarised in Figure 3.2. The authors identify the need for future research to focus on understanding (and possibly designing a guiding map on) how to identify and intentionally trigger positive tipping. The authors emphasise the importance of intervening in different places at the same time, for instance by considering coalitions of shared interests and how agents' interventions can initiate system-wide positive tipping points. Moreover, they advocate for integrating what already exists in inventive ways instead of coming up with new ideas.

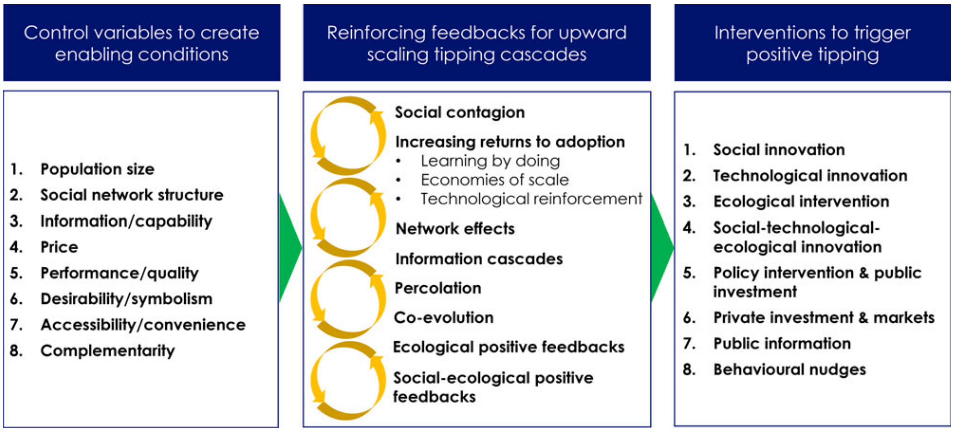

Figure 3.2: Framework developed by Lenton et al. (2022) on triggering positive tipping points

"The politics of enabling tipping points for sustainable development"

Fesenfeld et al. (2022) argue that policy strategies are essential to leverage political feedback from both technological advancements and behavioural changes and thereby facilitate the creation and crossing of positive tipping points. The authors propose a framework, illustrated in Figure 3.3, that links research on feedback mechanisms to three sustainability principles: efficiency, sufficiency, and substitution. The article stress that there is limited research on how policies can effectively lead to behavioural and technological changes. Fesenfeld et al. (2022) emphasise the need to comprehend how policy feedbacks concerning technological and behavioural changes occur in different contexts, as well as how to overcome the political opposition against sufficiency and substitution practices.

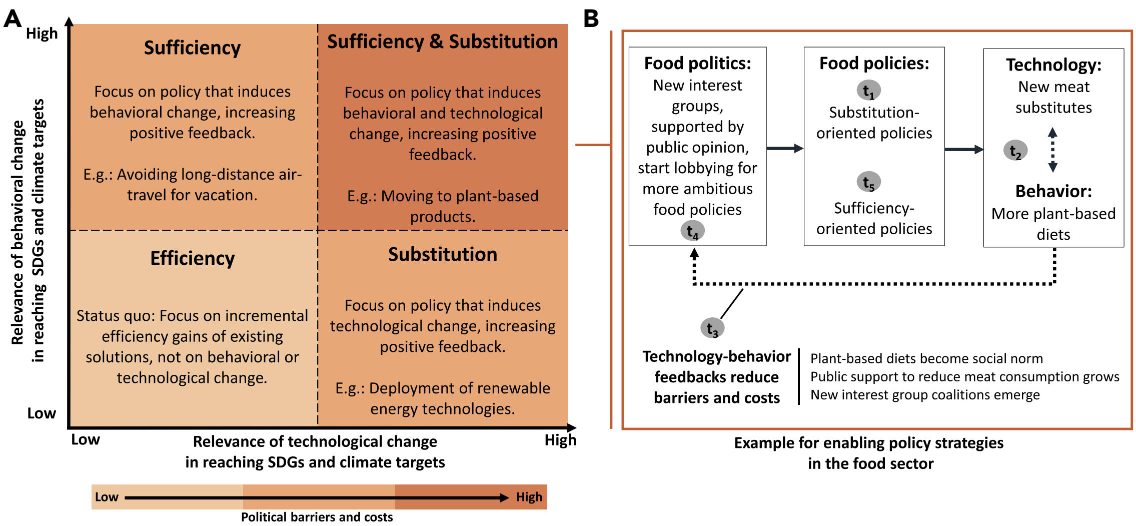

Figure 3.3: Behavioural and technological policies on enabling sustainable development (Fesenfeld et al., 2022)

Lenton et al. (2022) and Fesenfeld et al. (2022) present relevant frameworks concerning socio-technical tipping points. However, they leave it to the reader to draw a mental map of the interactions between different social groups. By comparison, Geels and Ayoub (2023) presented a *visual* framework showing reinforcing feedback loops between actors with routines, capabilities, beliefs, and interests.

"A socio-technical transition perspective on positive tipping points in climate change mitigation: Analysing seven interacting feedback loops in offshore wind and electric vehicles acceleration"

Geels and Ayoub (2023) developed a framework in the context of socio-technological tipping points that highlights the co-evolutionary interactions between technological advancements and actor re-orientations. Drawing on political science, discourse theory, business studies, consumption theory, and innovation studies, the paper employs the Multi-Level Perspective (Geels, 2019) to identify seven feedback loops in tipping point dynamics. These are shown in Figure 3.4, which is explained in Section 4.1.2 as it was used as the foundation for the conceptual framework of this thesis.

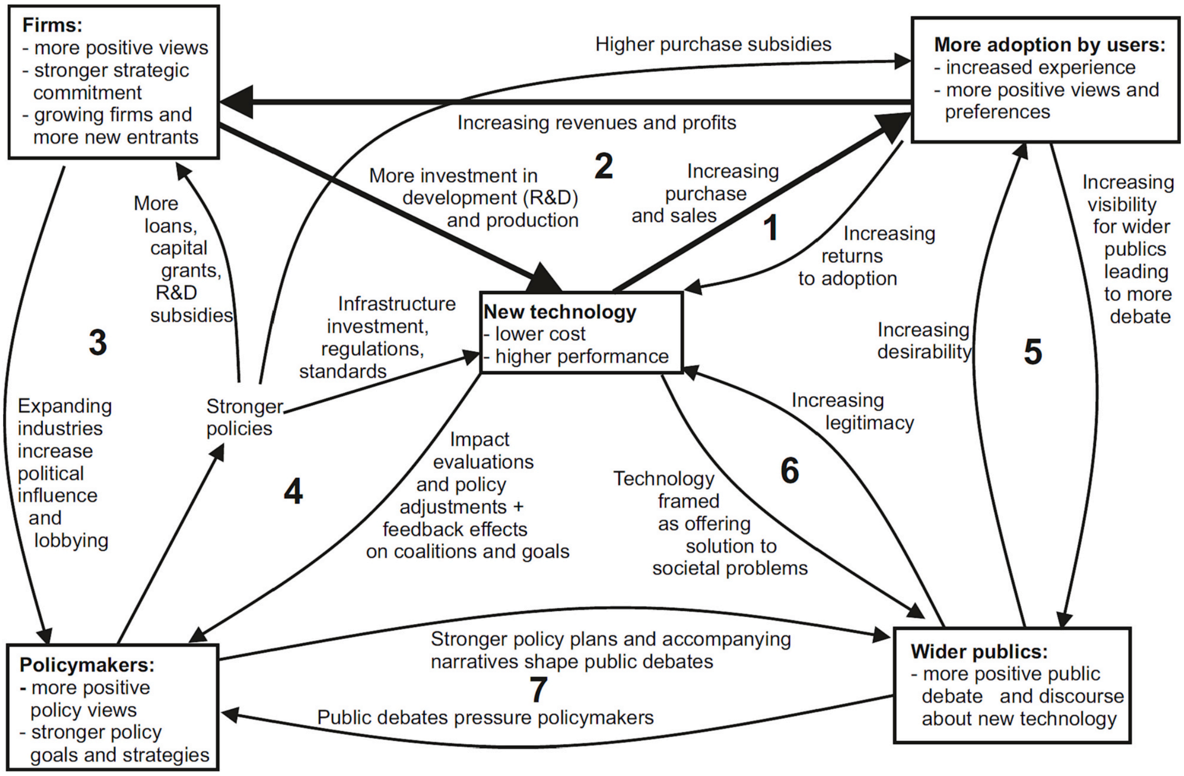

Figure 3.4: Feedback loop model of Geels and Ayoub (2023)

With their work, the authors paved the way to analysing the interaction between innovations and socio-technical systems, as invoked by Geels et al. (2017). They also contribute to understanding how to deliberately enable reinforcing feedbacks and positive tipping points using existing interventions as suggested by Lenton et al. (2022), and through policymaking as pointed out by Roberts et al. (2018). Moreover, their two case studies - offshore wind and electric vehicles in the United Kingdom (UK) - reveal the practical significance of interacting feedback loops and demonstrate different sequences of tipping point dynamics between the two sectors. Therefore, their case studies contribute to understanding how feedbacks exist in different contexts, as recommended by Fesenfeld et al. (2022).

Despite the relevant value of the study conducted by Geels and Ayoub (2023), several points can be improved concerning their work. Starting with the consistency of the diagram shown in Figure 3.4, the first improvement point relates to the blocks. While some represent an actor (*policymakers*, *firms*, and *wider publics*), another one has a complete sentence (*more adoption by users*), while the centre block represents a *new technology*. Apart from potential improvements in the labelling of the blocks, it would be clearer that different blocks represent distinct things if they had different shapes. For instance, the *new technology* block would benefit from having a distinct shape compared to the other blocks. Furthermore, the *firms* block currently represents a very wide group of actors as there are uncountable types of firms. Lastly, even though the case studies in Geels and Ayoub (2023) are performed for two SETs, the central block in their diagram reads *new technology*. It is, however, unclear whether their diagram and analysis can be applied generically to any new technology or solely to SETs.

The second improvement point related to the consistency of Figure 3.4 concerns the arrow labels. On the one hand, some of them include an interaction and the consequence of the same. Examples are *increasing visibility for wider publics leading to more debate* (feedback 5) and *stronger policy plans and accompanying narratives shape public debates* (feedback 7). On the other hand, some arrows have a sense of direction through the use of words as “higher”, “more” or “increasing” while others do not. It can be argued that what is relevant is that the interaction occurred and not whether that factor increased or decreased compared to a past period of time. For instance, it is by itself relevant that policymakers release loans, capital grants, R&D subsidies and purchase subsidies. It is not necessarily preferable to have more of these incentives if the ones implemented are effective.

Additionally, improvements could be made to the analysis and descriptions of the case studies. To start with, the attainment of a positive tipping point involves the participation of an expanded set of actors compared to the ones in Figure 3.4. This is suggested by Geels and Ayoub (2023) themselves and supported by Geels and Turnheim (2022), where a description of the diffusion of offshore wind and electric vehicles in the UK is given. Perhaps Geels and Ayoub (2023) did not intend for their feedback loop model to become too complex and therefore focused only on four actor groups. Nevertheless, the result was a simplified model that does not represent the whole reality of the factors involved.

Furthermore, the model of Geels and Ayoub (2023) only includes one interaction (i.e. arrow) that is not part of a particular feedback loop. This is *higher purchase subsidies*, from the policymakers to the users. Nevertheless, such ‘isolated’ interactions might play a big role in the technology’s deployment, at times being the ones responsible for triggering a reinforcing feedback loop in the first place.

Concerning the data collected and analysed, Geels and Ayoub (2023) lack a good criterion for which time frame and data is relevant, resulting in a broad scope. For instance, both case studies were analysed since the (early or late) 2000s until the present moment. Nevertheless, the positive tipping point occurred in 2009 for offshore wind energy and in 2019 for EVs, begging the question of whether it is relevant to analyse a similar time frame for both case studies. Just as what happened in the late 2000s might not have had a large impact in the EVs tipping point in 2019, the events that occurred after 2020 probably do not explain the 2009 tipping point for offshore wind energy. It is also unclear which factors were the most critical for the events in their two case studies to unfold the way they did. Particularly in this respect is the fact that Geels and Ayoub (2023) identify the relevance of policies and policymakers but do not, for instance, mention which policies were determinant in triggering the positive tipping point. The policy aspect could therefore be developed further in order to contribute to the knowledge gap identified by Fesenfeld et al. (2022) on understanding how specific policies promote technological and behavioural change through intentional reinforcing feedback loops.

The lack of good criteria to select relevant data and to identify the main contributing factors to trigger the positive tipping points was also revealed through pieces of information that did not seem to help create the feedback loop model or in reaching the conclusions taken. For instance, for the case study of EVs in the UK, the authors covered global EV developments by including China in the case study. However, the few information provided on the roll-out of EVs in China was quite broad and was only given for some actor groups during certain time periods. The role of this information in understanding the accelerated deployment of EVs in the UK is unclear. At the same time, Geels and Ayoub (2023) included a thorough description of EV-related plants, jobs, and supply chain firms in the UK after 2017. There is not a clear link between changes in these factors and the increased adoption rate after 2019. Besides, these considerations have not been added to their feedback loop model.

The data collected by Geels and Ayoub (2023) was written chronologically. Each piece of information was linked to the corresponding feedback loop by specifying its number between squared brackets. It is not always clear how each piece of information connects to that specific feedback loop. An example, among others, is when the authors state that purchase subsidies and positive public discourses contributed to a higher uptake of EVs after 2015, identifying feedback loops 4 and 5 as relevant. However, this information does not seem to directly relate to neither feedback loop. For one, providing purchase subsidies does not seem to belong to any particular feedback loop. For another, it is true that positive public discourses can lead to increased desirability for EVs, leading to more adoption. Nevertheless, in Figure 3.4, increased adoption is not a consequence of feedback 5 - only an increase in desirability.

Moreover, Geels and Ayoub (2023) utilised the electricity generated as a measure for deployment in offshore wind energy. However, this metric is contingent on weather conditions and may not accurately reflect actual roll-out figures. In comparison, the cumulative installed capacity would offer a more accurate reflection of the technology's adoption rate.

One final point that could be questioned about the analyses performed by Geels and Ayoub (2023) is that they classify significant shifts in actor attitudes as positive tipping points in that specific actor sphere (e.g., political, social, technological). However, defining when a tipping point occurs in firms, users, wider publics, or policymaker perspectives can be ambiguous as it is not as straightforward as basing the choice on quantitative deployment figures.

Having provided a sketch of the literature landscape on the topic of socio-technical transitions and tipping points, Section 3.2 identifies a series of knowledge gaps.

3.2. Knowledge Gap

Several knowledge gaps were identified from the literature review conducted, as enumerated below. These relate to socio-technical tipping points in general, and to the policies used in this context.

1. Lack of knowledge on how to deliberately trigger socio-technical tipping points
    - 1.1 Which actors are essential to trigger a socio-technical tipping point
    - 1.2 How actors promote a tipping point through interventions and interactions with other actors
    - 1.3 How do the socio-technical tipping point dynamics differ in different contexts
    - 1.4 How to deliberately cultivate reinforcing feedback loops
    - 1.5 How to identify a positive tipping point
    - 1.6 Performing socio-technical research with the help of model-based analysis
2. Lack of knowledge with respect to the role of policies in triggering socio-technical tipping points
    - 2.1 How do policies lead to behavioural and technological changes

2.2 How to overcome the political opposition against sufficiency and substitution practices
2.3 How sustainable are the positive feedbacks generated by transition policies

In this thesis, it was attempted to address knowledge gaps 1.1, 1.2, 1.3, 1.4 and 2.1. Knowledge gap 1.5 is also covered in this thesis, with the caveat that this is done in retrospect, i.e., looking at historical data. Another interesting research gap is understanding how to identify that a positive tipping point is about to the crossed or has just been crossed. However, this is not the goal of this thesis. This and the remaining knowledge gaps are left to be investigated in further studies. Having the relevant knowledge gaps in mind, Section 3.3 clarifies the goal of this Master's thesis.

3.3. Research Aim

Considering the knowledge gaps this thesis aimed to tackle (see Section 3.2), the main goal was to contribute to the lack of research on the dynamics of socio-technical tipping points and how to intentionally trigger them. In this quest, it is important to understand how the actor dynamics, the policies and the context play a role in promoting, triggering, and sustaining positive tipping points. It can be said that every framework presented in Section 3.1 lacks something, creating avenues for further research.

At the same time, the model of Geels and Ayoub (2023) in particular had potential to be refined and expanded (see Section 3.1). This research aimed to refine the authors' model by tackling inconsistencies in the labels of the blocks and arrows. In terms of expanding the model, this thesis aimed to include in it more actors and interactions among these, understand the role of policymakers, and contribute to expanding the knowledge base by conducting more case studies. An associated goal was to not make the model overly complex, which could compromise its readability. In Section 5.2.2 the criteria to decide which data was deemed relevant to collect and to add to the model is provided.

3.4. Research Questions

To achieve the goals of this research (see Section 3.3) a main research question and five sub-questions were formulated. The proposed research question was ***"How can the feedback loop model of Geels and Ayoub (2023) be refined and expanded to understand how positive tipping points can be triggered in the adoption of sustainable energy technologies?"***. Answering this question represented one more step in the direction of understanding how to accelerate the global shift towards sustainability. To answer the main research question, the following five sub-questions were answered.

1. How can the feedback loop model of Geels and Ayoub (2023) be refined to improve its consistency and readability?
2. Apart from the actor groups selected by Geels and Ayoub (2023), which other actors are relevant in promoting positive tipping points in the deployment of sustainable energy technologies?
3. What are the main actor roles in promoting a positive tipping point in the deployment of sustainable energy technologies?
4. Apart from the policy types identified by Geels and Ayoub (2023), which other policies are relevant in promoting positive tipping points in the deployment of sustainable energy technologies?
5. How can the feedback loop model of Geels and Ayoub (2023) be expanded to include a wider set of actors and interactions between these while maintaining its readability?

The main final output of the thesis was, firstly, four case studies which contribute to building empirical repertoire on the topic. Two case studies concerning wind energy, and two case studies concerning electric vehicles were analysed. Secondly, the thesis concludes with two feedback loop models[1] similar to that in Figure 4.2 where more actors and feedback loops are included.

Chapter 5 explains the methodology used to answer the questions above and to select the case studies. Sub-question 1 is answered in Section 4.2. Sub-questions 2, 3, and 4 are covered in Section 7.1.2, Section 7.1.3, and Table 7.15, respectively. Finally, Section 7.1.1 answers sub-question 5.

3.5. Significance of the Study

This study is significant within the broader landscape of socio-technical tipping points, adding depth to the existing knowledge base. The commitment to improve and build upon the model of Geels and Ayoub (2023) fostered the evolution of a relevant theoretical framework within the field, at the same time contributing to validate it. A key contribution lied in taking one more step in the direction of a visual framework of how actors interact with each other and intervene in socio-technical systems.

The case study analysis performed explored how feedback loops and positive tipping points manifest in diverse contexts, as suggested in the literature. By understanding which actor groups were relevant and how the actor dynamics unfolded in four case studies, this investigation contributed to understanding how to deliberately promote and trigger positive tipping points in the adoption of SETs in distinct settings. In interpreting the results, special attention was given to the role of policymakers, due to their importance in creating the necessary enabling conditions (Edmondson et al., 2019; Fesenfeld et al., 2022; Geels & Ayoub, 2023; Geels et al., 2017; Lenton et al., 2022; Roberts et al., 2018).

Conducting four case studies enhanced the applicability and generalisability of the findings, contributing to a more nuanced understanding. The actors and actor roles in the wind energy case studies differed slightly from those in the electric vehicle cases. However, they were consistent between the two wind energy studies and between the two electric vehicle studies. This suggests that tipping point dynamics may be similar within business-to-business and business-to-consumer clean energy technologies.

The findings of this research are relevant both for the scientific community, as well as for policymakers and industry players seeking to navigate the complexities of socio-technical transitions by facilitating sustainable technology adoption and behavioural shifts. Therefore, this Master's thesis provides a valuable contribution to the ongoing discourse on socio-technical tipping points.

This chapter described the research aim, how it fits within the existing literature, and how it contributes to relevant knowledge gaps. Chapter 4 proceeds by explaining the conceptual framework used, which was based on the work of Geels and Ayoub (2023).

[1] Two feedback loops are presented since key differences were found between the wind energy and the EV case studies.

4 | Conceptual Framework

This chapter presents the conceptual framework used in this investigation. Section 4.1 discusses the framework presented by Geels and Ayoub (2023), used as the basis for this thesis' conceptual framework. Following, Section 4.2 explains the refinements performed to this framework. The chapter finalises in Section 4.3 with possible expansions to this model concerning actors and actor roles.

4.1. Geels & Ayoub's Framework

The framework presented by Geels and Ayoub (2023) to study positive tipping points in socio-technical transitions was used as the basis for this thesis' conceptual framework. The author's proposed framework is rooted in the Multi-Level Perspective, initially presented in Geels (2002) and later on refined in Geels (2019). Section 4.1.1 starts by delving into the Multi-Level Perspective. Afterwards, Section 4.1.2 describes the conceptual framework itself, i.e. the feedback loop model of Geels and Ayoub (2023).

4.1.1. Multi-Level Perspective

The Multi-Level Perspective (MLP) built on Geels' foundational work is shown in Figure 4.1. It is called 'multi-level' because it considers transitions and innovations as occurring across multiple interconnected levels within a societal system, presented in the vertical axis of Figure 4.1. The lower one, the *niche innovation*, refers to an emerging, innovative, and radical technology. Then, the *socio-technical system* corresponds to the regime with its established practices. At the top, the *landscape* represents the broader societal context in which events unfold. Then, when the innovation is developing, four phases can be distinguished, on the horizontal axis: 1) experimentation, 2) stabilisation, 3) diffusion and disruption, and 4) institutionalisation and anchoring. *Experimentation* (phase 1) is characterised by the emergence of radical niche-innovations in niches via small projects. In the subsequent *stabilisation* period (phase 2) the innovation gains a foothold in small market niches and the technical design rules stabilise. This is followed by *diffusion and disruption* (phase 3), where the innovation enters mass markets, competing with existing systems and established technologies. Lastly, *institutionalisation and anchoring* (phase 4) occur when the new system becomes anchored in regulatory programs, user habits, and professional standards (Geels & Ayoub, 2023).

Geels and Ayoub (2023) define a positive tipping point as occurring between phases 2 and 3 of the MLP, as highlighted in Figure 4.1. When crossing this threshold, innovation dynamics transition from requiring substantial protective and developmental efforts to becoming self-sustaining through strong reinforcing feedbacks and alignment of socio-technical elements. This means that, when looking at a graph of the technology adoption over time, a positive tipping point is identified when the rate of adoption substantially increases from one year to the next and this rate is (approximately) maintained in the subsequent years, being eventually followed by a stabilisation phase. This behaviour can be visualised in Figure 3 and Figure 12 of Geels and Ayoub (2023), where a tipping point can be identified in 2009 and 2019 for offshore wind and electric vehicles in the UK, respectively.

The similarities with Figure 2.1 are significant. It could be said that phases 2, 3 and 4 in Figure 4.1 correspond to the enabling, accelerating, and stabilising phases in Figure 2.1, respectively. This definition also agrees with how Lenton et al. (2022) and Fesenfeld et al. (2022) identify a positive tipping point. Therefore, in this investigation the same definition of a positive tipping point was used.

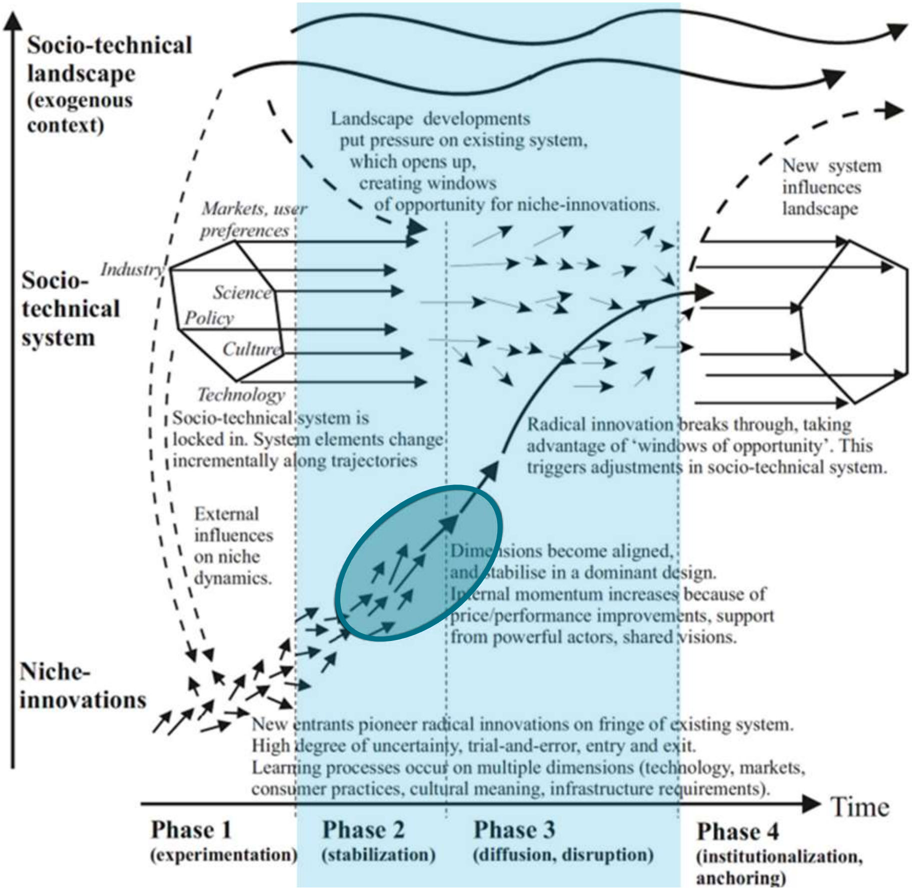

Figure 4.1: Multi-level perspective where the tipping point is identified by an ellipse (Geels & Ayoub, 2023)

4.1.2. Feedback Loop Model

The feedback loop model of Geels and Ayoub (2023), shown in Figure 4.2[1], was based on the MLP. It focuses on co-evolutionary feedback loops between a new technology and four actor groups. The framework integrates insights from wider social sciences, moving beyond traditional tipping point models. It focuses on actors with routines, capabilities, beliefs, and interests, emphasising reactive feedback loops across various dimensions (Geels & Ayoub, 2023). Below, a description of the model's blocks and feedback loops is given, alongside the actor roles that can be identified.

Explanation of Blocks

The article lacks an explanation of the blocks included in Figure 4.2. Therefore, definitions are provided below, corresponding to the ones used in the remaining of this report. These definitions are based on the information provided in Geels and Ayoub (2023) with the help of supporting sources.

[1]This is the same figure as Figure 3.4. It was here added again to support the explanatory text provided in this subsection.

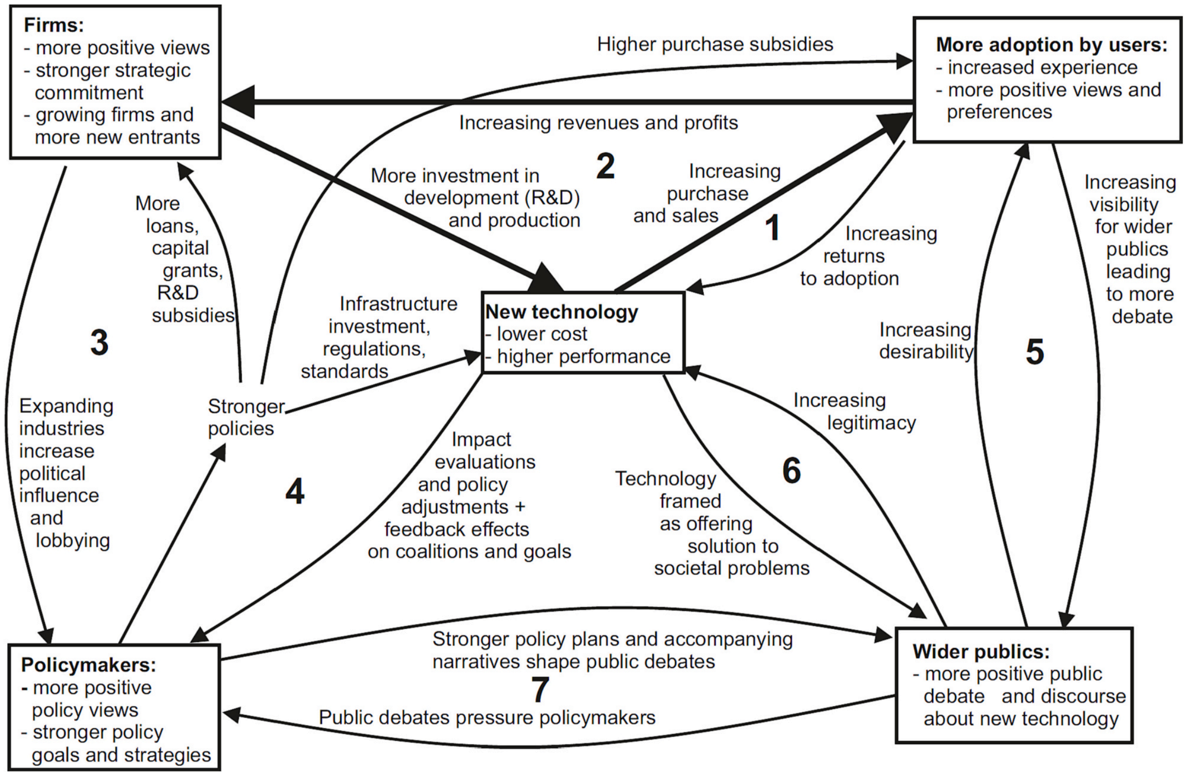

Figure 4.2: Feedback loop model of Geels and Ayoub (2023)

Geels and Ayoub (2023) focus on a ***new technology*** in the context of socio-technical tipping points, analysing two case studies concerning sustainable energy technologies. Representing the new technology separately allows to visualise perspectives about and interactions with (the idea of) the technology, irrespective of which firm is developing it. For instance, an actor might be against a certain firm, due to e.g., its principles, and yet support one or some of the technologies developed or sold by this firm. It is possible that by new technology the authors mean a clean(er) technology, despite not stating this explicitly. Since this thesis focused on promoting the energy transition, the new technology should be interpreted as a *sustainable energy technology* (defined in Section 2.1) from here onwards.

Since the framework proposed by Geels and Ayoub (2023) is based on the MLP, the new technology likely intends to represent a niche innovation trying to break into the socio-technical regime. The term 'niche innovation' is associated with radical innovations that are taking their first steps (Geels, 2019). Nevertheless, in this thesis the technology was not referred to as a niche nor radical innovation. This is because by now technologies such as electric vehicles or wind turbines are not radical innovations anymore and yet they are not part of some countries' socio-technical regime. Additionally, many sustainable energy technologies are not just introduced by new entrants since they are typically researched and developed by incumbents as well (Geels & Ayoub, 2023). In this thesis the focus was put on phases 2 and 3 of Figure 4.1, which considers a technology which has stabilised in a dominant design.

It can be deduced that the block ***firms*** is used to represent to *technology firms*, which design, develop, manufacture, and provide innovative technologies, products, and services (Geels & Turnheim, 2022). These firms are at the forefront of technological advancements. Within this category, two groups can be distinguished: incumbents and new entrants (Fang, Li, & Govindan, 2024; Geels & Ayoub, 2023).

Incumbent technology firms are well-established and often large companies (Karttunen et al., 2021) that have been operating for an extended period. Incumbents have a history of producing and distributing traditional technologies, typically having substantial resources, industry expertise, and infrastructure (Fang et al., 2024). An example of an incumbent which recently aligned their vision with a more sustainable future is Siemens (2023). After a long history in conventional power plants and transmission technologies, in 2004 they diversified to wind turbines and in 2020 Siemens Energy was founded.

New entrants are usually the ones beginning new technology cycles, having fresh perspectives, disruptive solutions, and emerging technologies (Geels, 2019; Karttunen et al., 2021). New entrants might be start-ups or relatively young and small companies (Fang et al., 2024) driven by having a positive environmental impact (Karttunen et al., 2021). Tesla (2023) is an example of a new entrant with a disruptive approach. It was not an established automaker with a history of internal combustion engine vehicles. Instead, it focused on electric mobility bringing fresh ideas and innovation to the market.

User engagement and preferences influence the adoption of SETs (Ekim, Mattsson, & Bernardo, 2023; Geels & Turnheim, 2022) and therefore their demand and returns profile (Geels & Ayoub, 2023). It can be concluded that ***users*** aim to represent the entities and individuals who buy and/or utilise SETs, being referred hereinafter by *adopters* to avoid confusion. While the term adopter and user can most of the times be used interchangeably when it comes to EVs, it is not as straightforward for wind energy. For instance, while energy or utility firms might adopt wind turbines for their own use, it might also be that private investors purchase and install a wind farm (therefore being viewed as adopters) but sell it to a final owner after the instalment, making the latter the actual user of the technology. Furthermore, confusion might also arise between the users of the technology versus the users of the electricity.

Adopters can be businesses (or “user firms” as described by Geels and Ayoub (2023)) or individual consumers. Some technologies are adopted by both business and individual consumers, such as solar panels and energy-efficient solutions for buildings (Ekim et al., 2023; Geels & Turnheim, 2022). However, others strongly depend on being adopted by either businesses (e.g., wind turbines) or individual buyers (e.g., EVs) (Geels & Ayoub, 2023). The former are commonly referred to as business-to-business (B2B) technologies, while the latter as business-to-consumer (B2C) technologies.

Wider publics refers to a broad and diverse set of stakeholders including the general public, communities, advocacy groups, and society at large, that impact and shape the adoption and advancement of SETs. More positive public debate and discourse about a new technology increase its legitimacy and desirability (Geels & Ayoub, 2023). This can lead to more adopters, helping accelerate technological diffusion. Conversely, negative public opinion can hinder the development and uptake of a technology, as exemplified by nuclear energy (Ming, Yingxin, Shaojie, Hui, & Chunxue, 2016). Hence, considering the wider public is crucial to incorporate behavioural changes in the model (Fesenfeld et al., 2022).

Finally, ***policymakers*** encompass “political parties, Parliament, courts, and lobby groups” (Geels & Ayoub, 2023) responsible for formulating, implementing, and overseeing policies, laws, regulations, and guidelines at various government levels, from local and regional authorities to national and international bodies (Sultana, Dwivedi, & Moktadir, 2023; Vivalt & Coville, 2023).

Explanation of Feedback Loops

Figure 4.2 portraits seven feedback loops among the five blocks explained above. Each interaction in the model illustrates the role of different actors in influencing technology adoption, development, and policy shaping. Feedback loops 1 and 2 represent the economically-oriented feedbacks, where the technology firms interact with the adopters. The remaining loops correspond to the socio-political feedback loops. Socio-political processes have special significance in early transition phases when economic feedbacks tend to be negative and the economic actors (technology firms and adopters) are reluctant to invest. Overcoming negative feedbacks, such as high costs and inertia, is a challenge in these early phases, often addressed by radical innovations emerging in niches with protective policy support (Geels & Ayoub, 2023). The seven feedback loops are briefly explained below[2].

- ***Feedback 1*** (*users and technology):* Increasing user adoption reduces technology costs, stimulating further adoption. This is also referred to as increasing returns to adoption;
- ***Feedback 2*** (*firms, technology, users):* Firms invest more in new technologies with increasing demand, improving technical performance, and lowering costs;
- ***Feedback 3*** (*firms and policymakers):* Growing technology firms have greater political access and hence influence on shaping policies;
- ***Feedback 4*** (*policymakers and technology):* Policymakers shape technology development and deployment through various instruments;
- ***Feedback 5*** (*users and wider publics):* Increasing adoption enhances learning-by-using processes, improving familiarity and perceptions of new technologies;
- ***Feedback 6*** (*wider publics and technology):* Positive public debates enhance the cultural meanings and societal legitimacy of new technologies;
- ***Feedback 7*** (*wider publics and policymakers):* Increasing public attention creates pressures on policymakers to introduce new or strengthen existing policies.

Actor Roles

It can be said that Figure 4.2 capture with their framework seven overarching actor roles, being them 1) technology development, 2) technology adoption, 3) legitimising technology, 4) providing financing incentives/options, 5) investing in infrastructure, 6) establishing legislation, and 7) lobbying.

The framework of Geels and Ayoub (2023) provides a comprehensive understanding of positive tipping points in socio-technical transitions, emphasising the interplay between actors, feedback loops, and contextual factors. Nevertheless, the model can benefit from improvements, as detailed in Section 3.1. The refinements applied to the original feedback loop model are presented in Section 4.2.

4.2. Feedback Loop Model Refinement

In refining the feedback loop model of Geels and Ayoub (2023), the blocks' labels as well as the labels of the arrows connecting two blocks were modified, following the arguments presented in Section 3.1. This is explained in Section 4.2.1 and Section 4.2.2, respectively. The refined version of the model is illustrated in Figure 4.3, which should be compared to Figure 4.2.

[2]For more information consult Geels and Ayoub (2023).

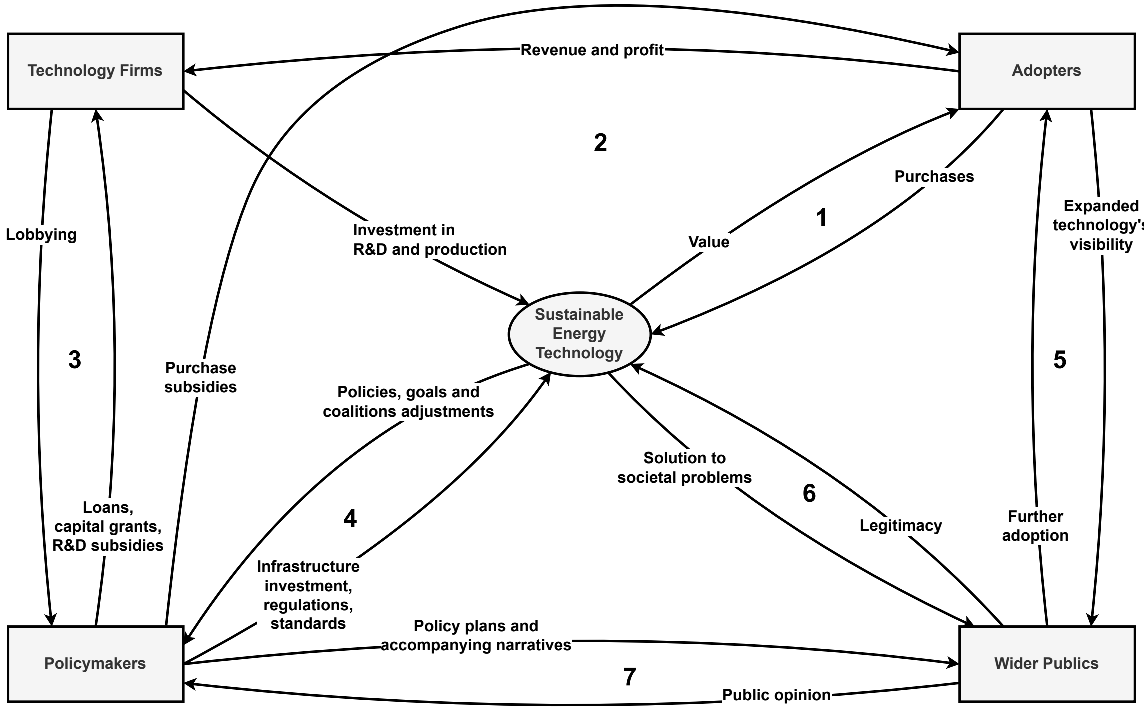

Figure 4.3: Refined version of the feedback loop model of Geels and Ayoub (2023)

4.2.1. Modifications to Blocks

Firstly, the block with *more adoption by users* was replaced by *adopters*. Secondly, the *new technology* block was changed into an ellipse so that it is clear that it does not correspond to an actor like the remaining blocks. Its label was also modified to *sustainable energy technology* since that is the focus of this thesis. This should not have an impact on the overall meaning of the diagram developed by Geels and Ayoub (2023). Rather, it helped in making the diagrams developed during this investigation more specific as the conclusions taken at the end of this research might not be applicable to all new technologies but solely to new *sustainable energy* technologies. Thirdly, the block labelled *firms* was changed into *technology firms*, following the reasoning given in Section 4.1.2.

Moreover, each block has now only its label and not a brief description of how the respective views, strategies and goals evolved over time due to the feedback loops. This reduced the complexity of the initial version of the model, which was especially relevant since the goal of this thesis was to add more actors and interactions to the model, inevitably increasing its overall complexity. The information conveyed by these labels was, nevertheless, not neglected and was incorporated in the explanatory text that accompanies the feedback loop model(s) presented in the remaining of this report.

4.2.2. Modifications to Arrows

Just like the block's labelling was thought to lack consistency, the labels of the arrows in Figure 4.2 could also benefit from improvements, as detailed in Section 3.1. For one, the consequence of an interaction was removed from the arrow's label such that the arrow label would only represent the interaction itself. For another, comparative adjectives such as "higher", "more" or "increasing" were removed.

Additionally, a system was created to build a sentence using: label block 1 + verb + *arrow label* + connector + label block 2. Block 1 is the one connected to the start of the arrow, while block 2 connects to the arrow's head. An example is: *policymakers* + give + *loans, capital grants and R&D subsidies* + to + *technology firms* (feedback 3). These points resulted in three rules for the labels of the arrows that were applied not only when modifying the arrows in the model of Geels and Ayoub (2023) but also when adding new arrows to the baseline model. The rules are summarised below.

- **Rule 1:** The arrow's label should only represent an interaction between two actors or an actor and the technology. The consequence of that interaction should not be included. *Example:* The label *stronger policy plans and accompanying narratives shape public debates* should not include *shape public debates*[3];
- **Rule 2:** Arrows should not have a sense of direction through the use of words such as "higher", "more" or "increasing". *Example: higher purchase subsidies* should be solely *purchase subsidies*;
- **Rule 3:** It should be possible to formulate a sentence using the following elements: block 1 label + verb + *arrow label* + connector + block 2 label. *Example:* The *sustainable energy technology* + provides + *value* + to + the *adopters*.

Apart from performing adjustments to several arrow labels such that these complied with the three rules presented above, two feedback loops suffered bigger adjustments. In feedback loop 1 it is not possible to formulate a sentence using rule 3 for the label *increasing purchase and sales* since it would resemble the following: the technology provides increasing purchase and sales to the adopters. It is true, however, that feedback 1 is meant to represent increasing returns to adoption, defined as a reduction in the technology's costs and increase in its performance as adoption rises (Geels & Ayoub, 2023). To try to capture this idea while following the established rules, feedback loop 1 now reads as: the *SET* presents (a higher) *value*[4] to the *adopters*, which complete (more) *purchases* of the *SET*.

Feedback loop 5 also suffered modifications. Presumably, Geels and Ayoub (2023) meant that more adoption by users increase the technology's for the wider public, leading to more public debate and desirability to buy the product, resulting in more adoption. First, the fact that there are more public debates is a *consequence* of the interaction between the adopters and the wider public and should not be part of the arrow label according to rule 1. Second, the higher desirability for the technology is at most an interaction between the wider publics and the technology, not the adopters. Thirdly, the resulting increased adoption is represented in the label of the users' block in Figure 4.2 but not in the arrow connecting the actors. For these reasons, the arrow going from the wider publics to the adopters was changed from *increasing desirability* to *further adoption*. It is thought that this does not change the meaning of feedback loop 5 while making it clearer. Lastly, the arrow label going from the adopters to the wider publics was also modified as to follow the rules established. Accordingly, now it reads as: *adopters* contribute to *expanded technology's visibility* for the *wider publics*.

Combining these labelling modifications, the model shown in Figure 4.3 is a refined version of the one in Figure 4.2. Nonetheless, based on evidence from literature it is expected that more actors and actor roles have a relevant contribution to the accelerated deployment of sustainable energy technologies. Section 4.3 covers potential expansions to the feedback loop model concerning these aspects.

[3]This specific arrow label also suffered other modifications in order to comply with rules 2 and 3.
[4]A higher value is associated with a better performance and a lower cost.

4.3. Feedback Loop Model Expansion

The model presented by Geels and Ayoub (2023) and explained in Section 4.1 has the advantage of being simple in the sense that it only includes four actor groups. However, this comes with the possible negative consequence of excluding important actors and respective functions. Section 4.3.1 provides an explanation for four actor groups, and associated actor roles, that other scientific sources deem relevant in socio-technical transitions. According to the information found about these actors, an initial version of an expanded feedback loop model is proposed in Section 4.3.2.

4.3.1. Actors & Actor Roles

In Section 4.1.2, the four actor groups included in the model of Geels and Ayoub (2023) are described. However, the authors themselves identified that their feedback loop model could benefit from the addition of more actor groups. Nevertheless, apart from financial firms, the authors did not provide other suggestions for additions. Apart from financial institutions, literature repeatedly refers to three other actor groups apart from the ones presented by Geels and Ayoub (2023). These are academic and research institutes, trade associations, and non-governmental organisations (NGOs). A description of these four actors and the functions they typically perform is provided below.

Academic & Research Institutes

Academic and research institutes function as innovation, learning, and knowledge hubs by researching and testing innovative and radical solutions. They include universities, research centres, technical schools, and academic departments. A range of partnerships exist between these institutes and technology firms, including student-centred partnerships focusing on workforce development (Becker & Brown, 2000) as well as research partnerships driven by innovation and sponsorship opportunities (Fraser et al., 2011). The translation of scientific advances into commercial products is facilitated by funding partnerships, where technology firms act as research sponsors (S. Chai & Shih, 2016). These partnerships are crucial for knowledge exchange and talent development.

NGOs

NGOs shape public debates and opinion via public awareness campaigns and supporting (and sometimes starting) grassroot movements. Moreover, NGOs actively advocate for policy changes - often in the name of the wider public - through direct and indirect lobbying (De Bruycker & Beyers, 2019) and their research activities. For instance, in the UK NGOs played a key role not only in advocating in favour or against certain technologies but also in drafting the 2008 Climate Change Act (Farmer et al., 2019; Geels & Turnheim, 2022). Furthermore, NGOs are involved in litigation and electioneering processes which directly affect policymaking and policymakers. Geels (2019) stresses that policymakers should aim for a more open and inclusive governance style by involving NGOs, which in turn leads to a more participatory democracy (Junk, 2016). The World Wildlife Fund (2023) is an example of an NGO that works on renewable energy initiatives, advocating for policies that promote clean energy adoption. They also partner with governments and businesses to support sustainable energy practices.

Financial Institutions

Public resources are limited and so financial institutions are needed to cover the large capital costs (Falchetta, Michoud, Hafner, & Rother, 2022) required by novel SETs. For instance, on the offshore wind case study of Geels and Ayoub (2023), it was found that although policymakers were able to drive firm strategies and technology deployment, it was essential that private investors were mobilised in order for costs to decrease and adoption to increase further. An increased access to equity and debt finance (like pension funds, insurance funds, sovereign wealth funds) led to lower risk profiles and reduced capital costs, which increased adoption. Nonetheless, the authors left this actor group out of their model. Other authors also identified private investment, such as bank loans (Xu, Kasimov, & Wang, 2022), as crucial for fostering universal access to electricity (Falchetta et al., 2022; Hinestroza-Olascuaga, Carvalho, & de Jesus, 2023), for developing the renewable energy industry, and for promoting the conservation of resources and of the environment (Xu et al., 2022).

Financial institutions facilitate the financing of SETs by providing financial services, investment, and funding They encompass a wide range of entities, including banks, investment firms, venture capital organisations, private equity firms, and public financing bodies, that contribute to the growth and advancement of SETs. For instance, the Green Investment Group (2023) is a specialist green investment entity known for its focus on investing in and financing renewable energy projects. They have committed or arranged more than £26 billion and contributed to more than 90 GW of green energy assets.

Trade Associations

Trade associations allow for better communication, knowledge exchange, and collaboration between businesses, professionals, and stakeholders, which constitutes an advantage for firms and consumer surplus. Furthermore, they represent and advocate for the collective interests of their members next to policymakers. These associations do not have a direct commercial interest and therefore they are better able to advocate, in the name of the individual companies, for policies, standards, and practices that support the development, deployment, and adoption of clean and renewable energy technologies. Besides, trade associations might help financial institutions assess industry trends, risks, and opportunities, engage in public awareness campaigns involving the wider public, and collaborate with NGOs on sustainability initiatives and policy advocacy (Boleat, 1996; Kirby, 1988).

Geels and Turnheim (2022) highlight the role of trade associations in low carbon transitions in the UK, namely concerning electricity consumption, offshore wind, building systems, and biomass heating. Different types of trade associations include industry, multi-industry, specialised, company, federal, national, and international associations. Besides, a specific example is the international trade association for wind power, the Global Wind Energy Council (2023). They conduct authoritative research and analysis on the wind power industry. Moreover, they work with governments and international institutions to provide them with transparent information about the advantages and potential of the technology. Besides, they foster collaboration between policymakers from various countries.

Policymakers

The literature did therefore suggest that the role of policymakers was more extensive than suggested by Geels and Ayoub (2023). In addition to what has been included in the descriptions above, policymakers can address resistance from incumbents by providing incentives to promote firm reorientation, which might include phase-out policies, professional training and qualification programs (Geels, 2019; Lenton et al., 2022; Rogge & Reichardt, 2016). Policymakers also appear as relevant actors in cultivating a positive public opinion on SETs since policies shape public debates. One way in which policymakers can foster public acceptance is via knowledge and education programmes (Sultana et al., 2023).

Indeed, a large list of policy instruments is typically utilised to promote cleaner technologies. To explore the full extent of the role of policymakers, this thesis analysed which specific policies had been relevant to trigger the positive tipping point of each case study. Due to the plenitude of policy instruments available, and since specific policies (names) differ between case studies, policy instruments were categorised according to their objective. Policies can be divided into three main groups: economic, regulatory, and information instruments (Rogge & Reichardt, 2016). Each instrument type was further sub-divided into three categories, as briefly explained below. This is explained in detail in Section C.1.

Firstly, **economic instruments** might involve financial incentives, market-based mechanisms, and R&D support schemes. *Financial incentives* aim to stimulate investment in renewable energy projects and promote the adoption of sustainable practices. Examples include purchase subsidies, feed-in tariffs, tax rebates, and green bonds (Cox, 2016). *Market-based mechanisms* leverage market forces to internalise the costs of environmental externalities and promote emissions reductions. Examples are carbon taxes, tenders, and net metering (Joskow & Schmalensee, 1998). *R&D support* aim to foster innovation and technological advancements through financial support for R&D and demonstration projects (Huergo & Moreno, 2014).

Secondly, **regulatory instruments** can relate to compliance and standards, strategic planning, or market facilitation. *Standards* ensure that products, practices, and operations meet specific requirements or guidelines. Examples include mandating products or practices, intellectual property rights, renewable portfolio standards, technology/performance standards, and product labelling (ISO, 2024). *Strategic planning* involves the setting of goals, targets, and long-term roadmaps to guide policy development and decision-making (Gregersen & Johnson, 2010; Newell & Simms, 2021). *Market facilitation* focuses on creating conducive environments for the development, growth, and integration of renewable energy markets and infrastructure. This is done via local market design/development, infrastructure provision, and grid access guarantees (Steinbach & Bunk, 2024).

Thirdly, **information instruments** encompass knowledge transfer, collaboration and networking, and outreach initiatives. *Knowledge transfer* is designed to facilitate the exchange of information, expertise, and skills among stakeholders. Examples include professional and entrepreneurship trainings and scientific workshops (Kochenkova, Grimaldi, & Munari, 2015). *Collaboration and networking* incentives aim to facilitate partnerships, cooperation, and knowledge sharing among stakeholders, which is accomplished through public-private partnerships, cooperative RD&D programs, thematic meetings, and clusters (Q. Chai & Zhang, 2010; Lehmann, 2006). *Outreach* instruments aim to raise awareness, educate the public, and engage stakeholders. Examples include rating and labelling programs, public information campaigns, and organised public debates.

The descriptions given in this subsection point at six additional actor roles compared to the seven identified in the model Geels and Ayoub (2023) (see Section 4.1.2). These would be 8) raising awareness, 9) fostering collaboration, 10) transferring knowledge, 11) giving & receiving feedback, 12) establishing market-based mechanisms, and 13) promoting education. Therefore, this subsection suggests that Geels and Ayoub (2023) did not consider important actors and actor roles in their analysis and model. In Section 4.3.2, a few additions are proposed to the feedback loop model of Figure 4.3.

4.3.2. Initial Version of Expanded Feedback Loop Model

Through this initial literature investigation, four additional actors were found to have an important contribution to triggering a positive tipping point in SET development and deployment. This came with additional roles, considered relevant to include in the feedback loop model. Based on the descriptions given in Section 4.3.1, it is possible to draft an expanded version of the feedback loop model, presented in Figure 4.4. While it was attempted to keep the diagram as simple as possible, these additions were thought to be essential as simplicity should not come at the cost of omitting relevant information. Therefore, despite more complex, Figure 4.4 is more complete than Figure 4.3. The grey blocks and black arrow labels were already included in the refined version of the model (see Figure 4.3). The orange blocks and orange italic labels correspond to the additions proposed.

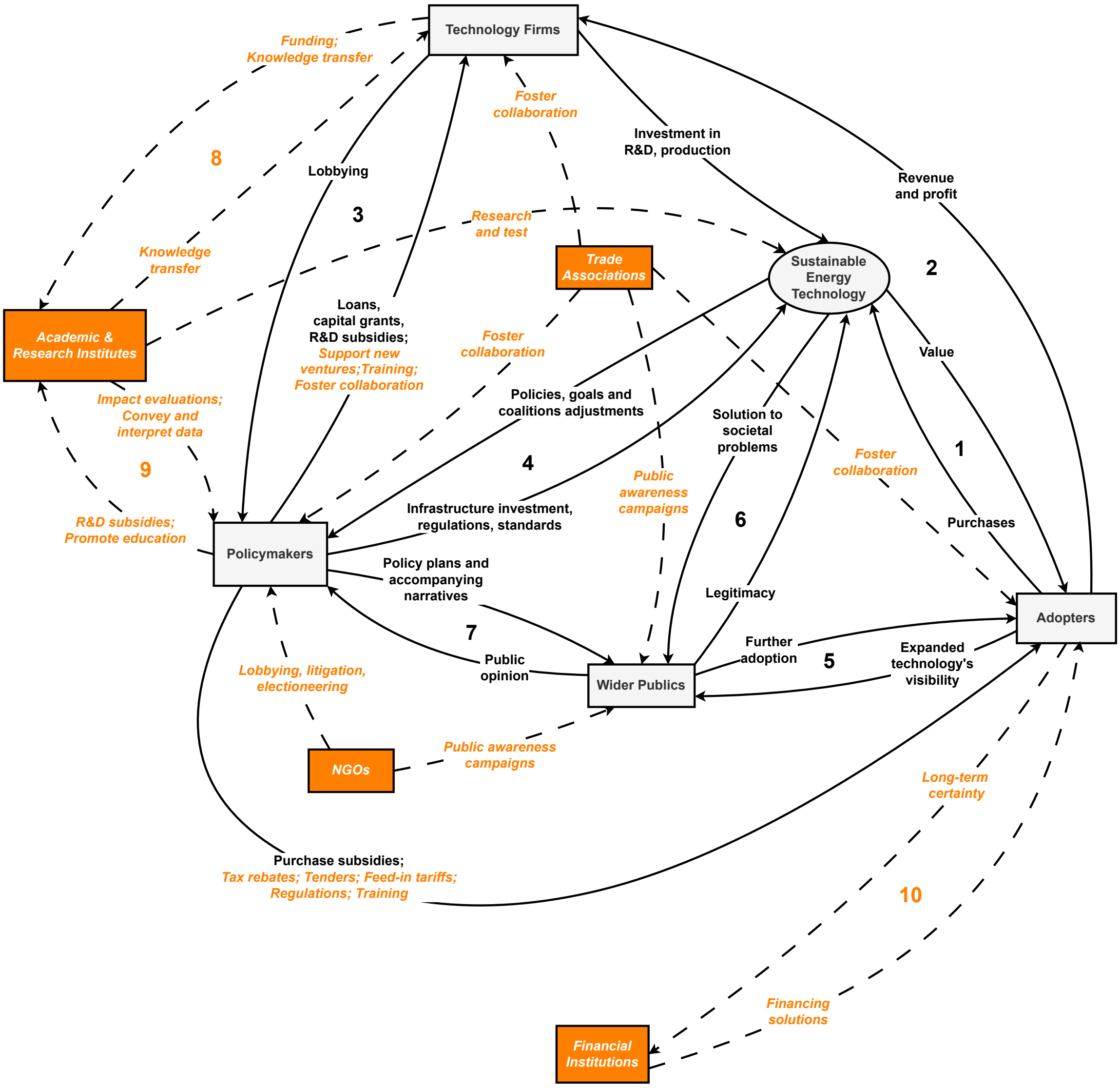

Figure 4.4: Proposed expanded version of the feedback loop model based on the literature presented in Section 4.3.1

This initial expanded version of the framework was tested with four case studies, allowing to understand whether these additions were found in practice and whether other important factors were still missing. Chapter 5 covers the case studies methodology utilised to conduct the research presented in this report.

5 | Case Studies Methodology

This chapter explains the methodology used to analyse the case studies. Section 5.1 provides the reasoning behind the chosen case studies and explains how they were analysed. In Section 5.2 the methods used to collect data are enumerated and it is detailed how the relevant data was selected. The chapter ends in Section 5.3 with the method used for the validation.

5.1. Case Studies Selection and Analysis

The concept of positive tipping points is fairly recent, with limited literature focusing on socio-technical tipping points (Geels & Ayoub, 2023; Lenton et al., 2022). An exploratory approach is thus adequate since it allows to understand the interactions between the different actors and among these and the SET. Case studies are a valuable research tool in exploratory research concerning under-researched fields (Fitzgerald, 1999). Besides, case studies are appropriate in examining qualitative dimensions like evolving perceptions and strategies, intricate interactions, and the tracing of processes. Lastly, a comparative design is useful to demonstrate distinct patterns and results (Geels & Ayoub, 2023).

To investigate the aforementioned propositions and to expand on the conceptual framework presented in Chapter 4, a comparative research design was used. Four case studies in which a positive tipping point had occurred were analysed. Section 5.1.1 gives the rationale behind the selection of the case studies, while in Section 5.1.2 the method used to analyse them is clarified.

5.1.1. Case Studies Selection

It is proposed that the actors engaged, their role, and the tipping points dynamics may exhibit variations not only when looking at B2B versus B2C, but also when looking at the deployment of the same technology in different contexts. For a B2B technology, such as wind or solar farms, the target customers are energy or utility firms that purchase large quantities of the technology to produce and sell energy. Comparatively, a B2C technology, like electric vehiles (EVs) or roof solar panels, is mainly purchased in small numbers by individuals, i.e. the end-consumer itself, and hence behavioural factors are expected to play a larger role (Geels & Ayoub, 2023). Further, it is proposed that the deployment dynamics of the same technology in different countries most likely involves distinct interactions between the actors and between these and the technology.

To compare the dynamics involved in the roll-out of B2B and B2C technologies, the adoption of wind turbines was compared with that of electric vehicles. Then, the impact of the context was evaluated by analysing the uptake of each technology in two countries. This design ensures that one variable, namely the type of technology remains constant, facilitating the examination of contextual changes in actors, actor roles, and feedback loops. Following this logic, four case studies were analysed, being them offshore wind in the UK, onshore wind in Portugal, EVs in the UK, and EVs in the Netherlands. Figure 5.1 gives a graphical representation of the chosen case studies.

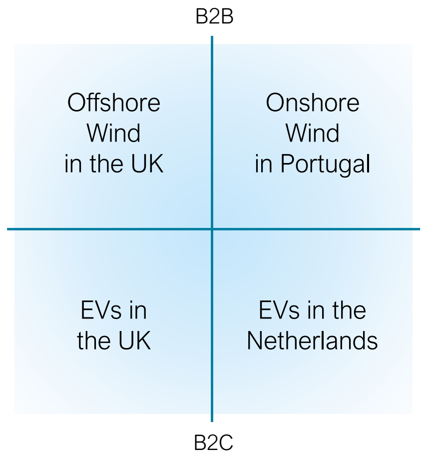

Figure 5.1: Matrix of the selected case studies, showing whether they are representative of business-to-business (B2B) or business-to-consumer (B2C) technologies

Offshore wind and EVs in the UK drew inspiration from the investigation of Geels and Ayoub (2023). Using their work as a starting point, the objective was to investigate whether additional actors were engaged in these two case studies and to what extent, i.e. what role they played and which feedback loops they contributed to. This was done by analysing information provided by other sources. Then, to observe the effect of context, the deployment of onshore wind turbines and of EVs was analysed in two other countries. Western-European countries were chosen because choosing a country with a completely different context and government structure (e.g., China) could mean that the observations differed so much from one case to the other that no parallel could be drawn.

For one, onshore wind energy in Portugal was examined since there was a noticeable acceleration post-2004 and an apparent stabilisation phase after 2010, as evident in the S-shaped curve of its cumulative capacity graph (see Figure 6.3). The onshore wind sector was analysed as the offshore sector is only now taking its first steps in Portugal (Costa, Simões, Couto, & Estanqueiro, 2021). This was, nonetheless, considered to be a relevant case study to compare with offshore wind in the UK for two reasons. First, onshore wind turbines are also a B2B technology. Second, both onshore and offshore wind are based on the same technology (even though the application constraints differ in each case). For another, the uptake of EVs in the Netherlands, which saw a substantial surge post-2019 (see Figure 6.9), was investigated and compared to the roll-out of the same technology in the UK.

The term ‘electric vehicle’ might have different interpretations (Contestabile, 2019; Geels & Turnheim, 2022). In this report, as in Geels and Ayoub (2023), it refers to cars able to operate fully electric, without the assistance of an internal combustion engine (ICE) or a fuel cell, i.e. in zero-emission mode. Many organisations use the term in this way, including the International Energy Agency (IEA, 2023b), from which the data to construct the graphs of EV stock over time (Figure 6.5 and Figure 6.9) was retrieved. EVs hence encompass battery-electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs). BEVs only rely on electric motors and batteries (Geels & Turnheim, 2022). PHEVs can also run on an electric motor and battery but use an ICE or fuel cell when the battery is discharged (Contestabile, 2019).

5.1.2. Case Studies Analysis

As pointed out in Section 3.1, Geels and Ayoub (2023) analysed a very broad time period, where perhaps not all events contributed to triggering the positive tipping point. In this thesis the dynamics of positive tipping points were used to select the relevant time period to analyse. Leveraging quantitative data on the deployment figures of each technology, a positive tipping point in adoption was identified as occurring when user adoption markedly accelerated, as described in Section 2.4. For the wind energy case studies, data on the cumulative installed capacity was used[1]. For the EV case studies, the stock of EVs was utilised. A graph of adoption over time was created in Python for each case study [2]. By adding to the graph the trend line before and after the identified tipping point it was possible to better observe how the rate of adoption changed from before to after the tipping point was crossed.

Having the goal of understanding what triggered each positive tipping point, a zoomed-in period around the tipping point was analysed for each case study. This way, events that did not directly contribute to triggering the positive tipping point were not analysed. The length of this time period was case-specific as different transitions take a different duration to unfold (Grubler, Wilson, & Nemet, 2016; Smil, 2016).

The period immediately before - belonging to the enabling phase in Figure 2.1 - was analysed as it creates the conditions for the tipping point to be triggered and the accelerated adoption to take place. The analysis started once a clear change in the attitudes of the main actors involved was observed. This means the actors became confident in investing significant resources and time into the technology, which had reached a stabilised design (Geels, 2019) (see phase 2 of Figure 4.1).

Additionally, in the years after the tipping point, that change of attitudes and investment decisions had to be sustained such that the self-perpetuating growth that occurs after a tipping point was present. Hence, for each case study the years immediately after the positive tipping point were also analysed. This covered part of the accelerating phase in Figure 2.1, but not all of it. One of the reasons was that, since the interest was in the period surrounding the tipping point, the analyses should not cover the years approaching the transition from the accelerating to the stabilising phase. The other reason was that for three of the case studies the technology is currently still in the accelerating phase, with the exception of the uptake of wind energy in Portugal, which has entered a stabilisation phase.

In each case study the actors and their respective roles were analysed, and a representative feedback loop model was created. Figure 4.3 was used as a starting point. If the blocks or arrows existent in this initial feedback loop model did not apply to that case study, they were removed. Subsequently, the additional actors found were added as blocks and any relevant interactions between actors and between these and the technology were added as arrows, using an appropriate label. An important aspect in comparison with Geels and Ayoub (2023) is that interactions that were not part of any feedback loop in specific were also added to the model. At the end, each case-specific model was compared to what had been found in the initial literature analysed (see Section 4.3.2). Each case study's feedback loop model was then described, providing an explanation for each arrow label of the model.This is considered an improvement compared to Geels and Ayoub (2023), where the corresponding feedback loop was added throughout the text between square brackets. As discussed in Section 3.1 this made it hard at times to understand which information exactly contributed to that feedback loop.

5.1.3. Case Studies Comparison

After analysing the enabling phase and part of the accelerating phase of each case study, the findings were compared among each case in order to understand whether a pattern existed among different

[1] Geels and Ayoub (2023) used figures on electricity production, which might not be the most adequate data in this case (see Section 3.1).

[2] These graphs correspond to Figure 6.1, 6.3, 6.5, and 6.9

cases. For one, the actors involved were compared. To do so, the actors were divided into different categories (corresponding to the blocks in the feedback loop models), making the implicated stakeholders comparable among case studies. This is similar to what Geels and Ayoub (2023) have done in their own model. As an example, even though government departments in different countries differ in name and possibly nature, they all fall under the 'policymakers' category.

For another, the roles played by the actors were compared through comparing the four case-specific feedback loop models. This comparison allowed to draw conclusions on the general actor roles present when triggering a socio-technical tipping point. This comparison was important since it was expected that the overall functions performed remained (almost) the same, even if that function was performed by different actor groups. One actor role that had special attention, including in the research sub-questions, was that of policymakers and their policy instruments. This was because there seems to be a large knowledge gap on how policymakers can enable positive tipping points. Hence, the policies employed in each case study were compared. To enable this comparison, economic, regulatory, and information instruments were divided into sub-categories (see Section 4.3.1 and Appendix C).

Based on this comparison, two final feedback loop models were derived. Namely, the two wind energy feedback loop models were overlapped, as was done for the EV models. The reason for two and not one final model lies in the fact that significant differences were identified between the B2B and B2C case studies concerning the relevant actors and actor roles. To make the similarities and distinctions between the models clearer, different colours were used (as explained in Section 7.1.1).

5.2. Data Collection

Having explained the case studies' selection and analysis, Section 5.2.1 covers the data collection methods, while Section 5.2.2 explains how the relevant data was selected among all the data available.

5.2.1. Data Collection Methods

Geels and Ayoub (2023) employ a process tracing methodology in their case studies, emphasising its suitability for exploring phenomena marked by multiple causal pathways. This approach is particularly apt for investigations interested in temporal flow, sequences, and interacting feedback loops, and was therefore used in this Master's thesis. Process tracing seeks to unveil explanations detailing how a process unfolds over time, focusing on tracing conjunctions and steps in a developmental sequence. In this investigation, the aim was for an analytic explanation, which involved converting a historical narrative into an analytical causal explanation. By combining quantitative and qualitative information, the investigation delved into how agency, techno-economic developments, and interacting feedback loops contributed to the emergence of socio-technical tipping points.

In terms of collecting the necessary data for the case studies, the articles from Vasseur, Kamp, and Negro (2013), Mazur, Contestabile, Offer, and Brandon (2015), Rosenbloom, Berton, and Meadowcroft (2016), Kamata, Khosla, and Narayanamurti (2020) and Geels and Ayoub (2023) provide a good overview of common practices. The case studies employed quantitative data extracted from (national) statistical databases to track deployment figures. This included sources such as Statista (2024), BVG Associates (2021), and RenewableUK (2024)[3] for offshore wind in the UK, Costa et al. (2021) for on-

[3]For the case of offshore wind in the UK three sources were necessary to build its deployment graph (provided in Figure 6.1) since each of them provided data for different time periods.

shore wind in Portugal, and IEA (2022) for EVs both in the UK and in the Netherlands. These sources were found through the Google search engine by searching for: *technology's name + country's name + statistics/deployment rate/over time*. An example would be: *offshore wind + UK + statistics*. Quantitative data was also collected concerning the number of public EV chargers in each country over time by searching for instance *public chargers + electric vehicles + country's name*. In this respect, DfT (2023) was used for the UK and Statista (2023) was used for the Netherlands.

While a positive tipping point is in this thesis identified by a rapid increase in technology deployment or user adoption, numerous factors accumulate gradually, allowing the crossing of this threshold. As emphasised by Geels and Ayoub (2023), substantial changes manifest in companies' perspectives and (investment) strategies. Additionally, policymakers may enact considerable alterations in policy goals and instruments over time. Furthermore, noteworthy surges in public attention or shifts in discursive content could contribute to crossing a positive tipping point. These significant changes in strategies and perspectives were not, however, identified in this thesis as positive tipping points in themselves, unlike what was done by Geels and Ayoub (2023). In the current study these dynamics simply contributed to the interactions and feedback loops that led to each socio-technical tipping point.

Qualitative data sourced from newspaper databases was utilised to monitor the nature of interactions between actors. Newspapers prove valuable as mass media coverage is seen as the most relevant means of attention and political communication (Geels & Ayoub, 2023). For example, information about protests against or in favour of a technology that might influence its deployment profile can usually be found in newspapers. Newspapers also showed valuable in discovering large investments and industry coalitions. Keywords such as '*offshore wind*', '*wind energy*' and '*electric vehicles*' were used, as well as the year of interest. Such data was especially relevant when conducting the two fully new case studies, i.e. wind in Portugal and EVs in the Netherlands. This is because for the case studies researched by Geels and Ayoub (2023) data had already been collected concerning these aspects.

To identify shifts in perceptions, strategies, and objectives, websites, (annual) reports, white papers, and newsletters, as well as academic, industry and governmental publications were consulted. These provided information on the timeline of events, on the policies employed, and on the interactions between the different actors. Interviews with organisations and field experts were not used to collect insights on these aspects since written sources are more reliable than the partial perspective of interviewees. While most of these data sources are accessible via the Google search engine using appropriate key words academic publications were searched for differently. Some were found through the reference list of other relevant articles. Others were found via article and book finders such as Google Scholar, ScienceDirect (2024), Connected Papers (2024) and Elicit (2024).

As an example, for the case study of EVs in the Netherlands[4], Science Direct was searched for '*Netherlands + EV*' and for '*Netherlands + electric vehicles*'. Besides, searches in Google Scholar were performed using these same entries, both in English and Dutch. Through the articles found in this way, other relevant articles, reports and websites were found via the reference list. These sources provided invaluable information on the evolution of the technology over the past years, a lot of the times with a focus on the policies employed. At last, in order to find additional information, sometimes related to a specific actor group, other reports and websites were searched for with the Google search bar. Examples include '*ICCT electric vehicles + Europe/Netherlands + [year]*', '*electric vehicles + Netherlands + [year] to [year]*', '*electric car subsidies + Netherlands*', again searched in English and in Dutch.

[4] A similar method was used for the other case studies.

5.2.2. Collecting Relevant Data

Concerning which data was relevant to collect, firstly, a general understanding had to be gained about each case study such that the main actors, events and milestones before and after the positive tipping point were understood. For this, sources that provided an overview of the technology's development over time were crosschecked. Also at this stage, information related to changes in actors' perspective and strategies was used to determine the duration of the zoomed-in period surrounding the positive tipping point. This information was only used to understand the context and the background of the deployment history and to determine the years to include in the case study analysis.

Then, the analysis continued on the identified zoomed-in period. This way, the remaining information collected was narrowed down and the focus was put on information about the actors involved (who were the active actors?), and the actions of those actors (what did actors do that affected another actor or the technology development?). Specific information was searched concerning the interactions included in the model of Geels and Ayoub (2023) and the ones proposed in Figure 4.4. Information that did not provide any insights on the actors and actor roles involved was in general not included in the report unless it was necessary to provide background information to the reader.

Two Word documents were used to collect the relevant data for each case study. In the first one, an entry was created for each visited source, under which all the relevant information was pasted. In the second document this information was assigned to the relevant feedback loop(s) and actor interactions. There was an entry for each interaction identified so far in the previous feedback loop models. This document had a structure similar to that of the sections in Chapter 6. The second Word document also had an entry for information concerning the introduction and the conclusion to the case study. This way, the information found in the different sources could be attributed to the corresponding document entry for that specific case study: interactions between actors, case introduction, or case conclusion. If an interaction was found to be important for the technology developments but was not yet captured in the model, a new entry was added to the document. This process was iterative. For instance, if a new interaction was found on the second case study, the first case study would be re-evaluated to understand whether that interaction had been missed by accident. At last, the raw information collected on the second Word document was converted into the case study descriptions in Chapter 6.

Thus, to be relevant information had to comply with at least one of three criteria. First, it had to correspond to an interaction between two actors or between an actor and the technology during the period analysed. Second, it corresponded to general information on the deployment of that technology in the respective country, particularly on adoption figures, during the period being analysed. The third option was that the information provided direct insights into which were the main contributing criteria to triggering the positive tipping point.

As much information as possible was collected from the most 'easy-to-find' sources. The second step was to check which entries in the second Word document were still missing information. Information concerning these specific topics was searched for. To limit the complexity of the case-specific and final feedback loop models, only the most relevant actors and interactions were included in the models. Usually, if an actor group was 'relevant', meaning it had a significant role in promoting the fast development or adoption of the technology, it was referred to in (several) articles and/or reports that provided an overview of the technology's development in that country. Examples include policymakers, technology firms, adopters, academic and research institutes, and NGOs. At other times, however, it might be that a certain actor group is not mentioned at all or is only briefly referred to in one or two of the visited sources. This is already a sign that most likely this actor category was not (as) essential to trigger the positive tipping point. If after searching for more specific information on that actor group or interaction not a lot of information was found and/or this information was very hard to find, then it was assumed that it was not a big contributor to the accelerated technology adoption.

For instance, in the EV case studies there were financial institutions that provided leasing options and made it easier for private car owners to buy a (electric) vehicle. However, information on this topic was not provided in any of the scientific articles and official reports analysed, most of which provided an overview of the main developments concerning EV uptake in the UK, in the Netherlands, or in Europe. Some, very segregated information, was only found after searching specifically for leasing options and for the name of particular banks that operate in each country. However, even so, financial solutions did not appear to specifically target electric vehicles. As this actor group did not seem to have a decisive role in promoting EVs in neither country, it was decided to not add it to the respective feedback loop model. This way, the complexity of the model was not increased unnecessarily. These findings agree with sources such as Muratori et al. (2021).

5.3. Validation

The case studies and the final feedback loop models were validated through semi-structured interviews with relevant stakeholders who worked in the specific sector and country of one of the case-studies, or who were very familiar with the concept of positive tipping points. The interviewees are kept anonymous but some general information about them and the topic they validated is provided in Table 5.1.

Three of the four validation interviews were performed via a video call on Microsoft Teams, which was recorded with the interviewees' consent[5]. The remaining interview was performed via e-mail. In all the validation interviews, a PowerPoint presentation was prepared where the main findings (relevant to the interviewee) were included. The interviewee was then asked to provide feedback on them and comment on whether it was a good representation of reality. Based on the feedback received, a few adjustments were made to the case studies, as described in Section 7.2.

Table 5.1: Description of experts interviewed for the validation

Interviewee	Employer	Position	Validation topic
1	Big 4 consultancy firm	Manager	Offshore wind and EVs in the UK (Section 6.1 and Section 6.3)
2	Company focused on wind energy production	Project manager	Wind in Portugal (Section 6.2)
3	Big 4 consultancy firm	Senior manager	EVs in the Netherlands (Section 6.4)
4	Dutch technical university	Postdoctoral researcher	Conclusions and final feedback loop model (Section 7.1 and Section 7.3)

Having explained the methodology related to selecting, analysing, and validating the case studies, as well as collecting the necessary data, Chapter 6 presents the four case studies conducted.

[5]These recordings were deleted once notes from the interviews were taken.

6 | Case Studies

In this chapter the case studies are presented. Section 6.1 and Section 6.2 cover the expansion of the (offshore) wind sector in the UK and in Portugal, respectively. Then, Section 6.3 and Section 6.4 elaborate on the deployment of electric vehicles in the UK and in the Netherlands, in this order.

6.1. Wind Energy in the UK (2002 - 2014)

The United Kingdom has established itself as a global leader in offshore wind deployment, representing 21.6% of the world's cumulative installed capacity by 2023, with only China having a larger market share (GWEC, 2023). This growth is evidenced by a significant increase in offshore wind electricity generation, rising to 13.8% of the total electricity produced in the UK in 2022 (RenewableUK, 2023).

As shown by Figure 6.1, the offshore wind industry in the UK markedly accelerated after 2009, going from a slow to a rapid growth phase. Offshore wind kept growing steadily afterwards. The exceptions were 2014-2016 due to an overlap between two similar policies (McNally, 2022), and 2019-2021 in light of the Covid-19 pandemic (BVG Associates, 2021). However, in both cases, the industry quickly picked up afterwards. It can thus be said that in 2009 a positive tipping point was crossed (Geels & Ayoub, 2023). In 2002 policymakers introduced the Renewable Obligation (RO), which represented a clear shift towards renewable energy (Geels & Ayoub, 2023). Since then, this policy was amended and other policies were introduced. Therefore, 2002 was defined as the beginning of the enabling phase. With the tipping point occurring in 2009, it was decided to analyse the case study until 2014, the year in which Contracts for Difference were introduced and effectively a new stage within the accelerating phase started (McNally, 2022). With this being said, this case study was analysed from 2002 until 2014.

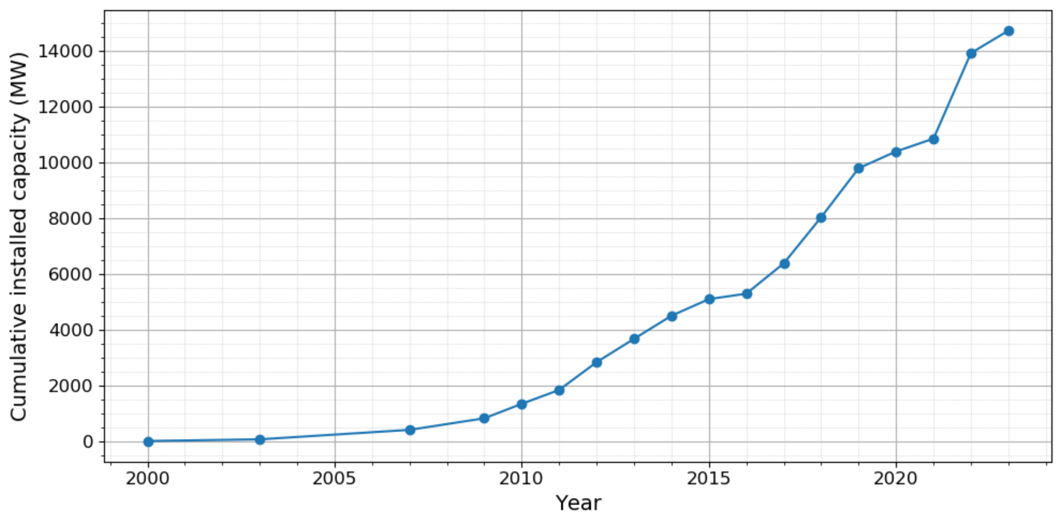

Figure 6.1: Offshore wind energy in the United Kingdom from 2003 to 2022 (BVG Associates, 2021; RenewableUK, 2024; Statista, 2024). The detailed data is given in Table A.1

As pointed out by Geels and Ayoub (2023), policymakers, firms, adopters, and wider publics were four of the main actors involved. Nonetheless, the deployment of offshore wind in the UK involved a highly networked coalition of actors, including large utilities, government bodies, research institutes, environmental NGOs, and industry networks. This collaboration has been crucial in boosting the credibility of offshore wind and channelling resources into its development. The involvement of both public and private entities underscores the complex and multifaceted nature of the offshore wind sector in the UK (Geels & Turnheim, 2022; Kern, Smith, Shaw, Raven, & Verhees, 2014; Toke, 2011).

Figure 6.2 shows a representation of the interactions among these actors, as well as among them and the technology for the period of 2002 until 2014. Ultimately, this is representative of the role that each actor played in the accelerated deployment of offshore wind in the UK after 2009. In Figure 6.2, the grey blocks and black labels were retrieved form Geels and Ayoub (2023). The orange blocks and labels correspond to actors or interactions that were proposed based on general literature (see Figure 4.4.) The blue labels are additions made solely based on the case study analysis.

As it can be observed, in some occasions information was added to the interactions identified by Geels and Ayoub (2023). Besides, several other interactions were included in the model. As a result, three new feedback loops were identified, alongside several 'loose' interactions. Overall, it can be said that the complexity of the model significantly increased in comparison to Figure 4.3, with twice as many actors and more interactions. Nonetheless, it is argued that the model in Figure 6.2 provides a better understanding of how the development of offshore wind in the UK unfolded in the period of time immediately before and after the positive tipping point.

The involvement of *technology firms* included wind turbine manufacturers such as Vestas (since the early 2000s) and Siemens (since the late 2000s), as well as civil engineering contractors (e.g., Balfour Beatty since the late 2000s) involved in developing the transmission infrastructure (Kern et al., 2014). *Adopters* refer to buyers of offshore wind turbines, who either utilise the electricity directly or sell it to end-consumers. Initially, the buyers of wind turbines were the energy firms themselves, who acted as project developers. Nevertheless, in the mid-2010s offshore wind farms started being developed by alliances of project developers and investors who then sold them to operators (Geels & Ayoub, 2023).

Below, an explanation of the role that the relevant stakeholders played is given, starting with the feedback loops and concluding with the interactions that are not associated with any particular feedback loop. For clarity, a title in bold is added before each explanation; these correspond to the arrow labels in Figure 6.2. As in the figure, the new labels are shown in italic and in either orange or red.

Feedback 1 & Feedback 2: Technology Firms ↔ SET ↔ Adopters

Investment in R&D, production, *and infrastructure:* The period from 2005 to 2009 was especially relevant as it marked a shift towards commercialisation in the UK's offshore wind sector. This was accompanied by equipment manufacturers of offshore wind turbines investing large amounts in R&D to improve their technical and data gathering abilities (Geels & Ayoub, 2023; Higgins & Foley, 2014). Besides, civil engineering contractors (e.g., Balfour Beatty since the late 2000s) were involved in developing the transmission infrastructure (Kern et al., 2014). As a result, the time period between 2002 and 2014 was characterised by significant technological advancement, leading to the development of wind turbines with higher capacities, as well as initiating an intense rivalry among turbine manufacturers to produce larger and more efficient turbines (McNally, 2022).

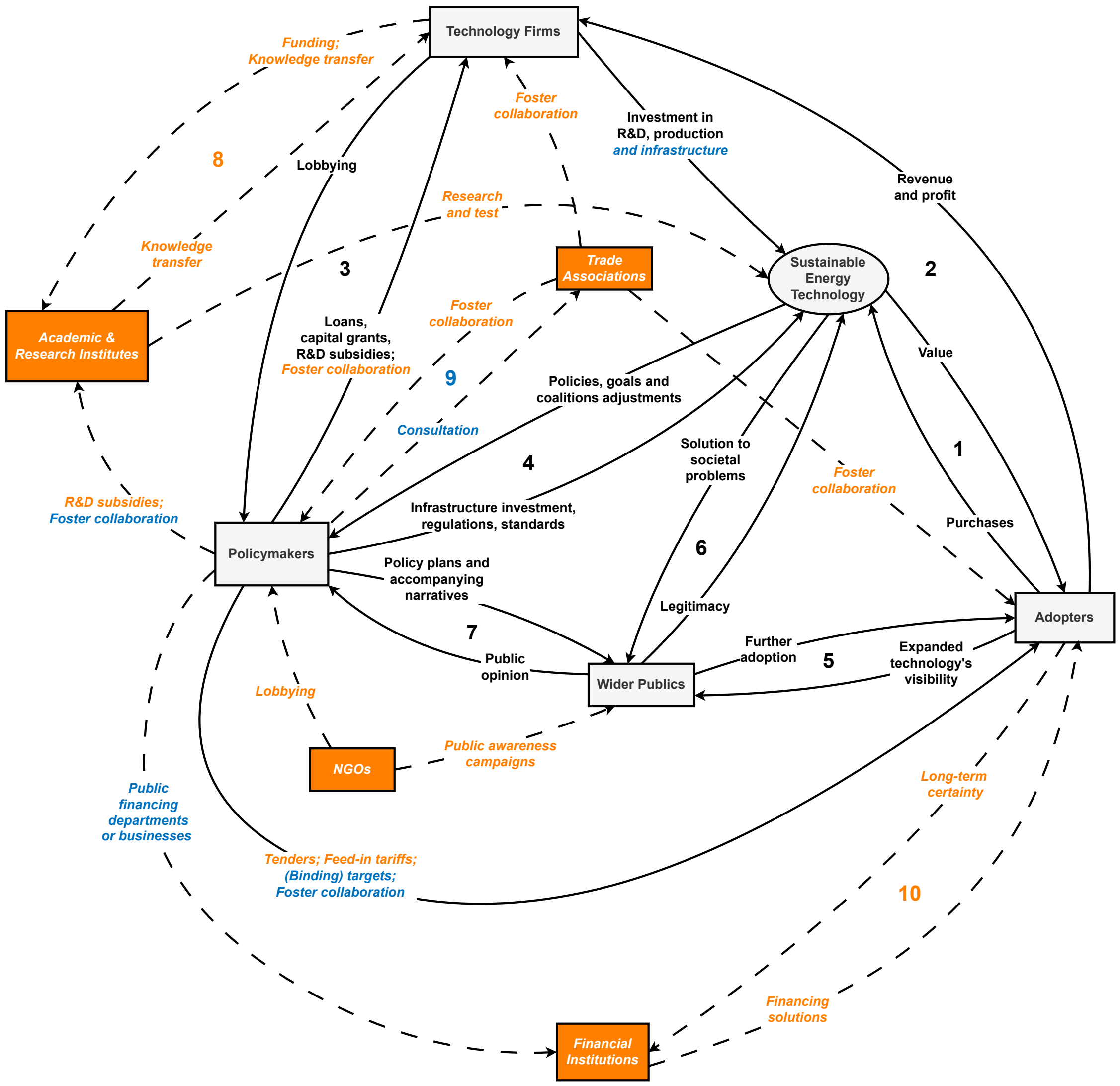

Figure 6.2: Feedback loop model showing the relevant actors and respective roles in the diffusion of offshore wind in the UK for the period of 2002-2014

Value: The commitment of technology firms to technological advancements resulted in wind turbines with higher sizes, capacities, and efficiencies, especially after 2010, meaning an overall better value for adopters (McNally, 2022). With the improved technical performance came lower costs too as the cost of components, seabed foundations, undersea cables, installation, commissioning, operation and maintenance reduced (Geels & Ayoub, 2023).

Purchases; Revenues and profit: The better value proposition of offshore wind turbines due to technological improvements and the amended Renewable Obligation in 2009 in combination with positive discourses led project developers to invest increasing amounts in offshore wind energy, in turn increasing the revenue and profit of technology firms (Geels & Ayoub, 2023).

Feedback 3: Policymakers ↔ Technology Firms

Lobbying: After the policy changes of 2009 the confidence and interest of potential project developers in offshore wind energy increased. However, they perceived the strong dependency of the market on subsidies as a risk. Therefore, both project developers and manufacturers (technology firms) lobbied for policy changes via the Offshore Wind Developers Forum and the Offshore Wind Cost Reduction Task Force (Kern et al., 2014).

Loans and capital grants: The Offshore Wind Capital Grants Scheme was launched in 2002 by the government's Department of Trade and Industry in order to promote the early development of offshore wind. With the intention of encouraging technology firms to improve their products, processes, and capabilities related to offshore wind energy it had the goal of reducing costs and increasing confidence in the technology. The twelve projects, all completed in 2003 had a total funding of £117 million (Higgins & Foley, 2014; IEA, 2014). Other grant schemes include the capital grants given by the Environmental Transformation Fund, which between 2009 and 2011 provided three projects with £26 million in order to promote understanding of supply chain technologies, as well as the Offshore Wind Manufacturing Funding which provided £130 million between 2011 and 2015 for the establishment of manufacturing capabilities at ports (Kern et al., 2014).

R&D subsidies: Public funding accelerated after the mid-2000s, with R&D subsidies aiming at improving efficiency, reducing costs, and developing larger and more robust turbines. The Offshore Wind Accelerator, funded by the Carbon Trust between 2008 and 2014, is an example of a collaborative RD&D programme having the goal of reducing the costs related with offshore wind by 10% until 2015 (Kern et al., 2014).

Foster collaboration: The Department of Energy & Climate Change (DECC), established in 2009, set up critical policies, provided funding, and promoted collaboration between technology developers and support innovation. Another actor which, among other things, was involved in fostering collaboration through organising supply chain events was the Crown Estate (CE), which actively promoted offshore wind energy since 2000. Despite being a private body, the CE was established by the government (interviewee 1) and has the overall goal of bringing prosperity for the nation (The Crown Estate, 2023). Hence, its contribution was included in interactions involving policymakers. Besides, the Technology Strategy Board (TSB) also aimed to facilitate knowledge sharing (Kern et al., 2014).

Feedback 4: Policymakers ↔ SET

Policies, goals, and coalitions adjustments: The amended Renewable Obligation was a direct result of evaluating the efficiency of the original policy, which did not bring about the desired outcome. This led policymakers to adjust the RO and start providing stronger support to more expensive technologies, which effectively meant that offshore wind energy received twice as much support as before (Geels & Ayoub, 2023). Furthermore, as the technology advanced and offshore wind became more attractive and feasible, policymakers were more inclined to form coalitions with industry stakeholders to support the continued development of offshore wind projects. This is showcased by the collaborative opportunities offered by the CE, the DECC, and the TSB (see Feedback 3). Additionally, policymakers adjusted their goals related to renewable energy production and offshore wind energy based on the evolving capabilities and potential of the technology. For instance, both UK and European renewable energy targets have been updated over time (see the interaction Policymakers → Adopters).

Infrastructure investment: In 2009 the DECC introduced the Interim Connect and Manage programme, helping streamline the grid connection process, typically complex and time-consuming. This was followed by the Connect and Manage programme, fully implemented in 2011 by the DECC, through which new projects applied for a quick grid connection. The difference was mostly that the latter programme was established as a more permanent framework for allocating and managing grid capacity for offshore wind projects (Metcalfe & Sasse, 2023; Ofgem, 2013).

Regulations and standards: Some regulations and standards concerned the technology in general rather than technology firms or adopters in specific, even though these actor groups had to comply to such regulations. For example, an Environmental Impact Assessment had to be completed for offshore wind projects, ensuring projects complied with environmental regulations. Furthermore, there were regulations related to habitats and species protection, creating a safety zone around the offshore wind farm, and decommissioning the wind farm (SEA, 2009). A last example are grid connection regulations, which were established to govern the connection of offshore wind farms to the onshore electricity grid (BVG Associates, 2019).

Another important regulation was the European Emissions Trading System (EU ETS), introduced in 2005, which imposed a cap on emissions that can be emitted by the different companies. Tradable emission allowances are then issued to these entities, which can be bought or sold on the carbon market. Ultimately, this meant that offshore wind projects became more economically attractive compared to fossil fuel-based energy generation (European Commission, 2021). The EU ETS was complemented, in 2013, by the introduction of the Carbon Price Floor, which established a minimum price on carbon emissions from the power sector. This policy promoted low-carbon energy generation by further increasing the cost of emitting carbon dioxide and setting a stable and predictable carbon price, which helped reduce investment uncertainty for renewable energy projects like offshore wind (HM Revenue & Customs, 2018).

Feedback 5: Adopters ↔ Wider Public

Further adoption; Expanded technology's visibility: The enhanced deployment of offshore wind farms in the UK in the early 2010s was propelled by both the 2009 policy adjustments and positive discourses among the industry and the wider public, which sparked the interest of international and British energy firms in the technology. Furthermore, the increased adoption of the technology led to economies of scale, created more debates, and gave it further visibility, which in turned spurred more interest among investors (Geels & Ayoub, 2023).

Feedback 6: SET ↔ Wider Public

Solution to societal problems; Legitimacy: In 2009/2010 there was a surge in public attention for offshore wind due to the positive debates on the RO amendment. These public and political discourses touched upon topics such as decarbonisation, jobs, energy security, industry growth, UK's offshore conditions, and the social acceptance of offshore wind compared to onshore (Kern et al., 2014). Overall this helped frame offshore wind as part of the solution to tackle climate change, which legitimated the technology (Geels & Ayoub, 2023).

Feedback 7: Policymakers ↔ Wider Public

Public opinion; Strong policy plans and accompanying narratives: During the 2000s public concerns about climate change grew and started to pressure the policymakers. In response, the UK government started taking more climate action. For instance, in 2008 the Climate Change Act was introduced, defining that in 2050 the country's emissions should have lowered by 80% compared to 1990 levels. This was also followed by the 2009 adjustments to the RO which gave an appealing support premium to offshore wind projects. As a result, in the early 2010s there were both public and political positive discourses (Geels & Ayoub, 2023; Kern et al., 2014).

Feedback 8: Technology Firms ↔ Academic & Research Institutes

Funding: Interviewee 1 highlighted the relevance of adding this interaction to the model. Indeed, Siemens, a major player in wind turbine manufacturing, established a research centre at the University of Sheffield in 2010. This collaboration aimed to advance offshore wind technology through joint research projects, knowledge exchange, and training programs (University of Sheffield, 2019). Furthermore, ScottishPower Renewables, another major player in the UK offshore wind sector, collaborated with academic institutions like the University of Strathclyde. These partnerships focused on research areas such as grid integration, offshore wind farm optimisation, and novel turbine technologies (University of Strathclyde, 2022).

Knowledge transfer: Universities such as the University of Strathclyde and the University of Edinburgh provided from 2009 and 2012, respectively, doctoral programmes with offshore renewable energy training, alongside entrepreneurial and commercial skills development. Some of this training was provided by businesses such as EDF Energy, E.ON, BP, Shell, Caterpillar and Rolls-Royce. From such programmes resulted job-seekers that were very specialised in offshore wind energy and could join the technology firms as experts. Knowledge transfer also happened from the knowledge institutes towards the technology firms. Indeed, academic and research institutes were essential to the development of offshore wind energy in the UK, namely when it came to technology's cost reductions and performance improvement. Three of the most important publicly funded organisations that contributed to research and innovation were the Carbon Trust, the Energy Technologies Institute (ETI), and the National Renewable Energy Centre (NAREC). All were active in the field of offshore wind since the late 2000s, with the ETI starting a dedicated offshore wind programme in 2009 (Geels & Turnheim, 2022; Kern et al., 2014). The knowledge obtained in such institutions would then be transferred to the industry through published reports and articles, as well as collaboration opportunities such as the Offshore Wind Cost Reduction Task Force (RenewableUK, 2012). Furthermore, knowledge and expertise was shared for instance by NAREC, which provided test and technical services since the late 2000s (BVG Associates, 2021).

Feedback 8: Policymakers ↔ Trade Associations

Consultation; Foster collaboration: Several trade associations were involved in representing its members next to the government (see Feedback 9), that way fostering collaboration between the industry and policymakers. Examples include RenewableUK, the Offshore Wind Developers Forum, the Offshore Wind Industry Council, the Global Underwater Hub (previously SubseaUK), and the Scottish Renewables (Global Underwater Hub, 2024; Kern et al., 2014; RenewableUK, 2012; Sottish Renewables, 2024). Trade associations were not the only ones approaching policymakers, with the latter seeking advice from the former (interviewee 1). For instance, in 2009 the DECC consulted 56 parties, including trade associations, to obtain feedback on their most recent Strategic Environmental Assessment for offshore wind leasing (DECC, 2009). Besides, Offshore Wind UK, who claim to be the “leading representative body for the UK’s offshore energy industry”, mention they engage with regulators and governments (Offshore Energies UK, 2024).

Feedback 10: Technology Firms ↔ Financial Institutions

Long-term certainty: The amended Renewable Obligation in 2009 effectively doubled the subsidy for electricity produced by offshore wind turbines, making the technology more attractive for investors (McNally, 2022). The amended RO provided generous and long-term (20 years) support, creating a subsidised market for offshore wind and boosting investor confidence (Geels & Ayoub, 2023). The confidence of financial institutions, however, increased more significantly after the introduction of the Contracts for Difference, in 2014, which helped bring down the cost of offshore wind energy projects (BEIS, 2019).

Financing solutions: This long-term certainty led private investors to gradually lower their interest rates which helped secure private financing (Geels & Ayoub, 2023). Nevertheless, most of the sponsoring came directly from energy and utility firms, with financial institutions taking a smaller role. Besides, most of the banks and institutional investors involved were state-owned or state-backed as these were willing to invest in higher-risk projects like offshore wind (BEIS, 2019).

Policymakers → Adopters

Feed-in tariffs: The RO, released in 2002, required utility firms to have a specific amount of renewable electricity in their portfolio. Renewable Obligation Certificates (ROCs) were distributed among utility firms, with the same number of ROCs attributed to every renewable energy technology. Utilities could then trade these certificates until each one had their required amount (Geels & Ayoub, 2023). In 2009, the RO was amended and the number of ROCs per megawatt-hour (MWh) increased for offshore wind. This was a consequence of introducing banding to adjust the support based on the technology’s maturity (Geels & Turnheim, 2022). This adjustment effectively doubled the subsidy for electricity produced by offshore wind turbines and provided an estimated premium on top of the retail price of £100/MWh (Geels & Ayoub, 2023).

From 2013 to 2015 the Final Investment Decision Enabling for Renewables (FiDeR) system was in place to help developers make investment decisions before the Contracts for Difference (CfD) regime was established, in 2015 (DECC, 2013). The CfD provided a fixed ‘strike price’ during 15 years to the winners of a bi-annual auction. This provided protection against wholesale prices volatility, attracting private investors (BVG Associates, 2021).

Tenders: The regulator of gas and electricity markets in the UK, Ofgem[1], was established in 1990 and played a key role in arranging the necessary grid connections (Geels & Turnheim, 2022; Kern et al., 2014). In 2009, the Ofgem and the DECC were involved in launching competitive tenders for offshore wind transmission licenses (Metcalfe & Sasse, 2023), which aimed to promote efficient transmission infrastructure development. Furthermore, the CE, which manages the seabed in UK waters, offered leases for offshore wind farm development. Interested parties would bid or apply for these leases through a competitive process. Successful applicants would then be granted the rights to develop and operate offshore wind farms in the designated areas. During the period analysed there were two lease rounds, Round 2 and Round 3. Round 3, conducted in 2009, was especially important and marked a significant expansion in scale. It was the first time that the CE identified itself the zones with the most potential to be explored and co-invested next to the developers (Kern et al., 2014).

(Binding) targets: Since 1990, the UK government has set or signed up to ambitious targets, some of which were binding, which played an essential role in setting the industry's direction. Firstly, in 1990 the Non Fossil-Fuel Obligation specified the amount of capacity that should be generated from non-fossil sources (McNally, 2022). In 2007, the UK government signed up to the binding EU targets of the European Renewable Energy Directive, which required 15% of the country's energy to come from renewable energy sources by 2020 (McNally, 2022). This directive provided a broader framework for renewable energy adoption, including offshore wind. This was followed, in 2008, by the Climate Change Act, which set the UK's long-term climate targets in law for the first time. The Act aimed to reduce GHG emissions by 80% from 1990 levels by 2050. In 2009, the European Renewable Energy Directive came into force (Metcalfe & Sasse, 2023).

Additionally, the 2011 Renewable Energy Roadmap outlined the government's long-term commitment to increasing the share of renewable energy in the UK's energy mix. By setting clear targets and objectives for renewable energy deployment, including offshore wind, the roadmap provided policy certainty and signalled to investors and developers that offshore wind was a priority to the government (DECC, 2011). This was followed by the 2013 Offshore Wind Industrial Strategy, which provided a roadmap for the development of the offshore wind sector in the UK, addressing aspects such as policy, investment, supply chain, cost reduction, and job creation to support its growth and competitiveness. By laying out a long-term strategy, the government aimed to reduce investors' uncertainty and boost their confidence in the offshore wind sector (BIS & DECC, 2013).

Foster collaboration Several government initiatives involved adopters and developers in collaboration opportunities. An example is the Offshore Wind Investment Organisation. The in Northern Ireland the Offshore Wind Support Programme bridged wind farm developers with supply chain companies. Besides, the Carbon Trust Offshore Wind Accelerator is a public-private programme joining more than 75% of offshore wind developers in the UK (HM Government, 2014).

Policymakers → Financial Institutions

Public financing departments or businesses: Apart from the subsidies and support premiums (see Policymakers → Adopters), the UK government also financed offshore wind projects through state-owned or state-backed institutions. For example, the CE, the UK's sea bed leaser, co-invested in projects together with the project developers (Kern et al., 2014). The CE is an independent private organisation established by the government (interviewee 1). Besides, the Green Investment Bank (later acquired by Macquarie Group Limited) was established in 2012 (Green Investment Group, 2024) as an attempt to tackle the funding issue associated with large renewable energy projects and mobilise private financing into the sector (Higgins & Foley, 2014).

Policymakers → Academic & Research Institutes

R&D subsidies: From 2000 to 2004, the offshore wind energy sector in the UK experienced a focus on R&D and demonstration projects, stimulated by government support (Geels & Turnheim, 2022). However, research grants continue to be issued to this day in order to foster continuous

[1] Ofgem stands for Office of Gas and Electricity Markets (Ofgem, 2013).

technological developments. Namely, the Engineering and Physical Sciences Research Council (EPSRC) (UK Research and Innovation, 2024c) started providing funding for offshore wind projects since the 1980s, while the TSB has been active since the late 2000s (Kern et al., 2014).

Foster collaboration: Some government initiatives created collaboration opportunities including academic and research institutes. For instance, the Offshore Wind Cost Reduction Task Force, established in 2011, involved academic and research institutes, the industry, and the government (RenewableUK, 2012). Moreover, in 2013 ORE Catapult was created to bring together industry, academic and research institutes, government, and other stakeholders to drive innovation, research, and collaboration in the sector (ORE Catapult, 2022).

Academic & Research Institutes → SET

Research and test: Several academic and research institutes in the UK have been active in pursuing research and tests related to offshore wind, in diverse themes. These include the University of Strathclyde (2022), the University of Sheffield (2019), and the University of Edinburgh (2019), as well as the Carbon Trust, the ETI, and the NAREC (Geels & Turnheim, 2022; Kern et al., 2014).

Trade Associations → Adopters & Technology Firms

Foster collaboration: Although in the early phases of offshore wind the main energy firms did not show much interest, this changed over the years and one important proof was the rising number of members in trade associations such as RenewableUK (Toke, 2011). Trade associations connected stakeholders within the industry and bridged the gap between these actors and policymakers. For example, the Offshore Wind Developers Forum, was set up in 2010 for industry collaboration and to enable discussions about common problems in the industry. Furthermore, RenewableUK, the central trade body in the UK, organises yearly offshore wind conferences since 2002 (Kern et al., 2014). The Offshore Wind Cost Reduction Task Force was created by the government in 2011 in order to bring the cost of offshore wind down. This was a collaborative project between government, knowledge institutes and industry and the Task Force was chaired by RenewableUK, that due to its influence was able to foster collaboration and discussion on the topic (RenewableUK, 2012). For instance, even though energy-related companies started seeing offshore wind as a better business investment after 2009, they were still cautious due to the market's strong dependency on subsidies. As a consequence, companies lobbied for better policies through the Offshore Wind Developers Forum and the Offshore Wind Cost Reduction Task Force (Kern et al., 2014). These were not the only trade associations involved in fostering collaboration, however. The Offshore Wind Industry Council (OWIC, 2021), the Global Underwater Hub (2024), the Sottish Renewables (2024), and the Renewable Energy Association (2023) are examples of trade associations that work to promote the growth of the offshore wind sector in the UK.

NGOs → Policymakers

Lobbying: Environmental NGOs have shown enthusiastic support for offshore wind for, helping to create a window of opportunity for the technology. This includes campaigns in favour of large offshore wind projects from Greenpeace, Friends of the Earth (FoE), the Royal Society for the Protection of Birds (RSPB), and the World Wildlife Fund for Nature (WWF) (Toke, 2011).

NGOs → Wider Public

> ***Public awareness campaigns:*** NGOs such as Greenpeace, FoE, RSPB, and WWF spearheaded campaigns in support of offshore wind (Toke, 2011). For instance, the FoE published a booklet in 2012 clarifying frequently asked questions concerning offshore wind energy, aiming at raising awareness (Friends of the Earth, 2012). Besides, renewable energy lobby groups mobilised public concern about the perceived energy dependency to the point that, in 2008, 19% of UK citizens ranked energy as one of their top two concerns (Toke, 2011).

6.2. Wind Energy in Portugal (2000 - 2007)

Portugal does not have oil or natural gas reserves of its own but has historically relied substantially on fossil fuels. This resulted in a strong dependency on imports that challenged the country's security of supply. Portugal does have, nevertheless, strong renewable energy resources. To gain more energy independence and commit to a sustainable development, in the 1990s and early 2000s the Portuguese government started promoting renewable energy sources and the liberalisation of its energy market (IEA, 2004b; IRENA, 2013b). Wind energy, in specific, was strongly advocated for. Due to a very deep seabed in most of Portugal's sea area, fixed offshore wind turbines were either not technically suitable or too expensive to install and so the focus was put on onshore wind parks (IEA, 2004b, 2005, 2006a).

In large part due to a conducive policy environment, the adoption of wind turbines in Portugal saw a significant increase after 2004 (J. R. Ferreira & Martins, 2009; IEA, 2005, 2009a; Nunes, 2018), as observed in Figure 6.3. Between 2004 and 2009, more than 500 MW of wind capacity was installed every year (IRENA, 2013b). According to the definition used here, in 2004 a positive tipping point was then crossed. In this section, the period from 2000 until 2007 is analysed, with 2000-2004 being representative of the enabling phase and 2004-2007 of the beginning of the accelerating phase.

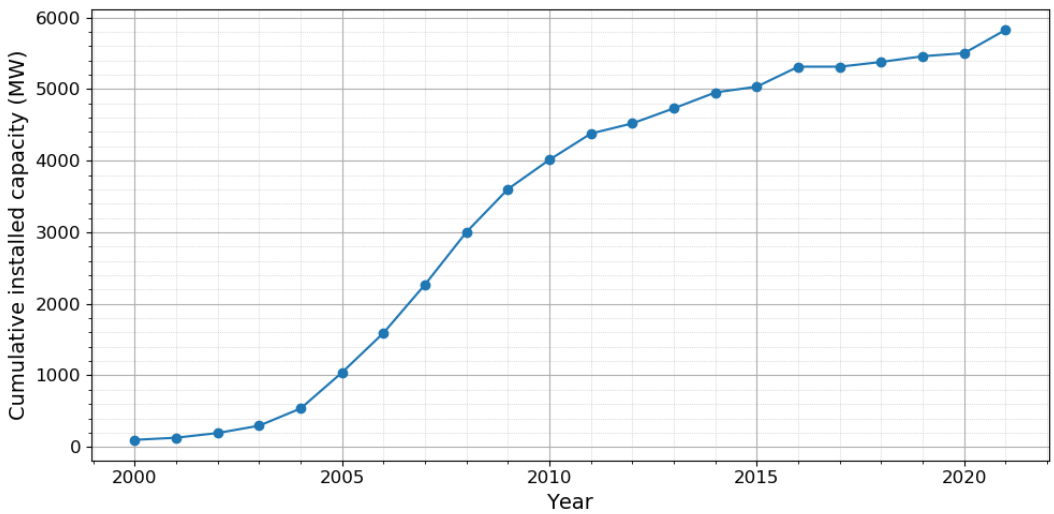

Figure 6.3: Wind energy in Portugal from 2000 to 2021 (Costa et al., 2021; IRENA, 2013b). The detailed data is given in Table A.1

One of the most interesting aspects of the diffusion curve of wind energy in Portugal over the last two decades is its S-shaped curve (see Figure 6.3), which resembles the curves found in tipping point literature, namely Figure 2.1. The reason for the flattening out of the curve after 2011 is in this case, however, a consequence of the country's economic crisis which was followed by regulatory instability and less favourable support schemes in the wind energy market (Frontier Economics, 2013; IRENA, 2013b). In different economic conditions, perhaps the total installed capacity of wind energy would have stabilised at a higher value. Nevertheless, despite of the unfavourable conditions of the 2010s, in the year of 2022 renewable energy sources contributed to 62% of electricity generation (IEA, 2024a) and wind energy in specific generated 28% of all electricity (IEA, 2024b).

From 2000 until 2007, all eight actor groups identified in Section 4.3.1 were active in the development and roll-out of wind energy in Portugal. Figure 6.4 portrays how these actors interacted with each other and with the technology. While the grey blocks and black labels correspond to the elements already presented in Geels and Ayoub (2023), (see Figure 4.3), the orange blocks and labels are interactions that were expected based on general literature (see Figure 4.4). The blue labels are additions made solely according to the case study findings. An explanation of each arrow label is provided below, where the colour of the titles follow the convention of the arrow labels in Figure 6.4.

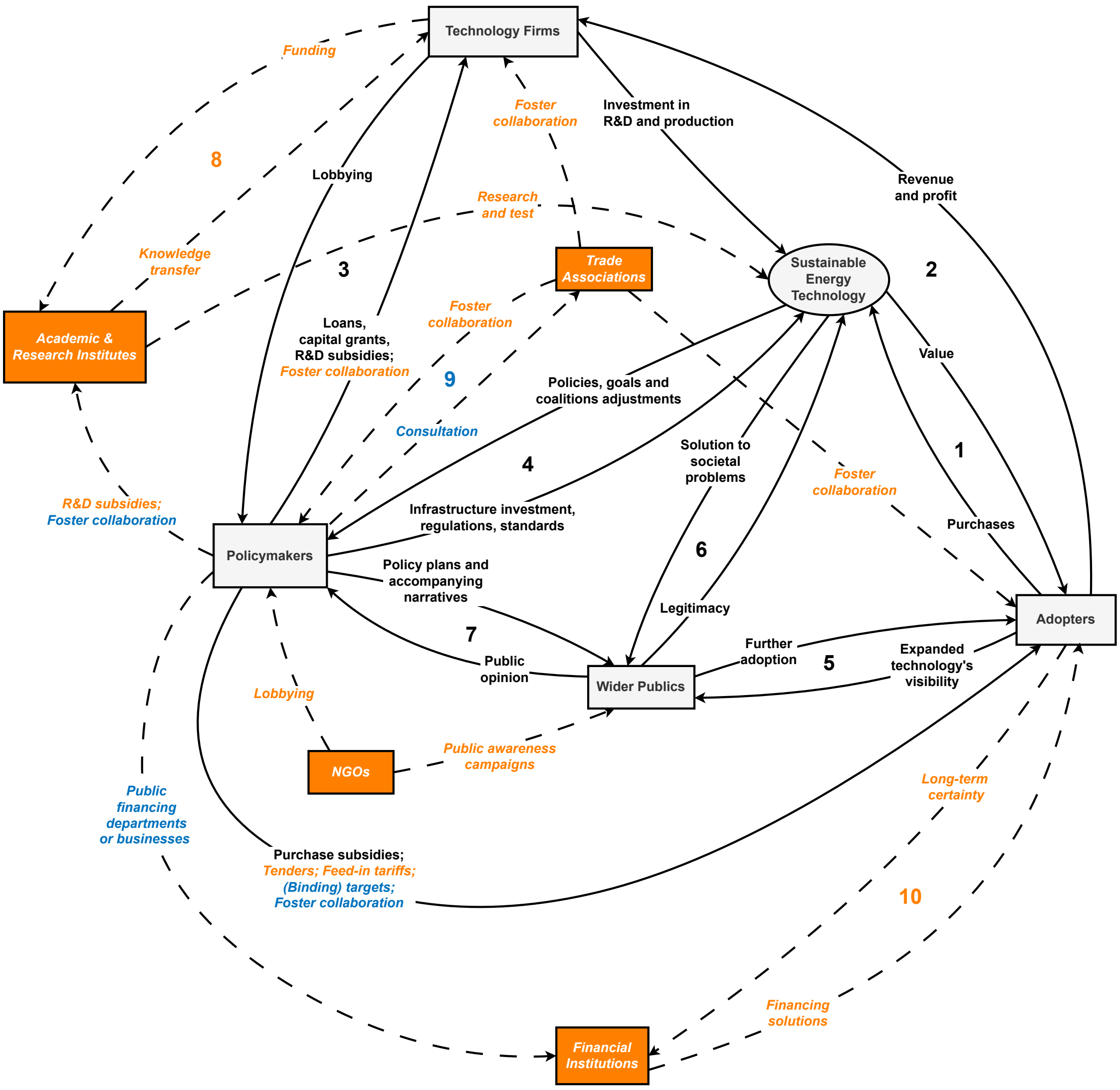

Figure 6.4: Improved feedback loop model based on the win energy in Portugal case study for the period of 2000 - 2007

Feedback 1 & Feedback 2: Technology Firms ↔ SET ↔ Adopters

Investment in R&D and production: During the period analysed, there were tower and electrical equipment manufacturers but there were no wind turbine manufacturing facilities in Portugal, despite a strong interest from the manufacturers side to establish production units in the country (IEA, 2004b, 2006a, 2006b). The main wind turbine manufacturers were Enercon, Vestas, Gamesa, Nordex, GEWE, Izar Bonus, Repower, Neg Micon, Ecotecnia, Fuhrlaender, Mitsubishi Heavy Industries, Winworld, Nordtank, Bornay, and WinWinD (IEA, 2003, 2005, 2006a). In 2007, Enercon established a factory in the north of Portugal as a result of the industrial cluster promoted by the government (J. R. Ferreira & Martins, 2009; Herman, 2013; IEA, 2008). These turbine manufacturers invested largely on R&D and production themselves, which was reflected in the new, better models released over time. For instance, Bornay, the leader of small wind turbines, offered eight models ranging from 60 to 12,000 W but was already developing higher capacity models, up until 50 kW. Also the capacity of the models produced by Enercon increased over time. Moreover, Gamesa developed new models by optimising the efficiency of their system in accordance with different site conditions (ENERCON, 2024; IEA, 2003).

Value: Over time, wind turbines and the complementary technology got better and started proposing a better value, i.e. a higher performance to cost ratio. As mentioned in the interaction above, turbines got bigger over time. From 2003 to 2004 the average wind turbine capacity of a new turbine increased by 6% (IEA, 2005). Furthermore, during 2003 and 2004 a wind turbine's unit cost reduced steadily (IEA, 2004b, 2005).

Purchases; Revenues and profit: Evidence of increased interest in wind turbines and their associated components were the 7,000 MW of new wind capacity applications received in 2002, which were installed in the following years (IEA, 2004b). For instance, the manufacturer Izar Bonus installed 60.3 MW of new wind capacity in 2002. In the first quarter of 2003 they sold another 52 MW, expecting to install 277 MW during the same year (IEA, 2003). Besides, in 2004 the Finish manufacturer WinWinD started selling beyond Finland, exporting to France, Portugal, and Sweden (IEA, 2005). This shows increased interest and purchases by adopters, which is translated into higher revenues and profits for technology firms.

Feedback 3: Policymakers ↔ Technology Firms

Lobbying: As confirmed by interviewee 2, lobbying from national technology firms was not a relevant interaction during this period due to the lack of national firms in the sector. However, there was lobbying at the European level that ultimately affect the landscape in which wind develops in Portugal. The Renewables Directive is cited as a key example of the influence of interest groups on EU environmental legislation. The EU Commission made significant alterations to its final draft proposal, particularly concerning the types of support mechanisms member states could use to increase their renewable energy production (Ydersbond, 2012).

Loans, capital grants and R&D subsidies: During the period analysed Portugal mainly relied on imports for its onshore wind industry (J. R. Ferreira & Martins, 2009; Herman, 2013; IEA, 2008). The main turbine manufacturers exporting to Portugal had manufacturing facilities in Germany (Enercon, Nordex, GEWE, Repower), Denmark (Vestas), Spain (Nordex, Gamesa, GEWE, Izar Bonus, Bornay) (ENERCON, 2024; IEA, 2002, 2006a, 2008). Thus, these technology firms' developments were shaped by loans and capital grants provided by the country/countries where they had manufacturing facilities in, most of them provided even before the year of 2000. Germany for instance, offered loans and grants to support research, development, and deployment of wind energy technology (BMWi, 2020). In Denmark, for another, grants, subsidies, and low-interest loans were provided by government agencies such as the Danish Energy Agency and the Danish Ministry of Energy. These funds were aimed at promoting innovation, research, and deployment of onshore wind energy technology (IRENA, 2013a). At last, in Spain one significant initiative was the Renewable Energy Promotion Plan, which provided subsidies, grants, and incentives to renewable energy projects, including wind farms (MITECO, 2005).

Foster collaboration: In 2005, as part of the tendering process, a wind energy industrial cluster was created with the aim of bringing together the project developers and local manufacturers, as well as expanding the production capabilities of the country. This industrial cluster collaborated in the establishment of rotor blades, concrete towers, and mechatronics factories. Industry members involved include Enercon, EDP, Finerge, Generge, SIIF and Térmica Portuguesa (J. R. Ferreira & Martins, 2009; IRENA, 2013b; Pinto, 2005). This shows that collaboration was not only fostered among technology firms but also among these and adopters (or project developers).

Feedback 4: Policymakers ↔ SET

Policies, goals, and coalitions adjustments: For instance, average feed-in tariffs went from a twelve-year support of 0.068 €/kWh in 1999 to 0.085 €/kWh in 2001 for an indefinite length of time. However, the government soon realised that the latter was not economically sustainable and in 2005 reduced the feed-in tariff to a fifteen-year support of 0.074 €/kWh. Therefore, not only the feed-in tariff was adjusted but also the state guarantee for this financial support (P. Ferreira, Araújo, & O'Kelly, 2006; IRENA, 2013b). Besides, the government started seeing wind energy more as a priority in the country's strategy after 2005 (P. Ferreira et al., 2006; IEA, 2006a). For instance, while in 2003 the government set the goal of having 3,750 MW of wind energy by 2010, in 2005 the goal of having 5,100 MW of capacity by 2013 was set (IEA, 2004b, 2006a). Coalitions also changed during this period. For one, in 2003 Portugal joined the IEA R&D Wind team (IEA, 2004b), while in 2005 the country established the creation of a wind energy cluster (IEA, 2006a).

Infrastructure investment: In Portugal, the wind potential is not uniformly distributed, many times being the highest in remote areas of the country without good access to the electricity grid (Barata & Quadrado, 2007). Consequently, in order to facilitate the integration of renewable energy generation, substantial investments were made in the transmission and distribution grid (IEA, 2009a), with the government providing financial support to project developers for the reinforcement of the network (Agência LUSA, 2004; IEA, 2005). From 2001 to 2003, the licence-granting process for grid access was clarified and the administrative procedures were simplified (IRENA, 2013b). Besides, the 2005 tendering process specified the available power injection capacity and reception locations for each grid zone in accordance with the National grid's projected future evolution such that the grid could be developed efficiently (P. Ferreira et al., 2006; IRENA, 2013b). Furthermore, the addition of capacity was facilitated by the fact that in Portugal the responsibility of allocating connection capacity lies only on one transmission and one distribution company (IEA, 2009a).

Regulations and standards: The national action plan aimed at combating climate change and giving top priority to renewable energy sources (IEA, 2004a). Feed-in tariffs and other financial incentives stimulated renewable energy sources, including wind energy (IRENA, 2013b). Despite the efforts to shift to renewable energy, however, one of the main obstacles that projects faced was the long and bureaucratic authorisation procedure to obtain the necessary permits. This could imply that between the application of the project and the start of its installation four to five years would have passed (IEA, 2004b). In 2004 it was decided to liberalise the electricity market, which meant opening it to every consumer (IEA, 2004a). With the market's liberalisation came also the further simplification of the administrative and licensing processes, which reduced the deployment time to only two years (IEA, 2005).

Feedback 5: Adopters ↔ Wider Public

Further adoption; Expanded technology's visibility: As wind parks gained popularity, mainly as a consequence of the attractive financial support available, the technology gained visibility. This played a big role in legitimising the technology, but also resulted in a social contagion effect towards energy firms that were still not (as) involved in producing electricity from wind energy. For instance, the development of wind energy in Portugal was largely led by Enersis and Enernova, with the latter being part of the EDP group (Climate Chance, 2018; L. Ferreira, 2008). The deep commitment of these energy firms gave a signal to the industry that, among other things, the technology had reached a decent maturity level. While in 2004 Enersis and Enernova had 50% of the market share of wind installed capacity (IEA, 2005), this number dropped to 40% by 2006, demonstrating the growing market share of other, smaller companies (IEA, 2006b).

Feedback 6: SET ↔ Wider Public

Solution to societal problems; Legitimacy: Wind turbines contribute to the reduction of detrimental emission and residuals (J. R. Ferreira & Martins, 2009; P. Ferreira et al., 2006). Wind energy contributes to the country's security of supply, which at the time was very much dependent on fossil fuel imports (J. R. Ferreira & Martins, 2009). Besides, wind energy promised to contribute to Portugal's economic growth and job creation. A study found that wind energy resulted in five times more jobs for each euro invested compared to other energy generation technologies (J. R. Ferreira & Martins, 2009). These advantages combined with a long pipeline of projects, and the redirection of some of the revenues of wind energy projects towards local municipalities played a big role in increasing the technology's legitimacy and public acceptance (IRENA, 2013b).

Feedback 7: Policymakers ↔ Wider Public

Public opinion; Strong policy plans and accompanying narratives: The Portuguese wider public had in general very positive views about onshore wind energy, with low local opposition numbers (IEA, 2009a). Apart from considering wind and solar power to be more environmentally friendly than biomass and hydropower, the wider public also view wind projects as an important source of local development (Ribeiro, Ferreira, Araújo, & Braga, 2014). One of the reasons for this, apart form job creation, might have been the government's policy establishing that 2.5% of a project's revenues were to be paid to the municipality where the farm was installed (IEA, 2009a). Perhaps also associated with the latter was the fact that the acceptance of new wind farms was larger among citizens of municipalities that had wind farms, in contrast to municipalities where wind farms had not been installed yet (Ribeiro et al., 2014).

Feedback 8: Technology Firms ↔ Academic & Research Institutes

Funding: During this period there were barely any technology firms established in Portugal, which meant that the R&D financing flowing from these firms to national academic and research institutes was limited. Nonetheless, a few technology firms belonging to the wind industry have provided R&D financing to academic and research institutes through consultancy contracts (IEA, 2008).

Knowledge transfer: The National Institute of Engineering, Technology and Innovation (INETI) created a wind atlas of Mainland Portugal as well as a simplified calculation sheet to compute a project's economical feasibility as a function of the investment. This resulted in more sales for technology firms after 2001 since project developers were able to secure financing more easily (Barata & Quadrado, 2007; IEA, 2004b; IRENA, 2013b). This programme allowed, for instance, to provide REN, the Portuguese Transmission System Operator (TSO), with wind energy production forecasts (IEA, 2004b). Besides, the software *VENTOS* was developed by the Engineering Faculty of the Porto University (FEUP), the Mechanics Engineering and Industrial Management Institute (INESC) and the research centre for Wind Energy and Atmospheric Flows as a tool to simulate the "wind draining behaviour on complex soils with or without arborisation" (Barata & Quadrado, 2007). Finally, well-educated professionals graduated from Portuguese engineering universities and integrated technology and energy firms. Some of the most relevant universities in this field were Higher Technical Institute (IST), FEUP, and Porto Higher Engineering Institute (ISEP). For instance, during the period analysed IST started offering a wind energy course (IST, 2024), while ISEP established a sustainable energy Masters programme (ISEP, 2024).

Feedback 9: Policymakers ↔ Trade Associations

***Consultation;* Foster collaboration:** Policymakers approach trade associations to gauge the industry's current state and that way be able to release effective policies (Delicado et al., 2013; Sintrão, 2005). In return, trade associations represent their members next to policymakers, making sure their concerns are heard. This is one way of fostering collaboration between their members and policymakers. Nonetheless, collaboration exists at other levels and is a two-way street, accompanied by continuous dialogue. For instance, APREN, the Portuguese Association for Renewable Energies, helps national and international policymakers draft energy policies for Portugal (APREN, 2024c). WindEurope, on the other hand, is involved in coordinating international policy, as well as in developing policy positions related to the industry's concerns. Through their lobbying efforts, a favourable legal framework is created for their members (WindEurope, 2016a).

Feedback 10: Technology Firms ↔ Financial Institutions

Long-term certainty; Financing solutions: Governmental support AND an extensive projects pipeline improved the industry's long-term market stability over time. The consistent nature of the financial incentives enabled investors to anticipate returns on investments reliably. Furthermore, the comprehensive wind resource assessment conducted by INETI that produced a national wind atlas helped in computing a project's returns. These elements collectively facilitated greater access to financing for wind initiatives, sparking an increase in new projects after 2000. This was the case until the economic crisis of 2010-2014 (IRENA, 2013b). For instance, the banking syndicate composed by BBVA, BES Investment, Caixa BI, and Millennium bcp Investment financed Enersis wind energy projects in €806 million (TVI Notícias, 2006). During this period wind energy projects in Portugal were also financed by the European Investment Bank (EIB, 2007).

Policymakers → Adopters

Purchase subsidies: One of the financial schemes that supported renewable projects between 2001 and 2005 was the Incentive Scheme for Rational Use of Energy (IRENA, 2013b). Furthermore, in 2007 the government released the PRIME/MAPE subsidy programme which funded more than 100 projects (IEA, 2008).

Feed-in tariffs: Between 2000 and 2007 the government used a feed-in tariff system as a means of promoting renewable electricity generation. This mechanism has the same effect as subsidies (IEA, 2004a). In 1999 the feed-in tariff started being calculated according to a formula that took into account the inflation rate, the avoided costs of investing, operating and maintaining a conventional power plant, and the avoided CO_2 emissions costs (IRENA, 2013b). The average feed-in tariff corresponded to 0.068 €/kWh and was paid during a maximum period of 12 years (P. Ferreira et al., 2006). In 2001, the feed-in tariff started differentiating between sustainable energy technologies, with wind receiving 0.085 €/kWh indefinitely (P. Ferreira et al., 2006; IRENA, 2013b). This was followed by another revision in 2005, according to which the tariff was reduced to 0.074 €/kWh during a maximum period of 15 years (P. Ferreira et al., 2006; IEA, 2009a; IRENA, 2013b).

Tenders: In 2005, the government released a winder energy tender for the allocation of 1,800 MW in specific points of the grid. The tendering was structured in three phases. During the first phase, occurring in 2006, the ENEOP consortium built 1,200 MW. The Ventiveste consortium then built 400 MW in 2007, while other small projects were responsible for the installation of 200 MW during the next phase (P. Ferreira et al., 2006; IEA, 2006b, 2009a; IRENA, 2013b). This instrument was one of the main drivers of wind energy in Portugal after 2005 (IRENA, 2013b).

(Binding) targets: Between 2000 and 2007, Portugal had targets not only concerning the percentage of electricity generated through renewable energy sources, but also wind energy in specific. In 2001, the E4 Programme (Energy Efficiency and Endogenous Energies) was launched. This programme set the goal of producing 39% of electricity via renewables as of 2010, which was later raised to 45% (IEA, 2004a; IRENA, 2013b). Besides, in 2003, the government's Cabinet Resolution set the goal of having 3,750 MW of installed wind energy by 2010 (IEA, 2004b). This was followed by a new target set in 2005 of having 5,100 MW of wind capacity by 2013 (IEA, 2006a).

Foster collaboration: The wind energy industrial cluster created in 2005 as part of the tendering process fostered collaboration between the project developers and local manufacturers (IRENA, 2013b). The cluster's members included Enercon, EDP, Finerge, Generge, SIIF and Térmica Portuguesa (J. R. Ferreira & Martins, 2009; Pinto, 2005), which demonstrates that several adopters (or project developers) were involved. Furthermore, the government also promoted cooperation between the municipalities where the wind turbines were installed and power producers. This was a result of the fact that part of the revenue of the wind projects was paid to local municipalities, increasing the acceptance of the projects (IRENA, 2013b).

Policymakers → Financial Institutions

Public financing departments or businesses: As mentioned in *Feedback 10*, financial institutions provided financing for wind energy in Portugal during the period being analysed. Some of these institutions were public, thus created by national or international policymakers with the intention of financing the adoption of the technology. One of these was Caixa BI, while the other one was the European Investment Bank (EIB, 2007; TVI Notícias, 2006).

Policymakers → Academic & Research Institutes

R&D subsidies: In Portugal, R&D was mainly conducted at and financed by academic and research institutes (IEA, 2008), with public R&D funding being the lowest of all IEA members as a percentage of the country's GDP (IEA, 2009b). Even though during this period there was no governmental programme specifically funding R&D in the wind energy sector, as a part of the Ministry of Economy and Innovation, INETI was partially sponsored by the government (IEA, 2004b). INETI has been one of the main wind energy researchers, but other names include the FEUP and the Research Centre for Wind Energy and Atmospheric Flows (IEA, 2008). Some wind-related research was, nonetheless, funded by the government through mechanical, electrical, and energy engineering grants (IEA, 2005).

Foster collaboration: Policymakers fostered collaboration among academic and research institutes. One significant example was Portugal's participation on the IEA R&D Wind Executive Committee. Portugal became a member in 2003, being represented by INETI (IEA, 2004b). Portugal was especially active on a multi-national programme on creating dynamic models of wind farms for studies about the power system, which involved sharing both measurement data and model descriptions with other members (IEA, 2004b). However, other tasks include for instance reporting on the R&D and roll-out figures of wind energy in Portugal (IEA, 2002).

Academic & Research Institutes → SET

Research and test: As highlighted in *feedback 8*, INETI, FEUP, INESC and the research centre for Wind Energy and Atmospheric Flows were active in performing wind-related research. INETI created a wind atlas of the country, while the remaining three worked on a software called *VENTOS* (Barata & Quadrado, 2007). Other research initiatives that contributed to the further development of the technology and the industry related to reducing the losses and improving the voltage profiles through reactive power control, as well as related to the stability of the power system (IEA, 2005).

Trade Associations → Adopters & Technology Firms

Foster collaboration: For one, APREN, founded in 1988, is the largest trade association in Portugal for renewable energies, having to date 34 Portuguese members that are wind energy producers, despite having non-producer members too. Overall, APREN represents more than 90% of the installed renewable electricity capacity in the country. The association has the goal to coordinate and represent their members within the Portuguese electricity sector, namely next to the government and respective ministries (APREN, 2024b, 2024c). As collaboration and knowledge sharing activities for their members, APREN organises summits, webinars, and debates (APREN, 2024a). For another, the European wind trade association WindEurope has not only large technology firms and adopters such as ENERCON, Vestas, EDP and Galp as members, but also 10 industry members that only operate in Portugal (WindEurope, 2016b). WindEurope represents and lobby for a variety of members, to whom they offer learning and networking opportunities. For instance, they organise workshops, seminars, exhibitions, and conferences to exchange expertise on different topics (WindEurope, 2016a)

NGOs → Policymakers

Lobbying: Despite advocating for renewable energy, environmental NGOs ensured new projects complied with high environmental standards by maintaining a continuous dialogue with national and European policymakers (Delicado et al., 2013; Quercus, 2024). The stringent requirements set by these organisations could result in up to five years to issue a permit for a wind energy project, mainly due to lack of trustworthy data to analyse the project's environmental impacts. This was in fact one of the main contributors to the long and bureaucratic process of obtaining the necessary installation and operation permits for wind farms (IEA, 2004b, 2005). Some of the NGOs involved include Quercus, the Nature and Biodiversity Conservation Institute, the Regional Hydrographic Administrations, and the League for the Protection of Nature (Delicado et al., 2013). Additionally, the Portuguese Society for the Study of Birds, highlighted in 2005 that Portugal did not have any strategy concerning the Environmental Impact Assessments for new wind parks, which ultimately negatively affected the environment and the project developers (Travassos et al., 2005).

NGOs → Wider Public

Public awareness campaigns: Apart from representing the wider publics next to the policymakers, NGOs raise the citizens' awareness both concerning the positive aspects of wind energy and their potential negative consequences to e.g., life quality (Delicado et al., 2013). Quercus, for instance, is dedicated to raising awareness among and providing information to the citizens. In their various projects and campaigns, they utilise dissemination tools and rely on several partnerships with relevant market actors (Quercus, 2024).

6.3. Electric Vehicles in the UK (2015 - 2021)

The adoption of EVs in the UK significantly increased in the previous years, as observed in Figure 6.5. In January 2024 the millionth BEV was driven on British roads, implying that despite their greater initial cost, EVs are becoming more common and attractive. In fact, 14.7% of all vehicles sold during that month were totally electric (CAR Magazine, 2024). Figure 6.6, shows that while initially PHEVs were more famous among adopters, BEVs gained popularity in the previous years. However, it should be noted that as of 2022 EVs had only 2.8% of cars' market share in the UK (IEA, 2022).

After a clear change in actor perspectives and attitudes after 2015, a marked acceleration can be seen after 2019, marking a socio-technical positive tipping point (Geels & Ayoub, 2023). In order to understand the dynamics that led to this tipping point to be crossed, it is relevant to look at the enabling phase and at the start of the accelerating phase (Lenton et al., 2023). Therefore, the focus of this section lies on the period between 2015 and 2021.

Several actors were involved in the roll-out of electric vehicles in the UK. Figure 6.7 shows a representation of the most relevant actors and how these interacted with each other and with the technology being deployed. The grey blocks and black labels correspond to interactions identified by Geels and Ayoub (2023). The orange blocks and labels are interactions that were identified based on general literature (see Figure 4.4), and the blue labels are interactions added when analysing the case study.

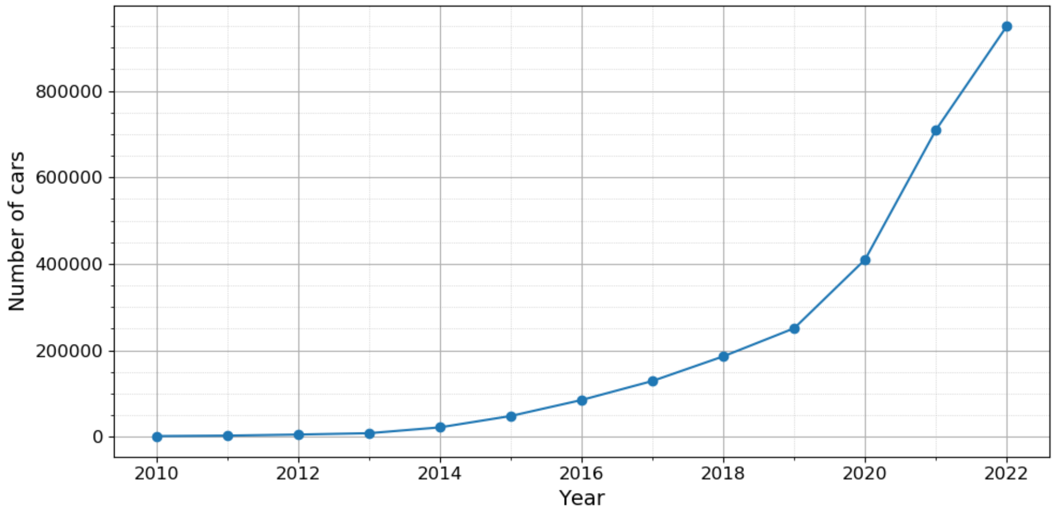

Figure 6.5: Stock of electric vehicles (BEVs and PHEVs) in the United Kingdom from 2013 to 2022 (IEA, 2022). The detailed data is given in Table A.2

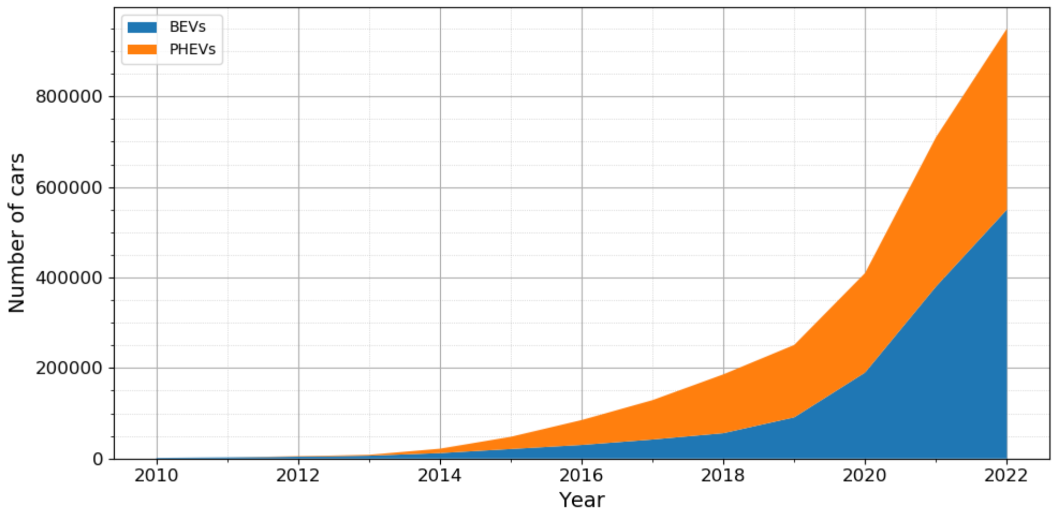

Figure 6.6: Stock of plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) in the United Kingdom from 2013 to 2022 (IEA, 2022). The detailed data is given in Table A.2

Before going into the details of the diagram, a clarification should be given concerning two of the actor groups. For one, *technology firms* refers to manufacturers of charging points, batteries, and vehicles or vehicle components and the respective raw materials, as well as charging infrastructure providers (Wills, 2020). For another, *adopters* are both individual end-consumers and companies who wish to have a more environmentally-friendly car fleet (CAR Magazine, 2024).

A second note concerns the fact that, unlike for the diffusion of wind energy, financial institutions did not play a key role in promoting the development and adoption of electric vehicles in the UK. This conclusion was taken after consulting several sources on the topic, which only mention the several public financial incentives as an enabler. It is true, however, that private financial institutions offer incentives such as the incentives for businesses offered by Barclays Bank (Barclays Bank, 2024) or the one for individuals provided by Lloyds Bank (Lloyds Bank, 2024). Nevertheless, incentives like these did not seem to be determining for the positive tipping point to be triggered as information concerning such incentives

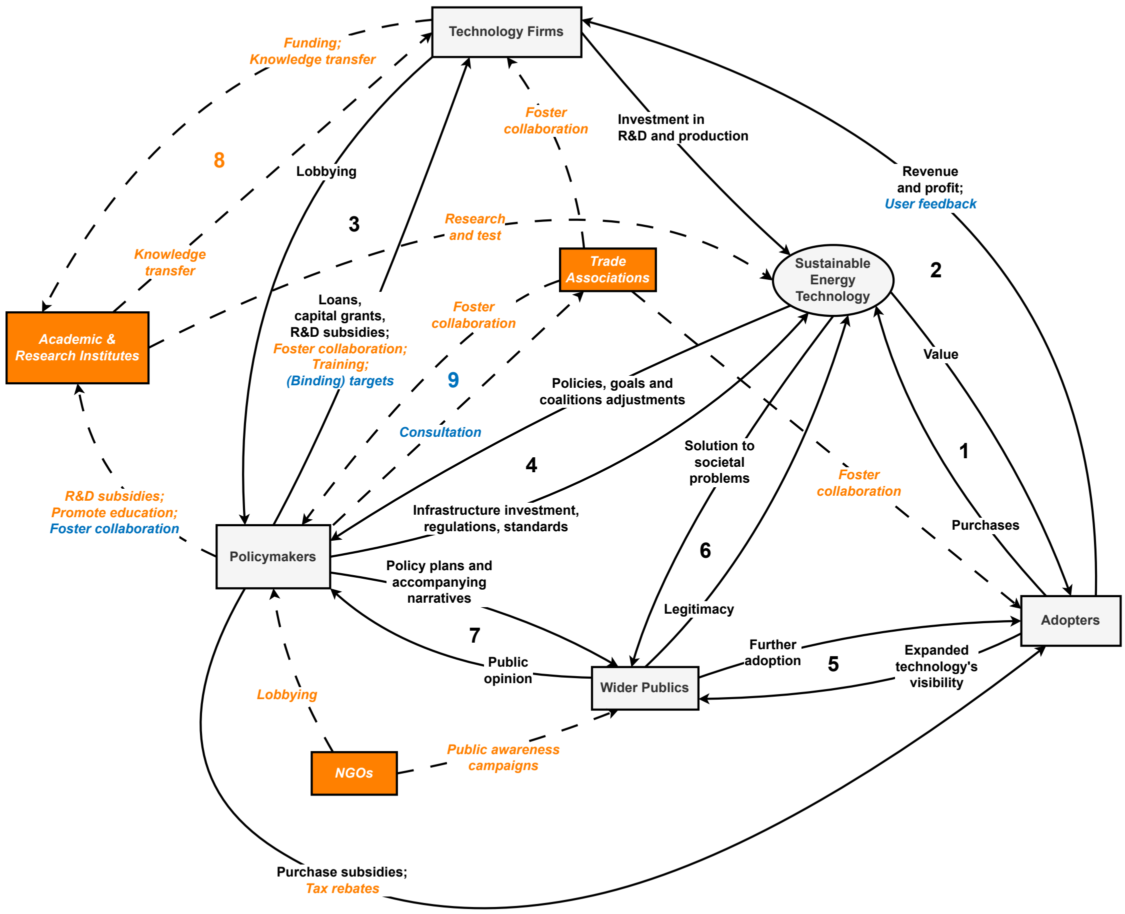

Figure 6.7: Feedback loop model showing the relevant actors and respective roles in the diffusion of electric vehicles in the UK for the period of 2015-2021

was not included in any documents having an overview of the main developments of EVs in the UK. Rather, information concerning private financial incentives was only found due to searching specifically for *leasing options EVs UK* and adding the name of specific banks that operate in the UK to the search.

Below, an explanation is given for the interactions in Figure 6.7, starting with the closed feedback loops and following with the interactions that are not part of a specific feedback loop. Each explanation is preceded by a small title corresponding to the arrow label in Figure 6.7, following the same colour code.

Feedback 1 & Feedback 2: Technology Firms ↔ SET ↔ Adopters

User feedback: Automakers invested in certain technology advancements due to the received user feedback. For instance, the range anxiety concerns of (potential) adopters led automakers to invest in R&D focused on improving battery efficiency, size and capacity (Geels & Ayoub, 2023).

Investment in R&D and production: Although between 2010 and 2015 more incumbent automakers started to diversify into electric vehicles, it was after 2015 that a clear expansion and diversification of EV models was observed. This was accompanied by large investments in building new skills and factories (Geels & Turnheim, 2022). Manufacturer's focus lied greatly on battery technology improvements, but manufacturers and providers of charging devices were also involved in pushing for EVs (Wills, 2020). This change of attitude was partly driven by the Diesel scandal of 2015, which led to an EV innovation race in the years to follow (Geels & Ayoub, 2023).

Value: The automakers' investment on battery improvements resulted in a nearly 1.5 times higher average driving range of BEVs in 2019 compared to 2015, with further increases in the subsequent years. Besides, enhancements were also made concerning the charging times, which were reduced due an increase in the average charging power (Geels & Ayoub, 2023). Furthermore, learning-by-doing and scale economies allowed the price of Li-ion battery packs, the primary cause of high EV pricing to drop by 63% between 2015 and 2019 (Geels & Turnheim, 2022).

Purchases; Revenues and profit: The trend observed since 2015 of higher performance and lower cost of EVs - meaning an overall higher value - together with the expansion of public charging devices increased the attractiveness of EVs and decreased user concerns (Geels & Ayoub, 2023). This meant an increase in purchases and therefore in automakers' revenues and profits after 2015, increasing the latter's confidence and hence investment in EVs (Geels & Turnheim, 2022).

Feedback 3: Policymakers $\leftrightarrow$ Technology Firms

Lobbying: Lobbying, among other factors, meant policies became more deployment-oriented after 2015. Nevertheless, despite the automakers' investments in EVs, car companies and their trade associations still lobbied against UK and EU climate legislation, including the phase-out of ICE vehicles (ICEVs), in an effort to slow down the transition (Geels & Ayoub, 2023).

Loans and capital grants: The 2017 Clean Growth Strategy announced subsidies and capital grants for stimulating automakers to build EV and battery manufacturing plants (Geels & Ayoub, 2023). Moreover, the 2017 Faraday Battery Challenge budgeted £541 million to be spent between 2017 and 2025 on, among other things, the manufacturing capability scale-up of batteries (The Faraday Institution, 2024; UK Research and Innovation, 2023)[2]. Further, the Supplier Competitiveness Improvement programme, outlined in the 2018 Automotive Sector Deal, aimed at enhancing manufacturing supply chain companies' productivity and competitiveness (SMMT, 2018).

R&D subsidies: The funds allocated to the 2017 Faraday Battery Challenge were also to be allocated to battery-related R&D activities (UK Research and Innovation, 2023). Besides, the 2018 Automotive Sector Deal also stated that the country's expenditure in R&D in the automotive sector was to be increased to 2.4% of the country's GDP by 2027 (BEIS, 2018).

Foster collaboration: The 2017 Faraday Battery Challenge involved several partners, one of which the Faraday Institution. This research centre focused on fostering collaboration between universities and industry to establish the UK as the premier location for novel electrical storage technology R&D (UK Research and Innovation, 2023). The collaboration among the industry and the government was also made clear in the 2018 Automotive Sector Deal (SMMT, 2018), which had the goal of aligning these two entities when it came to the EV transition (Geels & Ayoub, 2023).

[2] Note that there is an inconsistency between the information found on these official sources and the information provided in Geels and Ayoub (2023), which stated that only £330 million were allocated to this project.

(Binding) targets: To start with, EVs were seen as a crucial part of the country's industrial strategy by the 2017 Clean Growth Strategy, setting out a vision for the future of this technology in the automotive sector (Geels & Ayoub, 2023). Particularly, it announced the plans to phase-out new petrol and diesel cars and vans by 2040 (BEIS, 2017), which three years later was pushed to 2030, with all new cars needing to have zero-emissions after 2035 (Department for Transport & OZEV, 2020). These targets set a direction for the carmakers wanting to sell cars in the UK in the next decade, therefore setting out a course for an EV mass market (Geels & Ayoub, 2023).

Training: Beginning with a £64 million investment for digital and construction training, the 2018 Automotive Sector Deal established a National Retraining Scheme to assist individuals to re-skill according to the country's vision for zero-emission transportation (BEIS, 2018).

Feedback 4: Policymakers ↔ SET

Policies, goals, and coalitions adjustments: For instance, between 2015 and 2021 the funding allocated to R&D investment, infrastructure investment or to the Plug-in Car grant was updated over time, as were the targets for the phase-out of non-electric vehicles (BEIS, 2017, 2018; Geels & Turnheim, 2022). As the technology evolved the alliances among stakeholders changed too. For instance, new collaboration opportunities appeared after the 2017 Faraday Battery Challenge (UK Research and Innovation, 2023) and the 2018 Automotive Sector Deal (SMMT, 2018). Furthermore, with the technology maturing and new technology firms starting their involvement in the EV industry, trade associations saw their number of members increase, which means new alliances were formed (Automotive Council UK, 2024a; SMMT, 2018). Concerning feedback effects on goals, the outcomes and impacts of EV adoption influenced policymakers' perceptions, priorities, and long-term policy objectives. For one, between 2015 and 2017 policymakers started perceiving EVs as crucial in their transport decarbonisation strategy (Geels & Ayoub, 2023). For another, possibly due to observing an increasing EV adoption, in 2017 ambitious targets for the phase-out of petrol and diesel cars were set by policymakers (BEIS, 2017).

Infrastructure investment: In terms of direct public infrastructure investment, the On-street Residential Chargepoint Scheme, introduced in 2016, provided funding to local authorities to install on-street EV charging points in residential areas (OZEV, 2016a). Besides, £40 million of funding were allocated in 2016 to the Go Ultra Low Scheme, which promoted eight local authorities across the UK in their EV uptake, including the deployment of EV charging infrastructure (Department for Transport & OZEV, 2020; Fleet News, 2016; OLEV, 2014). The 2017 Clean Growth Strategy further set out investments and requirements for the charging infrastructure, aiming to make it one of the world's premier electric vehicle charging networks (BEIS, 2017). This was followed, in 2018, by the Automotive Sector Deal which announced an investment of £400 million to be made on the charging infrastructure (BEIS, 2018). These investments in the public charging infrastructure resulted in a rapid growth of the number of public chargers in the UK after 2019, as seen in Figure 6.8, according to which the total number of public charging devices grew by almost 27,000 from 2019 to 2023 (DfT, 2023). This was one of the main factors for the positive tipping point to be crossed, even though further improvements can be made to the charging infrastructure (interviewee 1).

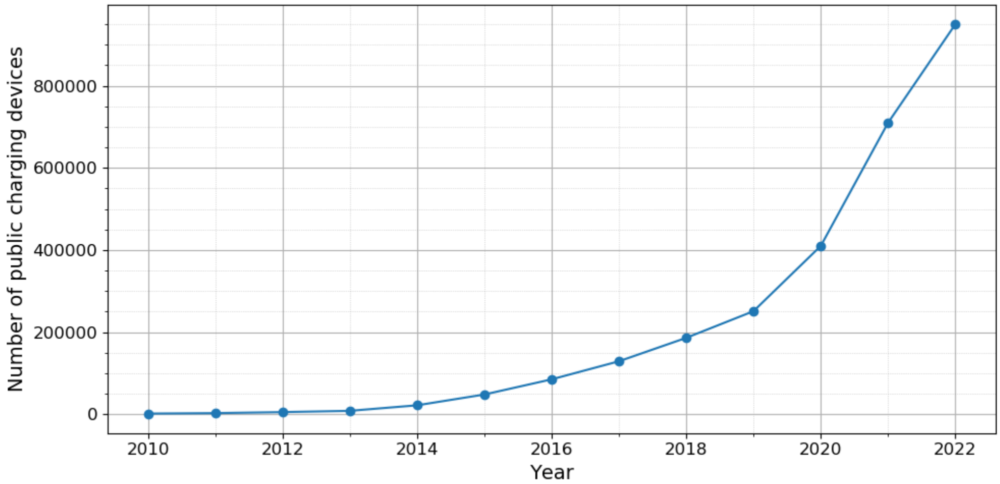

Figure 6.8: Total number of public chargers in the UK from 2015 to 2023 (DfT, 2023). The detailed data is given in Table A.2

Regulations and standards: The European Commission confirmed in 2019 that manufacturers must meet the 2014-established 95 g/km target for the average emissions of their sales after 2020/21. Strict fines were also imposed on businesses that failed to reach this goal, calculated by multiplying the number of cars sold by £83 (€95) for each gram over the limit. Even though Brexit took place in January 2020, the car market is a global market and so these regulations had a large impact on automakers' strategies. Overall, the industry's confidence in EVs increased in the light of such tight climate regulations (including the target of phasing-out new petrol and diesel cars by 2030) (Geels & Turnheim, 2022). Moreover, during this period, EVs did not pay or paid a reduced amount for parking in several cities of the UK, serving as an example of a regulation imposed on car owners that intended to promote the adoption of EVs (Rietmann & Lieven, 2019). Another intervention having a similar goal was the introduction of the London Ultra Low Emission Zone (ULEZ) in 2019 (SMMT, 2019), which specified that BEVs were free from the ULEZ and congestion charges, with PHEVs having to comply to certain standards to be eligible for this benefit (Garratt, 2024). This was a big incentive to switch to an EV since the London congestion charges can reach £2000 yearly (Rietmann & Lieven, 2019). Since then, seven other clean air zones have been established in the UK (Department for Environment, Food & Rural Affairs, 2020).

Feedback 5: Adopters ↔ Wider Public

Expanded technology's visibility; Further adoption: After 2015, as adoption grew and new policies were established, public attention grew. As a result, public discussions concerning EVs became more favourable and concentrated on topics such as job creation, economic growth, and clean air. Positive discourses fuelled consumers' curiosity and accelerated the uptake of EVs, which truly took off after 2019 (Geels & Ayoub, 2023).

Feedback 6: SET ↔ Wider Public

Solution to societal problems; Legitimacy: With early discourses covering aspects such as the fact that EVs were quiet, smooth, and allowed to reduce the emissions of the transportation sector, the technology started being framed as offering a solution to lessen fossil fuel dependency and cut on emissions (Alali, Niesten, & Gagliardi, 2022; Bunce, Harris, & Burgess, 2014). After 2015, increased EV adoption led to more positive public discourses, now also focusing on economic growth and job creation. The positive views increased the technology's legitimacy over time, which improved as the pitfalls of EVs saw technological advancements (Geels & Ayoub, 2023).

Feedback 7: Policymakers ↔ Wider Public

Public opinion; Strong policy plans and accompanying narratives: As concerns about climate change grew, public pressure contributed to policies becoming more deployment-oriented after 2015. The several policies aimed at promoting clean transportation in detriment of polluting vehicles substantially increased the attention of the wider public to the topic, which ultimately led to positive public debates that legitimised the established policies (Geels & Ayoub, 2023).

Feedback 8: Technology Firms ↔ Academic & Research Institutes

Funding: A £150 million building was built at the University of Warwick as a partnership between Jaguar Land Rover, Tata and the Warwick Manufacturing Group (interviewee 1). The goal was to create the biggest European automotive R&D centre and lead the way towards electric vehicles (Coventry Live, 2017). As another example, Ford funded a collaborative research project with Loughborough University to advance digital tools for EVs (Loughborough University, 2019).

Knowledge transfer: The UK Battery Industrialisation Centre was one of the organisations that collaborated on the 2017 Faraday Battery Challenge. This research centre is the national battery manufacturing development facility, assisting organisations in scaling up their battery technology into production. Another organisation involved, the Faraday Institution, combined expertise from academia and the industry to put the UK at the forefront of electrical storage technologies (UK Research and Innovation, 2023). These initiatives demonstrate a mutual transfer of knowledge between universities and technology firms, which is shown in Figure 6.7 as a feedback loop between these two actors. It represents that, as these collaborations become stronger and both parties see beneficial results, both the universities and the industry become more open to share more information with each other and collaborate further. Moreover, well-educated professionals from technical and higher education systems then joined different technology firms, helping push forward the EV transition in the UK (BEIS, 2018).

Feedback 9: Policymakers ↔ Trade Associations

Consultation; Foster collaboration: Policymakers consult trade associations to gauge the industry's and market's state. Examples include a public consultation in 2017 concerning vehicle weights, dimensions, and cleaner fuels, and one in 2019 about smart charging (Department for Transport, 2017, 2021). Trade associations such as the Society of Motor Manufacturers and Traders (SMMT) and the UK Automotive Council are involved in lobbying to assure that the industry is well represented at the government (Automotive Council UK, 2024b; SMMT, 2023). Such activities can also be used in a counterproductive way, as was the case when automakers and trade associations lobbied against legislation such as the phase-out of ICEVs, in the hope of delaying the transition (Geels & Ayoub, 2023). However, it is also an opportunity to bring the industry and the government closer, fostering an environment of mutual understanding where all parties work together in the same direction (SMMT, 2018). For example, the Automotive Council was involved in writing the 2018 Automotive Sector Deal (Automotive Council UK, 2024b; BEIS, 2018).

Policymakers → Adopters

Purchase subsidies: Over the years, there were several purchase subsidies involved, with the intent of promoting demand for ultra low emission vehicles (ULEV), which included electric vehicles. Firstly, the Plug-in Car grant, established in 2011, was still in place from 2015 to 2019, even though it suffered some alterations after 2018. When implemented, this grant assured that 25% of the purchasing costs of a BEV or PHEV were covered, up until £5000. In 2018, it was lowered to £3500 for BEVs (with further reductions in 2020 and 2021) and it was eliminated for PHEVs (Geels & Turnheim, 2022). The Clean Growth Strategy of 2017 further allocated £1 billion to support ULEVs, including £50 million dedicated to the taxi programme, with which taxi drivers could be eligible to up to £7,500 (BEIS, 2017). The 2018 Automotive Sector Deal set aside for the Plug-in Grant an extra £100 million (BEIS, 2018). Furthermore, the Electric Vehicle Homecharge Scheme was implemented in 2014 and lasted until 2022, when it suffered alterations and was renamed to the EV chargepoint grant. The scheme provided up to £350 to EV owners for the installation of home charging points with the aim of making it more convenient and affordable for individuals to charge their vehicles at home (British Gas, 2024). Finally, incentives were also given in the form of a voucher through the Workplace Charging Scheme to businesses wishing to improve their charging infrastructure, ultimately lowering the up-front costs (OZEV, 2016b).

Tax rebates: Implemented in the years prior to 2015 and still in place after 2019, EVs have benefited from tax reductions or exemptions. These include the Vehicle Excise Duty (VED), the Company Car Tax, and the Fuel Excise Duty (FED) (Geels & Turnheim, 2022). Since the VED and the Company Car Tax are calculated based on a car's tailpipe CO_2 emissions, this means that BEVs have more appealing tax reductions than PHEVs. Additionally, the FED also benefits greatly BEV than PHEV owners since it corresponds to the tax imposed on road fuels. Nonetheless, it can be concluded that BEV and PHEV have strong tax benefits compared to a petrol or diesel vehicle both for individuals and businesses (Zapmap, 2023).

Policymakers → Academic & Research Institutes

R&D subsidies: The 2017 Faraday Battery Challenge allocated funding to several topics and projects, for which research organisations were eligible (UK Research and Innovation, 2023). The 2018 Automotive Sector Deal increased the total investment in R&D to 2.4% of the UK's GDP until 2027 (BEIS, 2018). Other R&D funding was also provided by Innovate UK and the UK Research and Innovation (established in 2018), of which the Engineering and Physical Sciences Research Council is part (Innovate UK, 2024; UK Research and Innovation, 2024a, 2024b).

Foster collaboration: To bring the UK to the forefront of electrical storage technologies, the 2017 Faraday Battery Challenge brought together different organisations, including the two research centres UK Battery Industrialisation Centre and Faraday Institution. The latter was responsible for combining knowledge between the industry and academia (UK Research and Innovation, 2023).

Promote education: With a drive to become a world leader in the EV transition, in 2018 the government invested £406 million to create a world class technical education system. This was meant to fight the shortage of skills in science, technology, engineering and maths through allocating the money to maths, digital and technical education (BEIS, 2018).

Academic & Research Institutes → SET

Research and test: Academic and research institutes actively contributed to the development of electric vehicles and the surrounding technology. The Warwick Manufacturing Group aimed at being the largest R&D centre for EVs, with Loughborough University focusing on digital tools (Loughborough University, 2019; WMG, 2024). Moreover, the UK Battery Industrialisation Centre is the national battery manufacturing development facility, with the Faraday Institution focusing on electrical storage technologies (UK Research and Innovation, 2023).

Trade Associations → Adopters & Technology Firms

Foster collaboration: Trade associations such as the SMMT, the Automotive Council, and Recharge UK have several members, including technology firms (both automakers and supply chain firms), government, and research institutes (Automotive Council UK, 2024a; Recharge UK, 2024; SMMT, 2018). Such associations have been very active in promoting a clean future for UK's automotive sector. SMMT has been actively involved in assisting businesses who want to increase the competitiveness of their products and services by developing their workforce. Additionally, they have assisted in matching purchasing organisations with UK skills and have encouraged the sector to adopt a uniform strategy. Such advantages and collaboration opportunities have led, over the years, more parties to join trade associations such as SMMT, furthering fostering collaboration and discussion (SMMT, 2018). Moreover, Recharge UK is the biggest forum for electric vehicles in the UK, connecting over 100 organisations dedicated to improving the future of EVs in the country (Recharge UK, 2024). Furthermore, some associations such as the Electric Vehicle Association England represent England's current and future EV drivers, involving the adopters in the process (EVA, 2024).

NGOs → Policymakers

Lobbying: NGOs have been very supportive of electric vehicles, actively advocating for them and stating that they play a key role in fighting climate change (Campaign for Better Transport, 2022). For instance, Greenpeace UK wrote that the phase out of petrol and diesel cars by 2030 consisted of a big win (Greenpeace, 2020). This enthusiastic support is also seen through the different campaigns, publications released, and reports written, which advocate for certain policies in the interest of the industry and citizens that could accelerate the adoption of EVs (T&E, 2019).

NGOs → Wider Public

Public awareness campaigns: Several NGOs have campaigned for cleaner vehicles in the UK, covering topics such as climate change and air pollution. These include Campaign for Better Transport, Greenpeace UK, and Transport & Environment. Focusing on promoting the adoption of electric vehicles, these NGOs have been involved in organising campaigns and spreading petitions. For instance, Greenpeace UK blocked the entrance to the Volkswagen office, demanding they solely sell electric cars and offering advice to citizens (Greenpeace, 2018). Transport & Environment has also been very active in campaigning for electric vehicles in Europe, but also in the UK. For example, they publish an annual report where a campaign is always directed towards promoting electric vehicles. Besides, they have been involved in promoting petitions and organising street rallies, as well as advocating for new emissions controls (T&E, 2019).

6.4. Electric Vehicles in the Netherlands (2015 - 2021)

As observed in Figure 6.9, there was a significant surge in EV adoption in the Netherlands after 2018, marking the positive tipping point. After some years in which EV diffusion seemed to have stalled due to fluctuating tax rates (Hall, Wappelhorst, Mock, & Lutsey, 2020), adoption markedly picked up after 2018, especially that of BEVs, as observed in Figure 6.10. Compared to 2018, in 2022 there were 3.7 times more EVs on Dutch roads, corresponding to an increment of 270%.

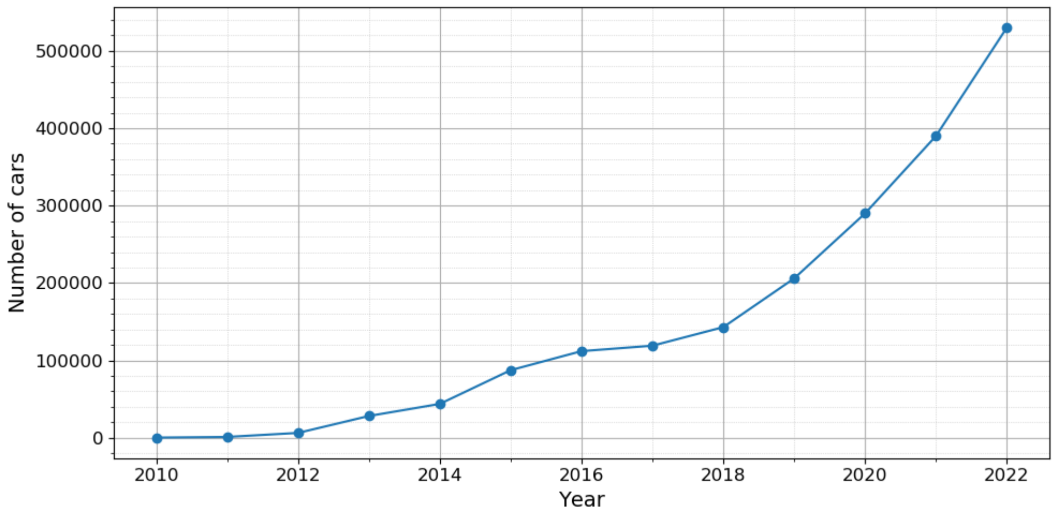

Figure 6.9: Stock of electric vehicles (BEVs and PHEVs) in the Netherlands from 2013 to 2022 (IEA, 2022). The detailed data is given in Table A.2

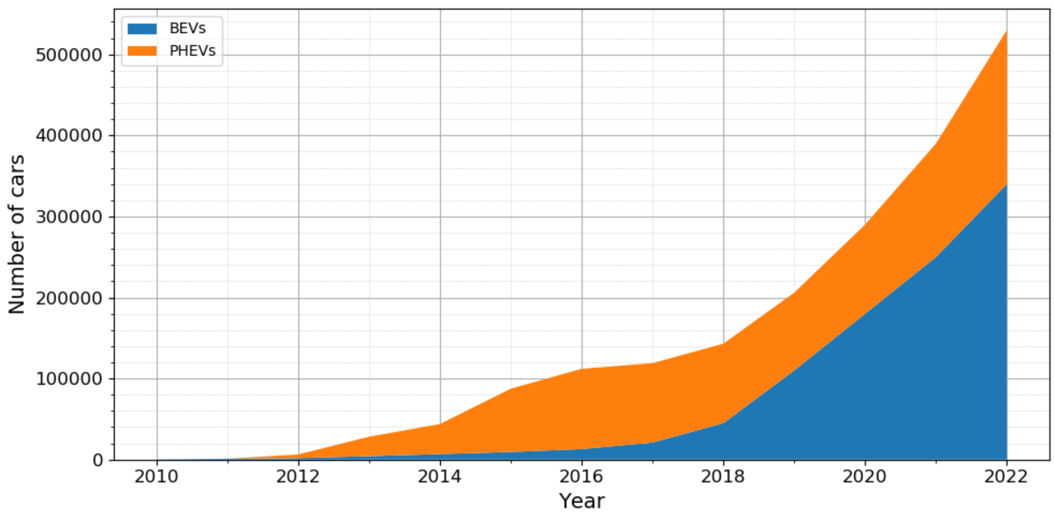

Figure 6.10: Stock of plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) in the Netherlands from 2013 to 2022 (IEA, 2022). The detailed data is given in Table A.2

Despite EV's having a market share of only 5.6% in 2022 (IEA, 2022) in the Netherlands, the country is a key player in the European EV market, consistently ranking among the top countries for EV sales shares (IEA, 2023b). In particular, the share of BEVs in total new car sales rose from 5.4% in 2018 to 20.3% in 2020 (Paradies, Usmani, Lamboo, & van den Brink, 2023). The Dutch government's ambitious goals and supportive policies (including generous subsidies) significantly contributed to this EV revolution and to the Netherlands maintaining its front runner status within Europe (Transport & Environment, 2016).

Cities like Amsterdam played a pivotal role, surpassing national average EV penetration rates (ICCT, 2023). The Dutch dynamic EV landscape, characterised by shifting market shares between BEVs and PHEVs, reflects both consumer preferences and evolving policy landscapes (Hall et al., 2020). The transformation witnessed underscores a collective commitment towards cleaner, sustainable transportation systems, setting the stage for continued innovation and progress in the years to come.

Different actors were active in developing, promoting, and adopting EVs in the Netherlands. Figure 6.11 illustrates the most relevant actor groups and their roles during the period analysed (2015 to 2021). The grey blocks and black labels correspond to elements already identified by Geels and Ayoub (2023). The orange blocks and labels were found on the case study but were already expected based on literature (see Section 4.3). The blue labels are additions made solely based on the case study findings. For a definition of the actor groups *technology firms* and *adopters* consult Section 6.3.

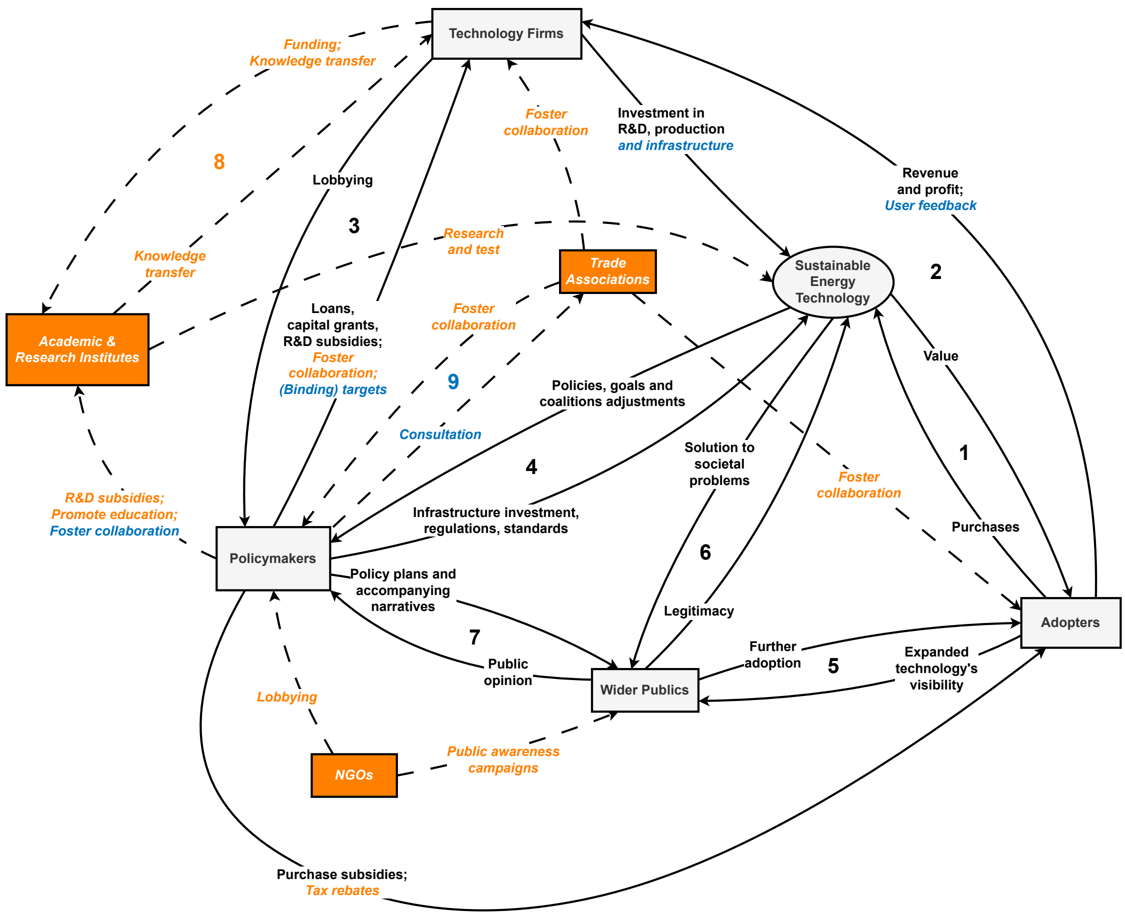

Figure 6.11: Feedback loop model showing the relevant actors and respective roles in the diffusion of electric vehicles in the Netherlands for the period of 2015-2021.

The period from 2015 to 2021 was studied. In 2015 the government showed a deep commitment to selling solely zero-emission cars in the near future (Transport & Environment, 2016) and large charging infrastructure investments were made after 2015 (IEA, 2023b). The Paris Agreement was also signed in 2015, setting GHG reduction targets (UNFCCC, 2022). For another, in 2021 subsidies suffered updates (Nederland Elektrisch, 2024b) and zero-emission zones were introduced (ICCT, 2023).

Like the diffusion of EVs in the UK, financial institutions did not play a key role in the uptake of EVs in the Netherlands. Financial options from financial institutions existed but this information was not found in any documents having an overview of the main developments of EVs in the country. Rather, it was only found after searching specifically for *leasing options* + *electric vehicles* + *Netherlands* and adding the name of specific banks that operate in the Netherlands to the search. Therefore, this actor group was left out of Figure 6.11. Each interaction depicted in Figure 6.11 is explained below, starting with the feedback loops and then the interactions outside specific loops. Each explanation is introduced by a small title corresponding to the arrow label in Figure 6.11, in the corresponding colour.

Feedback 1 & Feedback 2: Technology Firms ↔ SET ↔ Adopters

User feedback: Most automakers are active in many countries, so the improvements they invested in due to user feedback were probably a result of observations made in different markets. It is not easy to understand which developments were due to an event happening in the Netherlands. Thus, this interaction is in essence the same as for EVs in the UK (see Section 6.3). Feedback received from (potential) EV adopters was used by automakers in a constructive way, such that improvements were made to the technology. As an example, concerns about range anxiety were addressed through R&D by improving battery efficiency, size and capacity (Geels & Ayoub, 2023).

Investment in R&D, production, *and infrastructure*: Investment in EV-related R&D and production by technology firms relates to what was observed in the UK due to the fact that car companies act in an international context (Geels & Ayoub, 2023). The Diesel scandal of 2015 led to a change in attitudes, which resulted in an EV innovation race in the years to follow (Geels & Ayoub, 2023). After 2015, the number of EV models available increased and the offer became more diversified. Besides, new skills and factories were developed through large investments made by technology firms (Geels & Turnheim, 2022). Investments in technology advancements were made not only by car and battery manufacturers (on e.g., battery improvements) but also by charging infrastructure providers (Wills, 2020). In the Netherlands, some companies also invested in expanding the country's charging infrastructure (interviewee 3). For instance, since 2012 Fastned has been expanding its network of fast chargers (Fastned, 2019). Besides, Tesla has partnered with the Van der Valk Hotels and installed fast chargers in their premises (Van der Valk Hotels, 2024).

Value: From 2015 to 2021, the value proposition of EVs experienced improvements, driven by advancements in technology and market dynamics. Automakers enhanced battery capacity, size, efficiency, and range. The charging power also increased during this period and more charging options became available. All together, it meant that EVs were more practical and convenient to own (Geels & Ayoub, 2023; Milieu Centraal, 2024). Moreover, cost reductions in Li-ion battery packs contributed to making EVs more affordable and thus attractive (Geels & Turnheim, 2022).

Purchases; Revenues and profit: With the performance of EVs and their infrastructure increasing and their cost reducing, adopters' concerns were decreased and adoption became more appealing (Geels & Ayoub, 2023). As a result, purchases rose and the number if EVs on Dutch roads went from 87,400 in 2015 to 390,000 in 2021 (IEA, 2022; Milieu Centraal, 2024). Because of this trend, over time technology firms had higher revenues and higher profit from their EV segment, which increased their confidence and investment in the technology (Geels & Ayoub, 2023).

Feedback 3: Policymakers ↔ Technology Firms

Lobbying: Technology firms mainly lobbied via trade associations such as RAI, BOVAG, VNA, EVO, TLN, and VNO (VNA, 2024; VZR, 2022) (see feedback 9). As an example, RAI, BOVAG, and VNA lobbied against the system to determine a car's additional tax as one more or one less gram of CO_2 could make the difference between a higher or lower car sales number (VZR, 2022).

Loans, capital grants, and R&D subsidies: The Dutch government and the European Commission provided several financial incentives to promote innovation and develop the market for electric vehicles, which technology firms could apply to. This included both research and demonstration projects (RVO, 2017a). For instance, the Research and Development Promotion Act, which exists since 1994, offers a tax reduction to R&D projects (RVO, 2015). Since 2014 there was also the innovation incentive Region and Top Sectors for small and medium enterprises (SMEs) (RVO, 2023b) and the Demonstration of Energy and Climate Innovation scheme (RVO, 2023a), and since 2017 the Subsidy Scheme for Demonstration of Climate Technologies and Innovations in Transport (RVO, 2022a). During this period there were also other European-wide support schemes. Namely, the Interreg programme has existed since 1990 (European Commission, 2020; RVO, 2017b) and the LIFE subsidy programme since 1992 (European Commission, 2022; RVO, 2017c). Moreover, the Eurostarts programme initiated in 2007 and targets SMEs in specific (RVO, 2011), while the Connecting Europe Facility Transport scheme, existent since 2014, has the goal of improving the transport network (RVO, 2014).

Foster collaboration: Dutch policymakers strategically fostered collaboration among technology firms and between these and other actors to drive advancements in EVs and their charging infrastructure. A pivotal initiative was the Formula E-Team, established in 2016, forming a public-private partnership involving the technology firms, research institutes, and the government itself (Nederland Elektrisch, 2024a). This collaboration extended to various working groups focused on different aspects of EV adoption, such as the consumer market, light EVs, PHEVs, the charging infrastructure, and communication, among others (Nederland Elektrisch, 2019). Furthermore, the government has actively engaged in other public-private partnerships with local governments, firms, trade associations, and research institutes, as evidenced by the 2019 Climate Agreement and the Dutch National Charging Infrastructure Agenda (Nationale Agenda Laadinfrastructuur, 2022). These partnerships highlight a concerted effort to achieve climate goals and promote sustainable mobility through collaborative innovation and policy frameworks.

(Binding) targets: Policymakers have set ambitious and binding targets aimed at technology firms concerning EVs and their adoption. One of the most significant targets is that the Dutch government aims for all new vehicles sold in the country to be zero-emission vehicles by 2030 (Deuten, Vilchez, & Thiel, 2020; Hall et al., 2020; Klimaatakkoord, 2021; Nationale Agenda Laadinfrastructuur, 2022; Paradies et al., 2023; van der Kam, Meelen, van Sark, & Alkemade, 2018). Some cities have, however, even more ambitious targets. For instance, Amsterdam aims at only having emissions-free transportation in the city by 2030 (Hall et al., 2020). Additionally, national and European initiatives like the 2019 Climate Agreement and the 2021 Fit for 55 package set specific goals set for public transport and passenger cars. The EU has set in as early as 2015 CO_2 emission targets for new passenger car fleets (Agency, 2016; Paradies et al., 2023), while the Fit for 55 package set the goal of reducing by 55% the country's GHG emissions compared to 1990 (Nationale Agenda Laadinfrastructuur, 2022). Further, goals for the development of the charging infrastructure were set by the National Charging Infrastructure Agenda such that all electric vehicles had access to charging devices (Nederland Elektrisch, 2022).

Feedback 4: Policymakers ↔ SET

Policies, goals, and coalitions adjustments: After policies are implemented, their effectiveness is evaluated and, at times, the policy suffers adjustments (Geels & Ayoub, 2023). For instance, at first the incentives given by the Dutch government promoted PHEVs more than BEVs (Ashkrof, de Almeida Correia, & van Arem, 2020), leading to the adoption pattern observed in Figure 6.10. However, upon realising that PHEV owners only used their vehicles' electrical power 35% of the time, the purchase incentives given to PHEVs were reduced (Transport & Environment, 2016). Continuous adjustments were also performed to the taxation of PHEVs and BEVs, and to the purchase subsidies (Deuten et al., 2020; Hall et al., 2020). Besides, as the technology evolved, goals evolved too. Initially the focus was on increasing the market share of PHEVs. Over time it shifted to actually phasing out PHEVs. This was a consequence of their limited capacity to lower emission, associated with the fact that the battery capacity of BEVs was improving (Ashkrof et al., 2020). At the same time, this created more confidence in the technology and led to for instance the 2017 target of having 100% sale of zero-emission vehicles by 2030 (Deuten et al., 2020).

Infrastructure investment: The Netherlands has been one (if not the) leader when it comes to their charging infrastructure in terms of public chargers per capita, per electric vehicle, and in absolute terms, even though their public infrastructure consists of mostly slow chargers (Hall et al., 2020; ICCT, 2023; IEA, 2023b; Paradies et al., 2023). Indeed, as observed in Figure 6.12, the number of public recharging points raised from less than 10,000 in 2015 to nearly 75,000 in 2022 (Statista, 2023), with Amsterdam accounting most public chargers and new EV registrations (ICCT, 2023). This fast growth was due to effective policies and public investment (ICCT, 2023). Both the 2016 Green Deal and the 2019 Climate Agreement set goals and plans to expand and improve the country's EV charging infrastructure (Klimaatakkoord, 2021; Nederland Elektrisch, 2019; Rijksoverheid, 2020). As measures, for instance, the government and different regions allocated 15 million euros each to construct the national network (Nederland Elektrisch, 2020). Besides, in several Dutch municipalities EV owners can request that a public charger is installed for free in their neighbourhood. (ICCT, 2023; Nederland Elektrisch, 2024b).

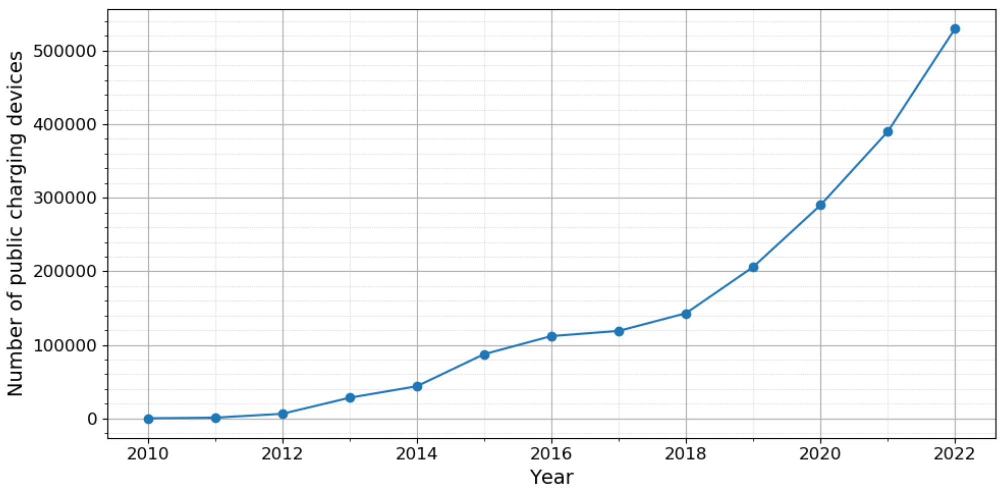

Figure 6.12: Total number of public chargers in the UK from 2015 to 2023 (Statista, 2023). The detailed data is given in Table A.2

Regulations and standards: In 2019 the European Commission confirmed that after 2020/21 manufacturers must have an average emission level of 95 g/km in their sales portfolio. If businesses failed to meet this target, they were subjected to stiff fines of £83 (€95) per car sold for each gram over the limit (Geels & Turnheim, 2022). Further, EVs started paying parking fees in many Dutch municipalities after 2018, even when at public charging points (Yellowbrick, 2018). Additionally, LEZs were implemented by some Dutch municipalities and significantly promoted EVs. Since 2018, Amsterdam has an environmental zone that does not allow old diesel buses or taxis into the city, promoting the use of EVs by taxi drivers. Arnhem went one step further in 2019 by banning any diesel car older than 2005 to enter the city. Furthermore, in Utrecht diesel cars with engines older than 2001 are also not allowed to drive in the city centre since 2015, and the same thing goes for Rotterdam since 2016 (Auto Siero, 2021; IEA, 2023b).

Feedback 5: Adopters ↔ Wider Public

Expanded technology's visibility; Further adoption: As the adoption of electric vehicles increases, the technology's visibility and acceptance seemed to increase too. In 2017, only 17% of the Dutch population had the intention of purchasing an EV in the coming five years. In contrast, in 2021 this percentage raised to 25% (ANWB, 2021).

Feedback 6: SET ↔ Wider Public

Solution to societal problems; Legitimacy: As the technology evolved, it started being framed more as a solution to some societal problems. Among them, environmental concerns listed high since EVs produce around 35 to 55% less CO_2 during their lifetime compared to an ICEV (ANWB, 2019, 2021; KiM, 2022). Another advantage are the lower operating costs of EVs compared to petrol cars. This is a result of lower charging costs compared to refuelling, lower maintenance requirements, and road tax exemption (ANWB, 2021; KiM, 2022). Concerning a vehicle's total cost of ownership, EVs actually had a lower value on average compared to petrol vehicles (ANWB, 2021). Besides, EVs are not as noisy as their counterparts and are odourless, making them a cleaner solution than fossil-fuel-based cars (ANWB, 2018; KiM, 2022). The better value offered over the years (see *Feedback 1*) and by tackling some car-related societal problems, the legitimacy of EVs increased, leading to higher acceptance of the technology (ANWB, 2019, 2021).

Feedback 7: Policymakers ↔ Wider Public

Public opinion; Strong policy plans and accompanying narratives: Dutch people are considerate of environmental problems and have been adapting their behaviour towards more sustainable practices such as purchasing EVs. Such concerns and preferences are heard by policymakers, who then create more ambitious climate policies (ANWB, 2019; European Investment Bank, 2022). This feedback between policymakers and the wider public is also visible in other aspects. For instance, the purchase subsidies introduced in 2020 targeted the public concern about high EV prices (ANWB, 2019). Moreover, being low vehicle range another concern, policymakers provided several R&D subsidies to help advance the technology (ANWB, 2019; RVO, 2017a). Lastly, even though the Netherlands has been a global leader in the charging infrastructure, in 2021 27% of the Dutch population still considered it to be too limited. The Dutch government has, however, been making huge investments in the public charging infrastructure (see *Feedback 4*) with the aim of promoting the technology and quieting these uncertainties (ANWB, 2021; ICCT, 2023).

Feedback 8: Technology Firms ↔ Academic & Research Institutes

Funding: Technology firms also fund academic and research institutes. For instance, the Formula Student Team of TU Delft develops and builds electric racing cars with the help of several business partners, who invest in their project (DUT, 2024). In 2018, the company Lithium Werks announced they would build an R&D centre in Enschede and collaborate with University of Twente to develop the new generation of batteries and flexible energy storage solutions. The project costed more than €100 million, which was funded by different sources (University of Twente, 2018).

Knowledge transfer: Technology firms and academic and research institutes collaborated in several projects, transferring knowledge and expertise among each other. The Formula E-Team was created in 2016 as a public-private partnership that brought together the government, knowledge institutions, and businesses. These parties collaborated on projects concerning knowledge development and sharing about electric transportation and the charging infrastructure (Nederland Elektrisch, 2022). One of these knowledge institutions was ElaadNL, a centre that investigates and tests EV charging solutions (ElaadNL, 2022a). National Charging Infrastructure Knowledge Platform Foundation (NKL), which is dedicated to lowering the public charging infrastructure costs by optimising its installation (Nederland Elektrisch, 2023). Furthermore, the four technical universities (4TU) of the Netherlands were one of the partners of the Formula E-Team, having therefore contributed to knowledge transfer among member (RVO, 2018). Through their EV-dedicated programmes, the 4TU - Delft, Eindhoven, Twente, and Wageningen - are committed to creating expert engineers and designers that can lead the industry (Nederland Elektrisch, 2019).

Feedback 9: Policymakers ↔ Trade Associations

Consultation; Foster collaboration: Policymakers involved trade associations in collaborative projects. The 2016 Formula E-Team, a public-private partnership to promote electric transportation included trade associations such as the Interprovincial Consultation, the Grid Operators Netherlands (*Netbeheer Nederland*) and the Association of Electric Drivers (IPO, 2024; Nederland Elektrisch, 2019; Netbeheer Nederland, 2024; VER, 2023). Trade associations also collaborated with the Dutch government and other actors, such as firms and academic and research institutes in e.g., the 2019 Climate Agreement (Nationale Agenda Laadinfrastructuur, 2022). Both instances show that the government actively engaged and consulted trade associations for their knowledge on the industry and market situation. Furthermore, trade associations played a big role in bringing the concerns of the industry and (potential) adopters to the policymakers, such that collaboratively a better solution could be found. These include the VZR, ANWB, RAI, BOVAG, VNA, EVO, TLN, and VNO. For instance, BOVAG, RAI, and VNA lobbied against the system of determining the additional tax of a car. Currently based on the vehicle's CO_2 emissions, one more or one less gram of CO_2 might mean the car pays 14% or 20% of additional tax (VZR, 2022).

Policymakers → Adopters

Purchase subsidies: At first, direct purchase subsidies and reduced registration costs mainly targeted PHEVs (Deuten et al., 2020; Transport & Environment, 2016). However, after 2017 BEVs started increasing at a high rate and in 2022 BEVs comprised 65% of Dutch EVs (IEA, 2022). Prospective owners of EVs have been benefiting since 2020 from €2,950 to buy or lease a new EV, while this subsidy lowers to €2,000 for second-hand cars (Milieu Centraal, 2024; RVO, 2017a, 2022b). Nonetheless, these premiums have been reducing as the industry develops (IEA, 2023b).

Tax rebates: Tax reductions and exemptions have also been serving as incentives to purchase an EV (Klimaatakkoord, 2021). After 2011 EVs were exempt from circulation and registration taxes, although the exemption for PHEVs was dependent on emission standards and ended in 2016 (ACEA, 2014; Transport & Environment, 2016). BEVs also enjoyed a tax advantage with a reduced addition to taxable income for company-owned cars of 4% from 2014 onwards. Similarly, PHEVs had reduced additions to taxable income over the years, starting at 7% in 2014 and increasing to 22% in 2017 (Deuten et al., 2020). Over time, tax benefits extended to acquisition, ownership, and company cars, favouring zero-emission vehicles. (Klimaatakkoord, 2021).

Policymakers → Academic & Research Institutes

R&D subsidies: Between 2015 and 2021 academic and research institutes could apply to some of the financial support provided by the Dutch government and the European Commission aimed at promoting the development of electric vehicles and their market (RVO, 2017a). One example was the Subsidy Scheme for Demonstration of Climate Technologies and Innovations in Transport, available since 2017 (RVO, 2017a, 2022a). Other European-wide support schemes include the Interreg programme, which was launched in 1990 (European Commission, 2020; RVO, 2017b) and the LIFE subsidy scheme, which exists since 1992 (European Commission, 2022; RVO, 2017c). Moreover the Connecting Europe Facility Transport scheme, created in 2014, has the goal of improving the transport network (RVO, 2014).

Foster collaboration: As mentioned in Feedback 3, Dutch policymakers fostered collaboration among different actors. This included knowledge institutions, which can be interpreted as academic and research institutes. One of the initiatives created by the Green Deal was the Formula E-Team, established in 2016 by the government, which consisted in a public-private partnership involving technology firms, knowledge institutions, and policymakers (Nederland Elektrisch, 2019, 2024a). One of these institutions is the ElaadNL which investigates and tests charging solutions for EVs (ElaadNL, 2022b). The 2019 Climate Agreement and the Dutch National Charging Infrastructure Agenda also highlight other public-private partnerships between local governments, firms, trade associations, and knowledge institutions (Nationale Agenda Laadinfrastructuur, 2022).

Promote education: As part of the Green Deal, the four technical universities (4TU), i.e. Delft, Eindhoven, Twente, and Wageningen, developed educational programmes on electric transportation to prepare future professionals for the transition (Nederland Elektrisch, 2019). Other secondary vocational education (MBO) and university (HBO) programmes also give EV related courses (Tweede Kamer der Staten-Generaal, 2016).

Academic & Research Institutes → SET

Research and test: In the Netherlands, several academic and research institutes research and test electric vehicle technology. ElaadNL, for instance, focuses on sustainable and smart EV charging for cars, buses, and trucks (ElaadNL, 2022a). Besides, NKL focuses on the optimisation of the public charging infrastructure (Nederland Elektrisch, 2023). The 4TU have also been committed to electric-vehicle-related education and research (Nederland Elektrisch, 2019).

Trade Associations → Adopters & Technology Firms

Foster collaboration: Trade associations were active in lobbying at the government and ministries in the name of their members, to whom they also fostered collaboration opportunities. Examples of trade associations are the RAI, BOVAG, VNA, EVO, TLN, and VNO (VNA, 2024; VZR, 2022). For instance, the RAI Association represents manufacturers and importers of several vehicle types (RAI Vereniging, 2024), while BOVAG was founded by car companies but now includes also other companies whose business is associated with vehicles. BOVAG offers professional support and knowledge sharing opportunities (BOVAG, 2023). Additionally, the VNA (Association of Dutch Car Leasing Companies) offers insights on future regulations and policies to the government to favour the car leasing industry. The VNA encourages their members to share their views on different topics. Besides, the VNA seeks collaboration with other trade associations, such as BOVAG, RAI Association, Evovenedex, ANWB, among others. VNA also represents private lease drivers (VNA, 2024). Other trade associations representing adopters include VER, which represents all electric drivers (VER, 2023), while the VZR is the voice of the business drivers (VZR, 2024). Moreover, ANWB stands up for the interests of mobility and tourism parties, for instance by offering retail, insurance, travel, and roadside assistance (ANWB, 2020).

NGOs → Policymakers

Lobbying: Environmental NGOs have shown enthusiastic support for electric vehicles in different ways. For instance, the *Natuur en Milieu* (Foundation for Nature Conservation and Environmental Protection) was one of the partners of the Formula E-Team, showing in this way their strong support for the technology (RVO, 2018). *Milieudefensie* (known in English as Friends of the Earth Netherlands) has also been engaged in environmental protection activities since 1971, including promoting clean mobility solutions such as electric vehicles (Knol, 2018). Transport & Environment is another NGO that acts at the European level and has been active in advocating for electric transportation (T&E, 2019). Nonetheless, it should be noted that NGOs also point out potential technological improvements to achieve a higher product sustainability. For example, *Natuur en Milieu* wrote about the sustainability of batteries (Penders & de Lange, 2022).

NGOs → Wider Public

Public awareness campaigns: NGOs share important information about different technologies such that they can raise awareness among the general public. This can be done through articles, campaigns, or petitions. For instance, *Natuur en Milieu* wrote about sustainable car batteries and the advantages of having an electric car (de Jongh, 2022; Penders & de Lange, 2022). A campaign meant to promote electric vehicles among Uber drivers was named the 'True Cost of Uber' and was launched by environmental NGOs from different countries, including the Netherlands. The campaign raised awareness through petitions in cities such as Amsterdam (T&E, 2019).

In this chapter, the four case studies performed are extensively described, providing insights into the tipping point dynamics of each case. Each case's main policies are summarised in Section C.2. Chapter 7 puts the findings into perspective, discussing them.

7 | Discussion

In this chapter, the results are discussed. In Section 7.1 the expansion of the framework developed by Geels and Ayoub (2023) is presented. This section covers which actors and actor roles are deemed relevant in triggering a positive tipping point in the adoption of wind energy and electric vehicles in specific, and of sustainable energy technologies in general. Then, Section 7.2 discusses the main outcomes of the validation process. Finally, some general remarks are provided in Section 7.3.

7.1. Model Expansion

The expansion of the framework of Geels and Ayoub (2023) is presented in Section 7.1.1, answering sub-question 5. Then, Section 7.1.2 and Section 7.1.3 elaborate upon the relevant actor groups and their roles, covering sub-questions 2 and 3, respectively. In Section 7.1.4, the specific role of policy-makers is discussed and sub-question 4 is answered[1].

7.1.1. Final Feedback Loop Models

Two final feedback loop models were created, one representing the wind energy case studies, and the other the EV ones. These are shown in Figure 7.1, and Figure 7.2, respectively. The figures were constructed based on the case-specific feedback loop models (shown in Chapter 6), by overlapping the interactions found in the two wind energy and in the two EV case studies[2]. The grey blocks and black labels can be found in Figure 4.3, the refined version of Geels and Ayoub (2023), and are common among both final models. The green and yellow blocks and labels are additions made based on this thesis' work. Two models are proposed because the main actors and actor roles differed in some aspects between the wind energy and the EV cases. This is discussed in Section 7.1.2 and Section 7.1.3. To make these differences clearer, in Figure 7.1, and Figure 7.2 green is used for elements that belong to both models, while yellow shows elements that are particular to either model.

In comparison, Geels and Ayoub (2023) presented a single feedback loop model. It is argued that this results in an inaccurate and too generic representation of the deployment of technologies that are fundamentally different, at least when it comes to their target audience and to the scale in which they are adopted. The differences between the wind energy and EV case studies suggest that there are differences between the tipping point dynamics of B2B and B2C technologies. Figure 7.1 and Figure 7.2 can thus be used as a *reference* for the socio-technical dynamics of positive tipping points in the adoption of B2B and B2C technologies, respectively. Nevertheless, it should be kept in mind that the results are based solely on four case studies that only focus on two technologies. Actors and actor roles might show variations when looking at other technologies and/or contexts.

[1]Sub-question 1 has been answered in Section 4.2.

[2]There are two exceptions, however. The interactions *promote education* and *training* were found in at least one of the two EV case studies and yet were left out of Figure 7.2. The reasoning for this is given at the beginning of Section 7.1.3.

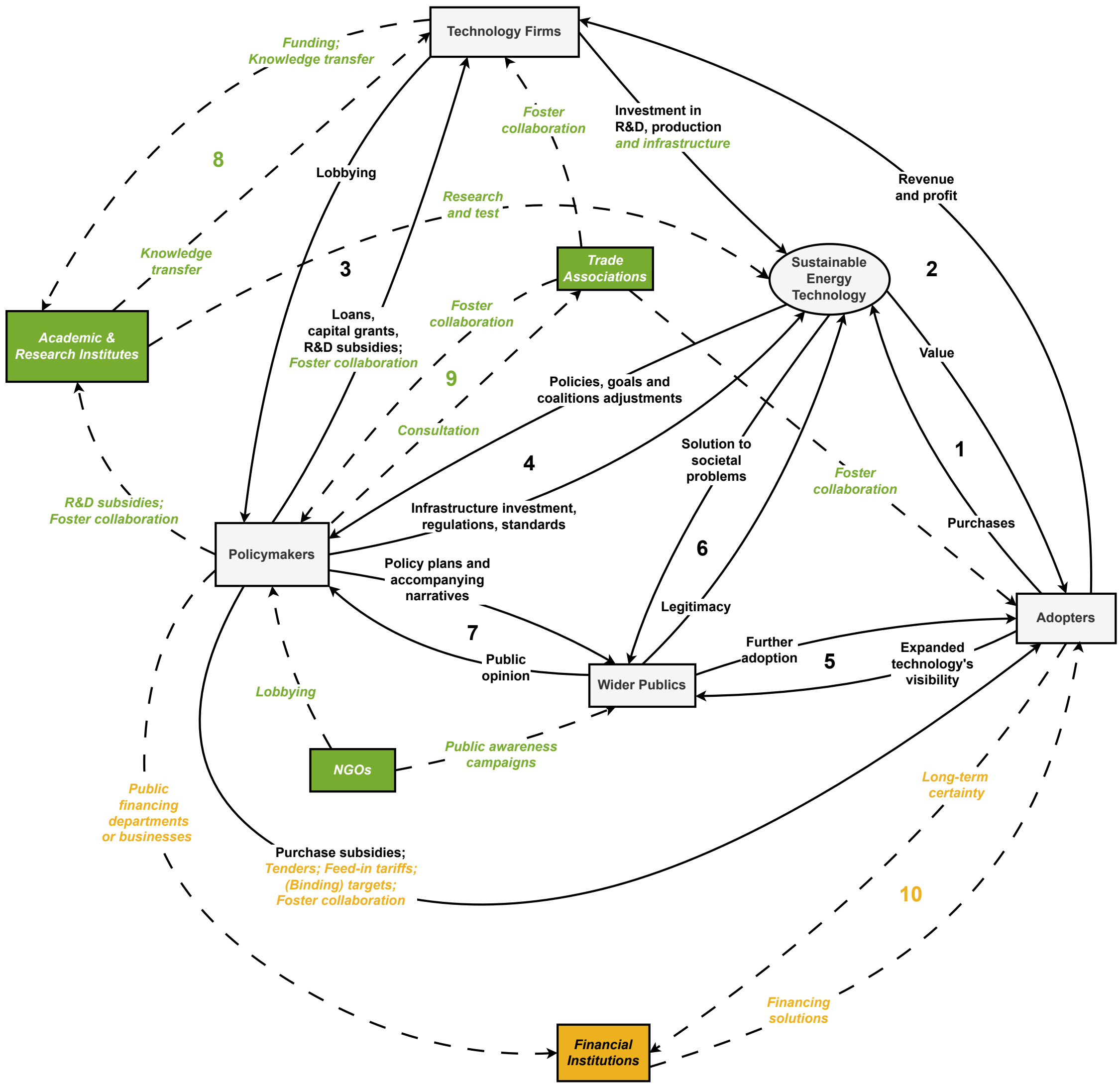

Figure 7.1: Feedback loop model showing the relevant actors and respective roles in triggering a positive tipping point in the adoption of wind energy. This model might be used as a reference for positive tipping points in the uptake of business-to-business sustainable energy technologies, i.e. mainly adopted in large numbers by businesses

Sub-question 5 - *How can the feedback loop model of Geels and Ayoub (2023) be expanded to include a wider set of actors and interactions between these while maintaining its readability?* - is therefore answered by the two feedback loop models illustrated in Figure 7.1, and Figure 7.2. Concerning maintaining the readability of the models, it was attempted to only include data that had been relevant in triggering the tipping point or maintain the subsequent accelerated growth (see Section 5.2.2).

Furthermore, Figure 7.1 and Figure 7.2 show several interactions between actor groups that are not part of a feedback loop. In contrast, Geels and Ayoub (2023) only included one of these 'loose' interactions in their model, the *purchase subsidies* given by policymakers to adopters. However, these interactions are important as they might be responsible for triggering or strengthening reinforcing feedback loops. For instance, financing incentives and (binding) targets helps set in motion and maintain feedback loops 1 and 2. As another example, public awareness campaigns of NGOs raise awareness among the wider public and shapes their opinion, strengthening feedback loops 5, 6, and 7.

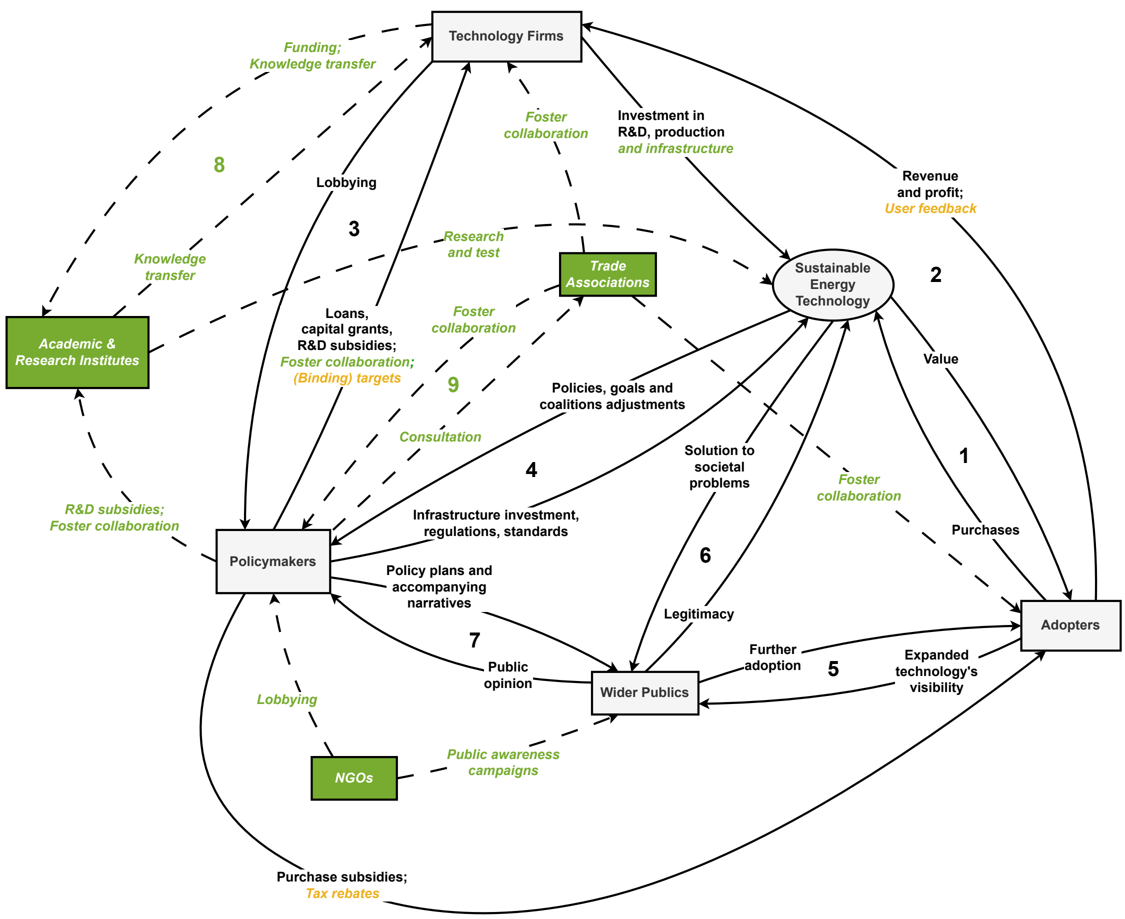

Figure 7.2: Feedback loop model showing the relevant actors and respective roles in triggering a positive tipping point in the adoption of electric vehicles. This model might be used as a reference for positive tipping points in the uptake of business-to-consumer sustainable energy technologies, i.e. mainly adopted in small numbers by individual buyers

As noted by interviewee 4, apart from the nine or ten feedback loops identified in Figure 7.1 and Figure 7.2, there might be other larger, hidden feedback loops occurring. For instance, in Figure 7.1 *investment in R&D and production* results in higher product *value* which allows potential adopters to give *long-term certainty* to financial institutions, resulting in more *financing solutions* available. This leads to more *purchases* and therefore higher *revenue and profit* for technology firms, which in turn use part of that money for more *investment in R&D and production*, repeating the cycle.

These larger feedback loops are important since they encompass more than two actor groups, truly showing how the socio-technical system is connected and the importance of having such an holistic view. Nonetheless, this thesis focused on particular interactions and feedback loops among only two actor groups. Consequently it is now hard to identify these larger feedback loops in Figure 7.1 and Figure 7.2. If they had been kept in mind from the beginning, perhaps the information had been presented differently in the feedback loop models or additional links would have been added. This is therefore one of the limitations of the current work, and could be an avenue for future research (see Section 8.3).

Section 7.1.2 discusses the actors present in Figure 7.1 and Figure 7.2, while Section 7.1.3 does so for the interactions and actor roles.

7.1.2. Actors

Table 7.1 provides a summary of the actor groups in Geels and Ayoub (2023), the wind energy case studies, and the EV ones, and how these compare to the actors found in the initial literature (see Section 4.3). The literature initially analysed suggested the relevance of eight actor groups in triggering tipping points in SET adoption: policymakers, technology firms, adopters, wider publics, academic and research institutions, trade associations, NGOs, and financial institutions. Geels and Ayoub (2023) only included the first four in their model. In contrast, as observed in Figure 7.1 and Figure 7.2, all eight actors were found important in the wind energy case studies, while only financial institutions did not appear relevant in the deployment of EVs. While public financial incentives proved essential for EV adoption, the influence of private financial institutions appeared to be limited. The results are in agreement with Muratori et al. (2021). Conversely, documentation on wind energy developments frequently cited financial institutions as a catalyst.

The answer to sub-question 2 - *"Apart from the actor groups selected by Geels and Ayoub (2023), which other actors are relevant in promoting positive tipping points in the deployment of sustainable energy technologies?"* - therefore has two parts. On the one hand, for B2B technologies like wind energy all eight aforementioned actor groups seem to be relevant. On the other hand, in the uptake of B2C technologies such as EVs, the same actor groups appear important with the exception of financial institutions. This difference was one of the reasons for having two final feedback loop models.

Table 7.1: Actor groups found on the feedback loop model of Geels and Ayoub (2023), and those based on the wind energy and EV case studies. The eight actor groups are the ones that were expected based on the literature presented in Section 4.3

Actor groups expected (Section 4.3)	**Geels and Ayoub (2023)** (Figure 4.3)	**Wind energy** (Figure 7.1)	**Electric vehicles** (Figure 7.2)
Policymakers	✓	✓	✓
Technology Firms	✓	✓	✓
Adopters	✓	✓	✓
Wider Public	✓	✓	✓
Academic & Research Institutes	✗	✓	✓
Trade Associations	✗	✓	✓
NGOs	✗	✓	✓
Financial Institutions	✗	✓	✗

Generalising the case studies findings to other (B2B and B2C) SETs should be done carefully. For one, this thesis focused solely on four case studies. Analysing different cases might lead to different conclusions. For another, only two technology types were analysed. More research, namely involving other technology types, should be conducted to improve the robustness of these generalisations.

A relevant observation is that, during the periods analysed, incumbents (both technology firms and adopters) were very committed to the transition, contrary to what was expected from literature (Geels, 2019; Lenton et al., 2022; Roberts et al., 2018). However, it might be that for many years incumbents fought change, with the periods analysed coinciding with the moment in which they eventually committed to it. This was partially suggested by interviewee 1 but also by Geels and Ayoub (2023). In their EV case study it is observed that, while initially Tesla was the biggest player, after the 2015 Diesel scandal all incumbents followed suit. The tipping point then occurred a few years after in the UK, the Netherlands, and globally. If this is true for other case studies too, the results might suggest that the involvement of incumbents is essential to trigger tipping points. However, performing case studies that cover more years prior to the positive tipping point is necessary to prove this hypothesis.

Additionally, as discussed with interviewee 1 and 2, some actors can fit in different actor categories depending on the situation. This is the case for consulting firms, which perform many activities. While they fit the best within *technology firms* they perform certain roles at times that align with other actor groups. Furthermore, project developers might fit in *technology firms* or in *adopters* depending on whether they are involved in the installation of the project or only on getting it to a ready-to-build phase.

Finally, despite useful, the concept of actors can be limiting if certain functions or actions are seen as pertaining solely to that actor group. It might be that a function can be performed by another actor. It is hence beneficial to think in terms of actor roles, as discussed in Section 7.1.3.

7.1.3. Actor Roles

Actor roles refer to the functions that the actors perform in the socio-technical system. This is a useful concept as it specifies roles that need to be fulfilled, rather than who fulfils it. They are shown in the feedback loop model as the interactions between actors or between an actor and the technology, which are represented by the arrows and respective labels. All the interactions included in the feedback loop models presented throughout this report are summarised in Appendix B.

Although in this thesis actor roles relate to interactions *between* actors, important system functions can be performed by a single actor group, independently. For instance, academic and research institutes might conduct research within their own organisation, without collaborating with other parties. In that case, despite relevant, this function is not captured in the feedback loop model. That is one of the limitations of Geels and Ayoub (2023) but also of this thesis, as mentioned in Section 8.3.

Upon an initial inspection of relevant literature (see Section 4.3), thirteen overarching actor roles were formulated. As shown in Table 7.2, twelve of these actor roles were identified in the wind energy case studies and eleven on the EV cases. The role of *promoting education* was not deemed relevant in the deployment of neither wind turbines nor EVs. Additionally, the role of *establishing market-based mechanisms* was not present in the EV case studies. In contrast, the model of Geels and Ayoub (2023) only includes seven actor roles, suggesting the authors left important aspects out of their model.

Table 7.2: Summary of the relevant overarching actor roles in achieving a positive tipping point and whether they were included in the feedback loop model based on Geels and Ayoub (2023), the wind energy case studies, and the EV case studies. These actor roles were expected based on the general literature presented in Section 4.3

Actor roles expected (Section 4.3)	**Geels and Ayoub (2023)** (Figure 4.3)	**Wind energy** (Figure 7.1)	**Electric vehicles** (Figure 7.2)
Technology development	✓	✓	✓
Technology adoption	✓	✓	✓
Legitimising technology	✓	✓	✓
Providing financing incentives/options	✓	✓	✓
Investing in infrastructure	✓	✓	✓
Establishing legislation	✓	✓	✓
Lobbying	✓	✓	✓
Raising awareness	✗	✓	✓
Fostering collaboration	✗	✓	✓
Transferring knowledge	✗	✓	✓
Giving & receiving feedback	✗	✓	✓
Establishing market-based mechanisms	✗	✓	✗
Promoting education	✗	✗	✗

These results can be used to answer sub-question 3: *"What are the main actor roles in promoting a positive tipping point in the deployment of sustainable energy technologies?"*. The findings suggest that (at least) the eleven actor roles that were found both in the initial literature and in the four case studies should be fulfilled to trigger a tipping point in the deployment of SETs. As for *establishing market-based mechanisms*, only present in the wind energy case studies, the results indicate that they are probably only relevant for B2B technologies. Nevertheless, it should be taken into account that the context can play an important role and should always be considered carefully. Furthermore, despite the consistency of the results obtained, more case studies should be conducted to verify them.

The only actor role not included in any of the final feedback loop models, *promoting education*, was actually found on the EV case studies. In the UK, policymakers created a retraining programme for technology firms to acquire new skills aligned with a zero-emission mobility future. It is possible that in the other case studies retraining happened within the firms themselves, not involving a special government programme, and therefore did not appear as an interaction *between* actors. Besides, in both the UK and the Netherlands policymakers promoted and invested in education programmes at academic institutes. However, educational programmes take time to be improved or developed, and it takes time for the students to graduate from these programmes and join technology firms or start producing relevant research. In the UK, large investments in education occurred only one year before the tipping point. In the Netherlands, the tipping point occurred two years after EV-specific courses and programmes were strongly developed. Upon interviewee 4 agreeing that the promotion of education by policymakers was not a relevant factor for either tipping point, this interaction was excluded from the final models.

Despite the high match between the actor roles expected from the initial literature and the case studies, not all interactions in Figure 4.4 are found in Figure 7.1 and Figure 7.2. This showcases that an actor role might be fulfilled in distinct ways by distinct actors. However, the fact that not all the exact interactions in Figure 4.4 were found in the case studies can be due to several reasons. Firstly, the literature concerned a socio-technical context but not necessarily related to *sustainable energy* technologies. Secondly, it is possible that actor roles differ in different stages of the technology's development and deployment and that perhaps some of the literature was specific of a particular phase. Thirdly, if more case studies were researched perhaps more of the interactions in Figure 4.4 would have been identified in them. Below, an explanation is given of the twelve actor roles found in the case studies.

Technology development

Technology development entails improving the technology's performance and reducing its cost, hence increasing its value proposition. Two main actor groups were involved in this process. As identified by Geels and Ayoub (2023), technology firms invest in R&D and production to improve the quality of their products and the efficiency of their processes. For another, academic and research institutes conduct research and tests, especially relevant for novel technologies. Table 7.3 summarises the interactions found on this report's feedback loop models related to technological development.

Table 7.3: Interactions related to technology development, as well as the actor groups involved

Interaction label	Source	→	Recipient
Investment in R&D and production	Technology Firms		SET
Value	SET		Adopters
Research and test	Academic & Research Institutes		SET

Technology adoption

As a technology's performance raises and its cost reduces, the role of *technology adoption* is stimulated. The feedback loop model interactions that relate to the role of technology adoption are listed in Table 7.4. Higher adoption levels increase the technology's visibility, making it more desirable to the wider public through social contagion and leading to more adoption. Higher purchases allow for higher revenues and profits for technology firms, allowing them to further invest in increase a technology's value proposition.

Table 7.4: Interactions related to technology adoption, as well as the actor groups involved

Interaction label	Source	→	Recipient
Purchases	Adopters		SET
Revenue and profit	Adopters		Technology Firms
Further adoption	Wider Public		Adopters
Expanded technology's visibility	Adopters		Wider Public

Legitimising technology

As public acceptance increases, the technology is legitimised. This is important because public opinion can strongly influence a technology's adoption, as shown by nuclear energy developments in several countries (Ming et al., 2016). A positive public opinion can create a conducive environment for a technology's development and adoption. In the case studies it was observed that two main factors contribute to shaping public opinion. The first one is to frame the technology as offering a solution to societal concerns, being them environmental or of another nature. Secondly, policymakers can also have a role in shaping public opinion through their policy plans and accompanying narratives. The feedback loop model interactions that are associated with legitimising the technology are summarised in Table 7.5.

Table 7.5: Interactions related to legitimising the technology, as well the parties involved

Interaction label	Source	→	Recipient
Policy plans and accompanying narratives	Policymakers		Wider Public
Solution to societal problems	SET		Wider Public
Legitimacy	Wider Public		SET
Public opinion	Wider Public		Policymakers

Providing financing incentives/options

Financing has proved essential in promoting the research, development, and adoption of the technologies analysed. In the model of Geels and Ayoub (2023) policymakers are the only ones providing financing options. However, the literature initially analysed (see Section 4.3) and the case studies showed that technology firms and financial institutions can also be important actors in this respect. Table 7.6 provides an overview of the feedback loop model interactions related to this actor role.

As included in Geels and Ayoub (2023), policymakers can give loans, capital grants, and R&D subsidies to technology firms to promote the development of new technologies or the improvement of existent ones. They can also give purchase subsidies to adopters, making technologies more affordable. Nonetheless, these are not the only financial incentives given by policymakers. For instance, in all case studies policymakers provide R&D funding and grants to academic and research institutes. Besides, feed-in tariffs were observed in both wind energy case studies, while tax rebates played an important role in the EV cases. Although this difference might be related to whether it is a B2B or B2C technology, it might also be a consequence of whether the technology is used to generate energy/electricity or not.

Furthermore, it was found on three of the four case studies that technology firms provide funding to academic and research institutes for research to be conducted (collectively or not) on topics that are relevant to the firm. This was confirmed and emphasised by interviewee 1. This interaction was most likely not found on the wind in Portugal case study because during the period analysed the country relied mostly on imports (interviewee 2). Additionally, financial institutions[3] provided financing support to the adopters of wind energy projects both in the UK and in Portugal. This was true especially after projects started providing long-term certainty. Project finance can at times be the distinguishing factor between the realisation or not of projects like wind farms, and should therefore not be dismissed.

Table 7.6: Interactions related to providing financing options, as included in the feedback loop model, as well as the parties involved

Interaction label	Source	→	Recipient
Loans	Policymakers		Technology Firms
Capital grants	Policymakers		Technology Firms
R&D subsidies	Policymakers		Technology Firms
			Academic & Research Institutes
Purchase subsidies	Policymakers		Adopters
Tax rebates	Policymakers		Adopters
Feed-in tariffs	Policymakers		Adopters
Funding	Technology Firms		Academic & Research Institutes
Long-term certainty	Adopters		Financial Institutions
Financing solutions	Financial Institutions		Adopters
Public financing departments or businesses	Policymakers		Financial Institutions

Investing in infrastructure

Table 7.7 shows the feedback loop interactions that correspond to this actor role. In the UK civil engineering contractors contributed to developing the transmission infrastructure for wind energy. Besides, in the Netherlands private firms invested in expanding the EV charging infrastructure. Hence, although infrastructure investment is usually a public endeavour, it can also be conducted by technology firms.

Table 7.7: Interactions related to investing in SET-related infrastructure, as well as the parties involved

Interaction label	Source	→	Recipient
Investing in infrastructure	Policymakers		SET
	Technology Firms		SET

Establishing legislation

Several interactions relate to estabilishing legislation, as summarised in Table 7.8. Regulations and standards can be effective in guiding development and adoption choices. For instance, the Renewable Obligation scheme in the UK mandated utility firms to have a specific percentage of renewable electricity in their portfolio. In Portugal, the installation of wind energy projects was promoted by liberalising the

[3] Some of the financial institutions were state-backed or state-owned.

energy market and simplifying the licence granting process. When it comes to EVs, the creation of clean air zones within cities was one of the EV promoters both the UK and the Netherlands.

Furthermore, setting ambitious but attainable targets, being them binding or not, was found to be a policy instrument capable of steering the industry and the market in the right direction. An important difference was found, nonetheless, between the wind energy and EV case studies, suggesting differences between B2B and B2C technologies. For one, in wind energy the targets were aimed at the adopters (e.g., energy or utility firms) as they concerned adoption figures for wind energy or renewable energy capacity. For another, in the EV case studies targets were directed at technology firms (e.g., automakers). These include the phase-out of polluting cars and CO_2 targets for the cars sold.

Finally, this actor role also relates to evaluating and adjusting policies, goals, and coalitions such that they are effective. This interactions was already included in Geels and Ayoub (2023) and was found to have been relevant in all four case studies. In fact, it was found in all cases that adoption accelerated after a certain policy or goal was adjusted. This is covered in more detail in Section 7.1.4.

Table 7.8: Interactions related to setting legislation, as well as the parties involved

Interaction label	Source	→	Recipient
Regulations and standards	Policymakers		SET
(Binding) targets	Policymakers		Technology Firms (wind energy case studies)
			Adopters (EV case studies)
Policies, goals, and coalitions adjustments	SET		Policymakers

Lobbying

The interactions and actor groups involved in lobbying are summed up in Table 7.9. Trade associations were involved in lobbying in the name of their members (both technology firms and adopters), leading to a more collaborative environment. Additionally, lobbying was also performed directly by technology firms and NGOs, with respect to for instance the industry's direction and environmental concerns. While lobbying can be performed to fight change, there can also be 'positive' lobbying, in which actors enthusiastically advocate for a certain technology. Both situations were observed. Furthermore, although lobbying was defined as a separate actor role, it closely relates to legitimising (or not) a technology.

Table 7.9: Interactions related to lobbying, as well as the parties involved

Interaction label	Source	→	Recipient
Lobbying	Technology Firms		Policymakers
	NGOs		Policymakers
Foster collaboration	Trade Associations		Policymakers
Public opinion	Wider Public		Policymakers

The seven actor roles described above were included in Geels and Ayoub (2023). However, five others were identified in the initial literature and in the case studies. These are described below.

Raising awareness

Raising awareness can be accomplished via public awareness campaigns, which were observed to be typically performed by NGOs. Trade associations also raise awareness through campaigns and publications, usually targeted at adopters. Both these interactions are summarised in Table 7.10.

Table 7.10: Interactions related to promoting public awareness, as well as the parties involved

Interaction label	Source	→	Recipient
Public awareness campaigns	NGOs		Adopters
Foster collaboration	Trade Associations		Adopters

Fostering collaboration

Collaboration played a key role in all case studies. The main actors fostering collaboration were policymakers and trade associations. Furthermore, the actor groups involved in the collaboration opportunities include policymakers, academic and research institutes, technology firms, trade associations, and adopters. This information is summarised in Table 7.11.

The involvement of adopters played a bigger role in the wind energy case studies than the EV ones due to the different nature of adopters of B2B and B2C technologies. In the wind energy cases the adopters were mainly a few well-established energy firms, facilitating collaboration. Conversely, most EV adopters are individual citizens, although companies with electric car fleets also fall under the adopters category. It is hence more impractical to involve EV adopters in collaborative opportunities. Nonetheless, both in the UK and in the Netherlands there were trade associations who represented EV drivers, fostering a collaborative environment between adopters, policymakers and technology firms.

The role of trade associations in fostering collaboration encompassed collaborative projects but also the representation of and lobbying for their members. By advocating for their members interests, trade associations fostered a cooperative environment in which the views of different stakeholders were valued. Lobbying in the name of technology firms led to more realistic and effective policies. Furthermore, voicing adopters concerns might result in technology firms improving certain aspects of a technology they had not yet considered, or to release stronger policies to help adoption uptake.

Table 7.11: Interactions related to fostering collaboration, as well as the parties involved

Interaction label	Source	→	Recipient
Foster collaboration	Policymakers		Technology Firms
			Academic & Research Institutes
	Trade Associations		Policymakers
			Technology Firms
			Adopters

Transferring knowledge

In the case studies, knowledge was transferred between academic and research institutes and technology firms. This mutual knowledge transfer relationship is summed up in Table 7.12. Academic and research institutes conduct relevant research that might help advance technologies. Knowledge transfer from academic and research institutes to technology firms can occur through journal and conference publications or through collaborative projects. When the latter applies, there is also knowledge shared in the opposite direction. Additionally, technology firms can provide training to academic and research institutes, as was found on the wind energy in the UK case study (Kern et al., 2014). Finally, many well-educated people leave academic and research institutes to join technology firms. There, they help advance the firm's technologies, transferring knowledge in this way.

Table 7.12: Interactions related to transferring knowledge, as well as the parties involved

Interaction label	Source	→	Recipient
Knowledge transfer	Academic & Research Institutes		Technology Firms
	Technology Firms		Academic & Research Institutes

Giving & receiving feedback

The interactions related to giving and receiving feedback are summarised in Table 7.13. Firstly, policymakers approached trade associations to gauge the industry's and the market's status. This can be referred to as (policy) consultation and helps policymakers draft and adjust their policies such that they are as effective as possible. This interaction was mentioned by interviewee 1 and was verified in every case study by different sources. Secondly, user feedback plays a role in the development of any technology since design is an iterative process that tries to accommodate for the preferences of all stakeholders. User feedback was, however, found to play a bigger role in the EV case studies.

The latter could be due to a number of reasons. For one, during the period analysed for the wind energy developments in Portugal (2000 - 2007), onshore wind turbines had already been widely implemented in other countries and therefore the technology had already gone through several iterative stages beforehand. For another, for the deployment of offshore wind in the UK (2002 - 2014), the technology was adapted from onshore wind turbines, which were well-established by then. At the same time, offshore wind turbines were also not that recent themselves, with the first commercial offshore wind farm being installed in Denmark in 1991 (Ørsted, 2019). In contrast, in the period analysed for the EV case studies (2015 - 2021) the technology underwent several improvements, for instance concerned with the battery's specific capacity (energy storage capacity per unit weight) and the car's range, with the global positive tipping point occurring only around 2020 (Geels & Ayoub, 2023; IEA, 2023a).

Table 7.13: Interactions related to giving feedback, as well as the parties involved

Interaction label	Source	→	Recipient
Consultation	Policymakers		Trade Associations
User feedback	Adopters		Technology Firms

Establishing market-based mechanisms

Another instrument that can be used by policymakers to drive adoption besides financial incentives are market-based mechanisms such as competitive tenders. Tenders are a commonly used instrument to deploy B2B SETs, with the potential to be more effective than feed-in tariffs (Bento, Borello, & Gianfrate, 2020). Tenders played an important role in both wind energy case studies, being associated with the attainment of both tipping points. In Portugal, tenders specified locations with wind energy potential that were located in grid-accessible places or places where it was relatively easy to expand the grid. It was also seen that in the UK the tender process became particularly effective after round 3, when the zones with more potential for exploration were identified by the Crown Estate. These results suggest that for B2B technologies tenders can be an effective instruments, especially if the zones with the highest potential are identified by the tender providers. Tenders are, nevertheless, not a common instrument in the deployment of technologies adopted at an individual level. Accordingly, they did not play a role in the EV case studies. Table 7.14 shows which actor groups were involved in the tendering processes.

Table 7.14: Interactions related to establishing market-based mechanisms as well as the parties involved

Interaction label	Source	→	Recipient
Tenders	Policymakers		Adopters

Having explained the different actor roles identified, Section 7.1.4 focuses on the specific role of policymakers, allowing sub-question 4 to be answered.

7.1.4. Role of Policymakers

Often policies are analysed in isolation. However, policies emerge from the interaction between policymakers and societal actors. They are part of a broader set of formal and informal rules that actors have to comply with. Hence, it is not appropriate to analyse policies isolated from the context they belong to (Edmondson et al., 2019; Fesenfeld et al., 2022; Roberts et al., 2018). Therefore, in this thesis policies were interpreted as an actor role and represented as only one element of Figure 7.1 and Figure 7.2, which illustrate how the policies interact with the actors and vice-versa.

As expected from literature (Edmondson et al., 2019; Fesenfeld et al., 2022; Geels & Ayoub, 2023; Roberts et al., 2018), policymakers were instrumental in achieving each case's tipping point, being involved in eight of the twelve actor roles identified in the case studies. These were legitimising technology, providing financing incentives/options, investing in infrastructure, establishing legislation, lobbying, fostering collaboration, giving and receiving feedback, and establishing market-based mechanisms.

Despite the importance of all these roles, financial incentives, infrastructure investment, legislation, and market-based mechanisms seemed to have the largest impact. Firstly, financial incentives substantially helped make the technologies more affordable, while market-based mechanisms (in the wind energy cases) promoted the strategic allocation of resources. In the wind energy case studies, purchase subsidies, feed-in tariffs and tenders were used to promote adoption. For another, the uptake of EVs both in the UK and in the Netherlands was fostered by purchase subsidies and tax rebates.

Secondly, in the four case studies policymakers were instrumental in developing the infrastructure. In the wind energy cases, they streamlined the connection processes and reinforced the grid, while in the EV case studies policymakers installed more public chargers. Despite the different types of infrastructure investment, the case studies show the relevance of it being mostly a public investment. For one, the national grid is most often publicly owned so public bodies are usually responsible for its reinforcement and expansion. For another, when it comes to EV charging points, not only public investment can help reduce range anxiety at an initial deployment stage (Patil, 2019), but also policymakers are usually the best equipped to optimally place charging devices within a city (Lamontagne et al., 2023).

Thirdly, in all case studies legislation steered the industry in the right direction, particularly the targets established. For wind energy, these targets were directed at the adopters and concerned the share of renewable sources in electricity and energy production, as well as wind installed capacity. For EVs, the targets were aimed at the technology firms and related to the phase-out of polluting vehicles. Despite directed at different actor groups, targets proved invaluable in all cases.

Therefore, in the four case studies the most influential policies were deployment-oriented, even though policies related to R&D and technology development activities were still observed. This is in agreement with Jennings, Tipper, Daglish, Grubb, and Drummond (2020), who states that as a technology matures the policies gradually shift from being technology-push to being demand-pull. In other words, from focusing on the development of technical knowledge to focusing on developing the market.

Although the tipping points analysed were a consequence of the interventions of several actors, their timing appeared to be correlated with the implementation or adjustment of a policy. The UK's offshore wind energy experienced a positive tipping point in 2009, the same year of the Renewable Obligation amendment, which doubled the financial support for offshore wind. In Portugal, the installed capacity of onshore wind accelerated after the feed-in tariffs were increased in 2001, leading to a spike in applications in 2002. However, this high interest was only reflected in adoption numbers after 2004 due to the high number of applications and the long licensing processes. In the UK, the number of EV adopters and public charging points increased after 2019, with plans to phase-out petrol and diesel cars made in 2017 and 2018. In the Netherlands, public chargers and EV adoption increased after 2018, with plans to sell only zero-emission vehicles after 2030 occurring in 2017. These results suggest that when a policy is effective its consequences are observed relatively fast. From this follows the importance of evaluating and adjusting policies and goals (part of the actor role of *establishing legislation*).

Each case study policies are listed in Section C.2. Table 7.15 summarises this information by showing which types of economic, regulatory and information instruments (see Section 4.3.1) were found on each case study, versus which ones were included in Geels and Ayoub (2023). In all case studies financial, regulatory and information instruments were employed. This suggests that, although some instruments might be more effective than others as discussed above, attaining a tipping point in SET adoption depends on a combination of policies, or policy mixes, as argued by Edmondson et al. (2019).

Table 7.15: Summary of the relevant policies on each case study, as well as whether those policy types were also found on Geels and Ayoub (2023). For a detailed explanation of the categories used see Section C.1

Policy instrument	**Geels and Ayoub (2023)**	**Wind Energy**		**Electric Vehicles**	
		UK	*Portugal*	*UK*	*The Netherlands*
Economic instruments					
Financial Incentives	✓	✓	✓	✓	✓
Market-based mechanisms	✗	✓	✓	✗	✗
R&D support	✓	✓	✓	✓	✓
Regulatory instruments					
Standards	✓	✓	✓	✓	✓
Strategic planning	✗	✓	✓	✓	✓
Market facilitation	✓	✓	✓	✓	✓
Information instruments					
Knowledge transfer	✗	✓	✗	✓	✓
Collaboration & networking	✗	✓	✓	✓	✓
Outreach	✗	✗	✗	✗	✗

Sub-question 4 can be answered with the help of Table 7.15, which reads as follows: *Apart from the policy types identified by Geels and Ayoub (2023), which other policies are relevant in promoting positive tipping points in the deployment of sustainable energy technologies?* Geels and Ayoub (2023) included financial incentives and R&D support as economic instruments, as well as standards and market facilitation as regulatory instruments. It was found that market-based mechanisms can also be a relevant economic instrument for wind energy in particular and B2B SETs in general. (Binding) targets were also another important regulatory instrument in all case studies. Furthermore, while Geels and Ayoub (2023) did not consider any information instruments, the case studies suggest that policymakers actively promoted knowledge transfer, collaboration and networking opportunities.

Some remarks should, however, be made. First, policymakers were not found to promote knowledge transfer in the uptake of onshore wind energy in Portugal. This could be because during the period analysed there was almost no national wind energy industry, with the country relying mostly on imports. Second, market-based mechanisms were only observed in the wind energy case studies, suggesting they might be more relevant for B2B technologies. Third, in none of the case studies were there outreach policy instruments. Nevertheless, this role was not left unfulfilled. In all case studies NGOs and trade associations raised awareness among and shared information with the wider public and the adopters. This shows that certain actor roles are interchangeable.

Lastly, looking back at the framework developed by Fesenfeld et al. (2022) (see Figure 3.3), in the case studies analysed the policies were substitution-focused as technological change was very relevant in both cases, taking precedence to behavioural changes. Even though a transition to more sustainable technologies is incredibly valuable, a next step in the direction of further fighting climate change might relate not only to substitution but also to sufficiency practices, requiring high behavioural changes too. To exemplify sufficiency, future policies might promote more strongly the use of public transportation versus a private electric car. These thoughts could be explored further in future research.

Having looked at how the model proposed by Geels and Ayoub (2023) was expanded based on this thesis findings, Section 7.2 presents the main points of the validation conducted.

7.2. Validation

To validate the case studies findings, and the final feedback loop models, four semi-structured interviews were conducted. A summary of the interviews can be found in Appendix D. Below, the main points are presented. First, some general comments are covered. This is followed by the validation of the case studies in Section 7.2.1, and of the final feedback loop models in Section 7.2.2.

For one, interviewee 1 agreed that consultancy firms fit nicely within the category of technology firms. However, they pointed out that such firms can fit in different boxes. This highlights that the actor groups included in the model can be fluid, being it possible for one stakeholder to belong to different categories.

For another, interviewee 1 believed that typically small and medium enterprises invest in innovations and trigger their tipping points, with incumbents only following suit once the technology is at a more developed stage. However, as discussed in Section 7.1.2, the results did not support this hypothesis.

7.2.1. Case Studies Validation

The validation of the case studies was a result of three interviews. The main points are here discussed, in the same order as the case studies were presented in Chapter 6.

Wind Energy in the UK

Interviewee 1 argued that, apart from the arrow reading *foster collaboration* from trade associations to policymakers, there should also be an arrow going back. This should represent input and feedback sought by policymakers from trade associations on the industry or market's state to inform the development of future policies and regulations (DECC, 2009; Offshore Energies UK, 2024). In the model, this was added as *consultation*, forming feedback loop 9. The other case studies were also checked for it.

Interviewee 1 also pointed out that academic and research institutes interact directly with the sustainable energy technology block through *research and test*. Furthermore, the interviewee argued that technology firms also provided *funding* to academic and research institutes and their projects. These two interactions were not being represented. After consulting other sources, they were included in the model. The other case studies were also checked for them.

In general, interviewee 1 agreed with the specific actors presented, but mentioned that ORE Catapult also performed relevant research, and that the Renewable Energy Association (REA) was also an influential trade association. These actors were therefore added to the description of the case study.

Lastly, interviewee 1 clarified that the Crown Estate is an independent private organisation set up by the government whose profit goes to the country's Treasury. It is a private firm with the mission of bringing prosperity to the nation (The Crown Estate, 2023). Therefore, it was interpreted as a financial institution (established by policymakers) and as a policymaker, due to their proximity to the UK's government.

Wind Energy in Portugal

The first comment made by interviewee 2 that is worth more attention relates to the interviewee's remark on the stabilisation phase post-2010. According to them, it was not only due to the economic crisis but also due to grid capacity constraints. Accordingly, the introduction of the case study was adjusted.

They mentioned that in projects involving wind or solar farms it is common for project developers to develop the whole project until the ready-to-build phase, selling it to the final buyer afterwards. They argued that in this case the project developer would not be an *adopter* but would fit better under *technology firms*. This was commented on in Section 7.1.2. The interviewee also highlighted the relevance of consulting firms in providing reassurance to adopters and validating the projects. These firms, while performing these competencies could also be integrated in the category of *technology firms* (as mentioned by interviewee 1). This discussion highlighted that the group *technology firms* might currently embrace a large set of actors, which can be seen as a limitation of this thesis (covered in Section 8.3). Nevertheless, it was decided not to create extra actor categories to limit the model's complexity.

The interviewee's commented that the numbers provided for the feed-in tariffs should be referred to as average numbers. Besides, they mentioned that the duration of this support differed per project as it depended on the park's energy production. The description of the case study was adapted accordingly.

Lastly, the interviewee said that according to their perception, while over time the turbines' power and rotor diameters increased, their cost per MW did not particularly decrease. This was contradicted by reliable sources (IEA, 2004b, 2005) and thus the description of feedbacks 1 and 2 was not modified.

Electric Vehicles in the UK

Similarly to the wind energy in the UK case study, ijnterviewee 1 argued that technology firms supported academic and research institutes financially. After consulting other sources, *funding* was added as an interaction between these two actors. Moreover, at the time of the validation meeting the interaction between trade associations and adopters of *fostering collaboration* was not part of the model. Interviewee 1 agreed that this made sense since adopters were mostly individual buyers. However, afterwards associations that directly represent adopter groups, such as EVA, were found and therefore this interaction was added to the case study's model (EVA, 2024).

Furthermore, the interviewee highlighted the importance of infrastructure investments. They considered that while EVs have been affordable for a long time, the lack of an extensive charging infrastructure was one of the main impediments to the technology's adoption. The interviewee also mentioned that the charging infrastructure still needs to be further expanded and that grid capacity needs to be increased. These comments were incorporated into the case study's description.

Electric Vehicles in the Netherlands

Interviewee 3 also highlighted the infrastructure's relevance to the EV deployment in the Netherlands. At the same time, they mentioned that the environmental zones within Dutch cities were effective in promoting the transition. These points were already discussed in the case study.

They mentioned that, additionally to what had been presented, there was an auction for fast chargers next to highways, which was seized by Fastned. Besides, they pointed out that Tesla also invested in expanding the charging infrastructure, namely in partnership with the Van der Valk hotels. This information was added to feedback loop 2, backed by other sources.

The interviewee commented that, apart from other advantages of EVs, it was "cool" to own one. This closely relates to enabling condition 6, desirability/symbolism, specified by Lenton et al. (2022). Despite a technology's price or performance it might attract potential adopters due to the higher social status it brings. Nevertheless, based on the data analysed it seemed that the increasing performance of EVs and the more extensive charging infrastructure were bigger factors in fostering adoption than status.

Finally, interviewee 3 pointed out that, although currently wind turbines and EVs seem like 'easy-to-implement' technologies, at first they faced several challenges. The difficulty is in kick-starting the industry, establishing the infrastructure, and choosing where to focus. This comment relates to this research's importance for the tipping points of other SETs and is followed up in Section 7.3 and 8.2.

7.2.2. Final Feedback Loop Models Validation

In general, interviewee 4 agreed with what was presented. However, they made clear that it was not straightforward to discuss some of the points without having knowledge of the case studies. Nonetheless, in the 1h validation interview it was not possible to provide deep details about all case studies.

Interviewee 4 mentioned that literature on social acceptance typically distinguishes between the general public and communities where the technology is (to be) located, each having a different level of acceptance. They suggested that in the feedback loop models the wider public could be split into two actor groups to include this nuance. However, that was not pursued since it would add unnecessary complexity. Rather, the influence of public opinion was explained in the descriptions of the case studies.

Concerning the role of financial institutions, the interviewee commented that they might still play a role in the EV case studies, even if it is not as straightforward. They mentioned that many people might take loans to purchase an electric vehicle. However, they mentioned that including this actor or not would depend on the case study findings. For one, it might be that these people would require a loan to buy another (non-electric) car. For another, after performing extra research, private financing did not appear critical in the EV case studies and was thus not included in the respective models.

Interviewee 4 also pointed out that, although the role of policymakers is typically the most visible, it is not necessarily the most important. Instead, groups such as global communities and wider public can also play a big role in shaping the system. This was kept in mind when writing Section 7.1.4.

Lastly, the interviewee questioned whether there were not any bigger feedback loops present in the model, apart form the nine or ten included in Figure 7.1 and Figure 7.2. This comment was very pertinent and was incorporated in Section 7.1.1 and as a limitation of the work in Section 8.3).

7.3. General Remarks

Some final, general remarks can be done about the results. If the focus is to be solely on the actor roles and not the actors, a causal loop diagram (CLD) could have been more suitable. CLDs focus on relationships and feedback loops between variables, leaving out the concept of actors (Sterman, 2000). This can be an advantage since some roles can be performed by different actor groups, as discussed in Section 7.1.3. Although this avenue was briefly pursued, it was decided to utilise a similar layout as that used by Geels and Ayoub (2023) as the main goal of this thesis was to expand on their work.

Furthermore, it was deemed that the concept of actor groups was still important. Actors evolved over time to be very specialised in certain tasks, making them probably the most suitable to fulfil a particular actor role. Besides, not all roles are interchangeable. For instance, it is unlikely that academic and research institutes are going to give financial incentives to adopters. Consequently, the use of feedback loop models as those presented in Section 7.1.1 (rather than CLDs) was considered to be an adequate way of portraying the dynamics involved in triggering positive tipping points in the adoption of SETs.

Thirdly, the uptake of wind energy in Portugal might have entered the stabilisation phase too early due to the economic crisis and grid capacity issues. This might mean that there is remaining wind energy potential and that, with the right set of policies or industry effort, another positive tipping point might be observed. Despite speculative, this could mean that it is possible for multiple positive tipping points to occur. This inspires a possible avenue for future research as discussed in Section 8.3.

Finally, the case studies demonstrate that the challenge is in kick-starting the industry, setting-up the infrastructure, and deciding where to focus (interviewee 3). While currently these innovations might seem like a given, both wind turbines and EVs faced significant challenges at the beginning. Studies like this one can shed some light on how to proceed with other SETs, helping them gain traction. Keeping this in mind, Chapter 8 covers conclusions and recommendations.

8 | Conclusions & Recommendations

The answers to this research's questions are summarised in Section 8.1. The scientific contributions are considered in Section 8.2. Then, the limitations and recommendations for future research are presented in Section 8.3. Finally, Section 8.4 covers the practical applicability of the work done.

8.1. Answering the Research Questions

This thesis answered the following research question: ***"How can the feedback loop model of Geels and Ayoub (2023) be refined and expanded to understand how positive tipping points can be triggered in the adoption of sustainable energy technologies?".*** This question was answered by answering five sub-questions. Insights were gathered from general literature on the deployment of (sustainable energy) technologies, as well as four case studies where a positive tipping point in adoption had been identified. The case studies covered the uptake of offshore wind energy in the UK, onshore wind energy in Portugal, as well as electric vehicles in the UK and in the Netherlands.

Sub-question 1 read as: *"How can the feedback loop model of Geels and Ayoub (2023) be refined to improve its consistency and readability?".* In answering it, a refined version of the authors' model was proposed in Section 4.2. It can be visualised in Figure 4.3.

Sub-question 2 asked: *"Apart from the actor groups selected by Geels and Ayoub (2023), which other actors are relevant in promoting positive tipping points in the deployment of sustainable energy technologies?".* Geels and Ayoub (2023) included in their model policymakers, technology firms, adopters, and the wider public. The initial investigation indicated that four other actor groups were relevant too. These were academic and research institutes, trade associations, NGOs, and financial institutions. As presented in Section 7.1.2, in the wind energy case studies all eight actor groups appeared to have a significant role, while financial institutions were not found to be a relevant actor in the EV cases. This suggests that financial institutions might have a bigger role in the uptake of B2B technologies.

Then, sub-question 3 read as follows: *"What are the main actor roles in promoting a positive tipping point in the deployment of sustainable energy technologies?".* It can be said that Geels and Ayoub (2023) cover seven overarching actor roles: 1) technology development, 2) technology adoption, 3) legitimising technology, 4) providing financing incentives/options, 5) investing in infrastructure, 6) establishing legislation, and 7) lobbying. In the literature initially analysed, six other actor roles were identified: 8) raising awareness, 9) fostering collaboration, 10) transferring knowledge, 11) giving and receiving feedback 12) establishing market-based mechanisms, and 13) promoting education. In the wind energy case studies only actor role 13 was not found relevant, while in the EV case studies, actor roles 12 and 13 were not identified (see Section 7.1.3). The results thus suggest that market-based mechanisms (actor role 12), observed in the form of tenders, are more suitable to promote B2B technologies.

Sub-question 4 is as follows: *"Apart from the policy types identified by Geels and Ayoub (2023), which* *other policies are relevant in promoting positive tipping points in the deployment of sustainable energy technologies?".* In their feedback loop model, Geels and Ayoub (2023) only covered policy instruments falling under financial incentives, R&D support, the establishment of standards, and market facilitation. This thesis' results suggest that a wider set of policies are involved in achieving positive tipping points, as presented in Section 4.3.1 and discussed in Section 7.1.4. Other important policies involve market-based mechanisms (in the case of the wind energy case studies), setting (binding) targets, promoting knowledge transfer, and creating collaboration and networking opportunities. Outreach instruments were expected based on the literature initially investigated, but were not found in any of the case studies. Nonetheless, other actors appeared to take on this role, namely NGOs and trade associations.

At last, sub-question 5 was: *"How can the feedback loop model of Geels and Ayoub (2023) be expanded to include a wider set of actors and interactions between these while maintaining its readability?".* As discussed in Section 7.1.1, due to the differences found between the wind energy and EV case studies, this question was answered using two separate feedback loop models, presented in Figure 7.1 and Figure 7.2. The former relates to the wind energy case studies and can be used as a baseline for B2B technologies, while the latter was based on the EV case studies and can be used as a reference for B2C technologies. Figure 7.1 includes three new feedback loops, while Figure 7.2 has two new ones. Besides, in contrast with the model presented by Geels and Ayoub (2023) both models include several interactions that do not directly relate to a particular feedback loop.

8.2. Scientific Contribution

This thesis aimed to tackle relevant knowledge gaps found in literature concerning positive tipping points, as covered in Section 3.2. Concerning the lack of knowledge on how to deliberately trigger socio-technical tipping points, this researched touched upon 1) which actors are relevant to trigger a socio-technical tipping point, 2) how different actors promote or hinder a tipping point through their interventions and interactions with other actors, 3) how do the socio-technical tipping point dynamics differ in different contexts, 4) the deliberate cultivation of reinforcing feedback loops, and 5) how to identify a positive tipping point. Furthermore, when it comes to the lack of knowledge with respect to the role of policies in triggering socio-technical tipping points, this thesis partially looked at how do policies lead to behavioural and technological changes.

Despite there being many possibilities to expand on these and other knowledge gaps, this investigation focused on how to trigger positive tipping points in the adoption of SETs, a domain that remains relatively understudied (Geels & Ayoub, 2023; Lenton et al., 2022). This was done by contributing to the creation of a visual framework showing reinforcing feedback loops between actors. The conceptual framework utilised corresponded to the feedback loop model of Geels and Ayoub (2023), which offers insights into socio-technical tipping points. This research's dedication to enhancing and expanding upon this model promoted the development of a pertinent theoretical framework in the field.

The four case studies conducted contributed to the empirical knowledge on the dynamics of positive tipping points in the adoption of SETs, as recommended by Fesenfeld et al. (2022), Geels and Ayoub (2023), and Roberts et al. (2018). This is relevant as empirical evidence from previously crossed positive tipping points may allow future ones to be intentionally triggered. The prospects of doing so brings hope in realising a successful energy transition (Fesenfeld et al., 2022; Frumkin, 2022), thereby preventing the Earth climate system from degrading to an irreversible state. Additionally, conducting these four case studies and testing them against the model of Geels and Ayoub (2023) contributed to validating the authors work. Indeed, all the interactions identified by Geels and Ayoub (2023) were found in the case studies analysed. Nonetheless, this research also contributed to the scientific community by expanding on Geels and Ayoub (2023) work, as appealed by the authors themselves. This was done by adding four new actors and five new actor roles to the feedback loop model.

By investigating which actors were important, this thesis contributes to having a better understanding of which actor groups are relevant in enabling and triggering a positive tipping point in SET adoption. Furthermore, the use of feedback loop models helped explore the interaction between innovations and the socio-technical system (Geels et al., 2017). By introducing the concept of *actor roles* this thesis focused on the specific *functions* that actors play in the socio-technical system (Lenton et al., 2022). This allows for a better understanding of the actor roles needed to create the necessary conditions to trigger positive tipping points, independently of the actor that performs it. It highlights the need to intervene in different places simultaneously (Lenton et al., 2022). Indeed, socio-technical systems are complex and their developments depend on the actions of many actors and the interactions among these. Without an in-depth analysis of these roles, it might seem like all the conditions are there to enable a positive tipping point, when in fact a very relevant role might have been neglected.

One specific actor group that was found to be very relevant in all four case studies were policymakers. By analysing their role and that of different policies, this thesis took one step further in understanding how policies can effect technological and behavioural changes, a recommendation made by Fesenfeld et al. (2022). The findings of this thesis are therefore relevant both for the scientific community, as well as for policymakers and industry players (see Section 8.4).

In accomplishing technological and behavioural changes through policies the use of a feedback loop model is relevant as it allows to visualise the contextual factors and complexities present, rather than looking at policies in isolation. These models can help understand how policy mixes affect socio-technical transformation and, in turn, how modifications to the socio-technical system influence the evolution of the policy mix, contributing to the work of Edmondson et al. (2019). The framework used in this thesis thus supports a more effective and sensible comparative policy analysis and design.

This thesis' findings relate to tipping points in the adoption of wind energy and EVs. However, the results might be extendable to other SETs. For one, the wind energy findings might relate to the deployment of other B2B technologies, mainly adopted in large numbers by businesses. For another, the results for electric vehicles might be representative of the uptake of other B2C technologies, typically adopted in small numbers by individual buyers. Nonetheless, it is important to keep in mind that different technologies might require additional actors or actor roles, since the context influences a technology's development and adoption. Additionally, since these actor groups are commonly involved in other socio-technical systems, these findings might be transverse to sectors not associated with SETs. However, more research would be needed to understand whether this is the case.

To sum up, this research tackles important knowledge gaps about how to intentionally trigger positive tipping points in the adoption of SETs, advancing understanding of the relevant actors and their roles in tipping point dynamics. It did so by refining and expanding a relevant model, that of Geels and Ayoub (2023). The results add significantly to the current discussion on socio-technical tipping points and have implications for theoretical frameworks as well as practical interventions.

8.3. Limitations & Recommendations

Several limitations can be found in the work conducted. This section covers this work's limitations and proposes recommendations on how to tackle them. These research possibilities contribute to some of the knowledge gaps identified in Section 3.2, as well as to the larger scientific scope. Section 8.3.1 discusses limitations and recommendations related to the research scope, while Section 8.3.2 cover the ones related to the analysis of the actors and actor roles. Section 8.3.3 focuses on the use of feedback loop models. Then, Section 8.3.4 considers future research avenues related to combining the direction taken by Geels and Ayoub (2023) with other frameworks. Finally, limitations and recommendations related to the operationalisation of positive tipping points are exposed in Section 8.3.5, while Section 8.3.6 concerns the relative importance and the temporal dynamics of interactions.

8.3.1. Research Scope

In terms of the scope of this research, a limitation follows from having only analysed two technology types. This inhibits the generalisability of the findings to other SETs. Future case studies should focus on other technologies such as solar photovoltaic, which offer both a B2B and B2C business model.

Additionally, all case studies concerned European countries. This was a deliberate choice such that the comparability of the case studies was enhanced. However, it might mean that the findings cannot be smoothly translated to other countries, where the context might significantly differ. This applies especially to countries with a notably different government model and developing countries. Coincidentally, triggering positive tipping points in countries such as China, India or Indonesia might have a large impact in tackling climate change (Climate Watch, 2021). Future research should therefore also analyse case studies in which a tipping point occurred in other countries, including non-European countries.

Conducting more case studies covering other technologies and countries would enlarge the empirical knowledge on tipping point dynamics in different contexts, as recommended by Fesenfeld et al. (2022), Geels and Ayoub (2023), and Roberts et al. (2018), and stated in knowledge gap 1.3. It would also help understand whether other interactions and feedback loop models emerge or whether Figure 7.1 and Figure 7.2 are indeed representative of other B2B and B2C technologies in general.

8.3.2. Actors & Actor Roles

Although the models presented are more comprehensive than that of Geels and Ayoub (2023), some actor groups still encompass a large set of actors. For instance, *technology firms* comprise the whole supply chain, including designers, manufacturers, infrastructure providers, consultancy firms, among others. Further, if project developers only get the project to the ready-to-build phase, they too fall under this actor group (interviewee 2). Future research could add additional actor groups to the model, providing a more nuanced understanding and contributing to knowledge gap 1.1 and 1.2. However, that increases the model's complexity, possibly compromising readability.

Besides, this thesis focused on the tipping point enablers, which are typically very prominent close to a tipping point. However, the barriers that had to be overcome can be as important to understand. These usually standout more at an initial stage. When conducting other case studies it can be useful to analyse more years prior to the tipping point, allowing to further understand how the tipping point dynamics relate to actors' interventions (knowledge gap 1.2), which might promote or hinder change. For instance, incumbents are typically seen as fighting change (Geels, 2019; Lenton et al., 2022; Roberts et al., 2018). Nonetheless, all case studies suggested that incumbents were very committed to the uptake of each SET. However, it might be that before the time period analysed incumbents resisted change and that the tipping point was only enabled because their attitudes shifted. Further researching how actors' attitudes are related to the attainment of tipping points can also prove relevant in the field of adoption of innovations (Ortt & Kamp, 2022; Ortt, Langley, & Pals, 2013; Rogers, 2003).

8.3.3. Feedback Loop Models

Another limitation related to having focused on tipping point enablers is that the feedback loop models only include reinforcing feedback loops, like the model of Geels and Ayoub (2023). However, dampening feedbacks prove relevant too as they relate to the barriers found at an initial stage. Future work could integrate dampening feedback loops into the models, to improve their completeness, contributing to knowledge gaps 1.2 and 1.4. A dampening feedback loop could occur for instance when individuals resist purchasing EVs due to a perceived lack of charging stations. This slow adoption reduces demand for charging infrastructure investment, exacerbates range anxiety concerns, and further delays the expansion of charging networks. By including dampening feedback loops in the models, the main barriers to technology adoption could be linked to the enablers, guiding the strategies of several actor groups (Edmondson et al., 2019; Geels et al., 2017). For instance, technology firms could use these insights to tailor their niche introduction strategies (Ortt & Kamp, 2022; Ortt et al., 2013). Using causal loop diagrams (CLDs) could facilitate the integration of dampening feedback loops as these models identify whether a change in one variable will be amplified or dampened over time (Sterman, 2000).

Moreover, this thesis focused on 'small' feedback loops between two actor groups, while there might be 'larger' feedbacks involving several interactions in the model. In the models these larger feedback loops are not apparent, as touched upon in Section 7.1.1. This concern was raised by interviewee 4, but due to time constraints, larger feedbacks were not integrated into the model. Doing so might have revealed important, hidden system dynamics, that can help understand how tipping points are enabled. This would have significance for knowledge gaps 1.3 and 1.4. Showing the larger feedback loops could have also been easier by using CLDs since these focus on the interactions in a system and not on the actors themselves (Sterman, 2000). The latter breaks the larger feedbacks into different segments.

A further advantage of using CLDs instead is their ease of conversion into computational models, a recommendation made by Geels et al. (2017) and acknowledged in knowledge gap 1.6 in Section 3.2. This is particularly relevant in the field of computational system dynamics, where numerical models are used to interpret the system dynamics and simulate different scenarios (Crielaard et al., 2022).

Lastly, this thesis focused on interactions *between* actors. However, a lot happens *within* an actor group. There might be feedback loops occurring inside an actor group without involving other actors, which were not captured in the models. These inner-group dynamics may influence the feedback loops between actor groups, strengthening or weakening important reinforcing feedbacks. Additionally, doing so would possibly reveal additional actor roles to the ones identified in this thesis, further contributing to knowledge gap 1.2. These dynamics within a single actor group could have been represented more easily by using a CLD since such models represent the relationships between system variables, rather than focusing on the actors themselves (Sterman, 2000). By converting the CLD into a numerical model, the interactions between inner- and outer-group dynamics could be modelled automatically.

8.3.4. Application of Other Frameworks

Geels (2002) introduced the Multi-Level Perspective, widely used in research on socio-technical systems. Recently, Geels has also entered the field of positive tipping points (Geels & Ayoub, 2023). When it comes to (positive) tipping points, Lenton et al. (2022, 2023, 2008) is one of the biggest names in the field. It would be interesting to combine the work of both authors for instance by applying the framework of Lenton et al. (2022) to feedback loop model analyses like the one performed by Geels and Ayoub (2023) and in this thesis. This could help understand how the dynamics observed link to specific enabling conditions, reinforcing feedbacks, and interventions (see Figure 3.2). It is possible that a pattern is found (perhaps between B2B and B2C technologies), which could give actionable insights on which enabling conditions, feedbacks, and interventions should be pursued to effectively trigger a tipping point. Such a research avenue could also result in additions to the framework of Lenton et al. (2022) and it would contribute to knowledge gaps 1.1 through 1.5.

Another possibility for future research is to analyse these and other case studies through the lens of Fesenfeld et al. (2022) to understand how not only substitution (this thesis' focus) but also sufficiency policies can drive positive tipping points. Sufficiency policies aim to reduce overall consumption or demand and typically face higher opposition as they require more behavioural adaptation. For instance, a feedback loop model analysis could be applied to case studies concerning e.g., the ban of inner-city cars, offering comprehensive understanding of policy mechanisms that accelerate sustainable technology adoption. This would tackle knowledge gap 2.1 on how policies result in behavioural and technological changes, and gap 2.2 on understanding how to overcome political opposition. Additionally, following this research avenue would bring together the work of Geels and Ayoub (2023) and Fesenfeld et al. (2022) but also be in line with recommendations made by Edmondson et al. (2019).

8.3.5. Operationalisation of Positive Tipping Points

The operationalisation of tipping points remains challenging. Currently, there is not a precise and quantitative method for identifying socio-technical tipping points, which might lead to the incorrect identification of one. What might seem like a tipping point might solely be a short-term fluctuation. This limitation is especially relevant for the EV case studies since less time elapsed since their tipping points. Future studies could establish operational metrics, such as specific percentages of market or sales share, that reliably indicate a tipping point, as suggested by Lenton et al. (2022). This could allow to identify whether a tipping point was approaching or had just been crossed, relating to knowledge gap 1.5. This would be valuable for policymakers and industry actors in anticipating and responding to the shift.

Another option is to investigate whether it is possible to have multiple positive tipping points and what this means. Typically adoption is represented as following an idealised S-curve ending in a stabilisation phase (Rogers, 2003). However, it might be that this stabilisation can be followed by another tipping point and one more stabilisation phase. For instance, onshore wind energy in Portugal might have stabilised too early due to the economic crisis and grid capacity considerations (see Section 6.2). It is hence plausible that with the right conditions in place a second tipping point can be triggered. The danger of getting a sense of completion when observing a tipping point followed by a stabilisation phase is that perhaps one does not realise that the system has not reached its full potential yet and that another tipping point could and should be enabled. It would be interesting to study multiple tipping points in SET adoption, which might have wider implications on diffusion of innovations theories.

8.3.6. Importance and Sequence of Interactions

Future research could study the relative importance of different interactions by comparing the case studies using a quantitative method. For instance, each interaction could be given a rating according to its importance to the technology's uptake. These ratings could then be compared between case studies to understand which interactions had a low, medium and high level of importance. This could allow to, for example, understand whether the same interactions were always the most or the least relevant across all case studies. Doing this for the period before and after the tipping point could allow to understand whether the relative importance of certain actors or interactions changed after the tipping point. This could be useful to understand to which extent actors promote reinforcing feedback and tipping points (knowledge gaps 1.2 and 1.4). At the same time, it could help in guiding actors' decisions throughout the transition, possibly paving the way towards the realisation of a roadmap, advocated by Lenton et al. (2022). Namely, this could contribute to the field of political science by studying the relative importance of different political factors in a technology's adoption (Roberts et al., 2018).

Besides, this thesis did not aim to compare the sequence of different events. In contrast, Geels and Ayoub (2023) analysed the temporal dynamics of their case studies, which differed between offshore wind and EVs. Performing such an analysis for the case studies presented in this report as well as others could be an avenue for future research. Indeed, it would be relevant to understand whether a pattern is also found in this respect among B2B and B2C technologies, contributing to knowledge gap 1.2, 1.3, and 1.4. By expanding the knowledge on *how* to intentionally trigger positive tipping, this research avenue could contribute to adoption of innovation theories (Rogers, 2003) and constitute one more step towards a guiding map, helpful for taking action (Lenton et al., 2022). It could also shed light on how to best determine the moment in which a tipping point is crossed, relating to knowledge gap 1.5. If a certain sequence of events was typically observed prior to a tipping point, this could help identify whether one is about to be triggered or has just been crossed, relating to Section 8.3.5.

A last avenue for research includes understanding who initiates certain feedback loops, which can be facilitated by analysing the temporal dynamics of events. Investigating the origins of these loops can reveal which actors are most proactive in triggering and sustaining interactions, contributing to knowledge gap 1.1. For instance, identifying whether government policies, technological advancements, or consumer advocacy groups are the primary initiators in the adoption of a technology can inform future strategies. Linking this with the field of behavioural economics, understanding the actors' motivations and decision-making processes can enhance the effectiveness of interventions (Rogers, 2003; Thaler & Sunstein, 2008). Knowing which actors drive these changes and how their behaviour influences the system can help design a guiding map with targeted interventions and policies, ensuring that feedback loops leading to positive tipping points are effectively triggered and maintained (Alkemade & de Coninck, 2021; Lenton et al., 2022). Thus, it would also contribute to knowledge gaps 1.2 and 1.4.

Despite the several limitations of this study and possibilities for future research, the work performed in this thesis has policy relevant and practical applicability, as explained in Section 8.4.

8.4. Policy Relevance & Practical Implications

Understanding system dynamics and identifying less obvious indicators can be instrumental in promoting the adoption of other (sustainable) technologies. Despite its limitations, this work contributes to the scientific community and holds political and practical relevance. Scientifically, as explained in Section 8.2, this investigation enhances the academic understanding of the socio-technical dynamics involved in the adoption of B2B and B2C SETs. Researchers studying innovation systems, policy analysis, and energy transitions can build upon these findings to further explore these complex interactions, as outlined in the recommendations in Section 8.3.

This work also highlights the importance of integrating knowledge from socio-technical transitions and political science, rather than examining policies in isolation (Roberts et al., 2018). It demonstrates the value of using policy mixes (Edmondson et al., 2019). By understanding the roles and interventions of policymakers in successful case studies, government agencies can design and implement effective policies, especially in wind energy and EVs. This way, policymakers can deliberately cultivate reinforcing feedback loops, driving tipping points in the adoption of SETs (Fesenfeld et al., 2022).

Finally, industry players and investors can benefit from understanding the policy landscape and its impact on adoption, contributing to strategic decision-making. This includes investment in R&D, infrastructure, and market positioning for SET-related companies, or identifying promising projects and effectively allocating resources for investors.

Due to the complexity and dimension of socio-technical systems, policies, technology developments, and sales are often analysed in isolation. However, this research underscores the importance of considering the interactions among the actors in the system. These interactions are the enablers of effective policies, improved technologies, and increased sales. The findings from this investigation suggest that involving a particular set of actors in the development and deployment of sustainable energy technologies is crucial. If the uptake of a technology is lagging and certain actor groups are not engaged, an effective strategy might be to involve these remaining actors. Alternatively, analysing the interactions between the actors and identifying which roles are not being successfully fulfilled could ensure that all relevant actor roles are covered, potentially leading to a positive tipping point in the technology's adoption. The involvement of certain actor groups and the fulfilment of specific roles can be facilitated by different agents within the socio-technical system. For instance, policymakers, technology companies, and trade firms can seek insights and create collaboration opportunities with other actors.

In conclusion, this research provides significant contributions to understanding how positive tipping points can be intentionally triggered in the adoption of SETs. By refining and expanding the feedback loop model of Geels and Ayoub (2023), this thesis addressed key research questions through a detailed analysis of four case studies: offshore wind energy in the UK, onshore wind energy in Portugal, and EVs in the UK and the Netherlands. The study identified critical actors and their roles, extended the range of policy types involved, and proposed new feedback loop models that incorporate additional interactions and actor groups. Despite some limitations, the findings are valuable for both academic research and practical applications. By enhancing our understanding of the dynamics between various actors and their interventions, this thesis offers a theoretical framework and practical insights that can guide policymakers and industry players in accelerating the adoption of SETs. This work ultimately supports the broader goal of achieving a successful energy transition and addressing climate change.

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A | Data

Table A.1: Cumulative wind installed capacity in MW in the UK and in Portugal, used to create Figure 6.1 and Figure 6.3

Year	Cumulative Installed Capacity (MW)	
	Offshore wind energy in the UK (BVG Associates, 2021; RenewableUK, 2024; Statista, 2024)	*Onshore wind energy in Portugal* (Costa et al., 2021; IRENA, 2013b)
2000	4.0	99.0
2001	-	129.0
2002	-	194.5
2003	64.0	297.0
2004	-	537.5
2005	-	1,041.0
2006	-	1,594.0
2007	404.0	2,269.0
2008	-	3,003.0
2009	819.5	3,603.0
2010	1,338.0	4,012.5
2011	1,838.0	4,378.5
2012	2,834.0	4,521.0
2013	3,671.5	4,731.0
2014	4,501.0	4,953.0
2015	5,096.0	5,034.0
2016	5,293.0	5,313.0
2017	6,381.0	5,313.0
2018	8,038.5	5,379.0
2019	9,795.0	5,459.0
2020	10,397.5	5,502.0
2021	10,857.5	5,828.0
2022	13,928.0	-
2023	14,735.0	-

Table A.2: Total stock of BEVs, PHEVs, and EVs, and total number of public charging devices in the UK and in the Netherlands. This data was used to create Figure 6.5, Figure 6.8, Figure 6.9, and Figure 6.12

Year	UK				Netherlands			
	BEVs	*PHEVs* (IEA, 2022)	*EVs*	*Public charging devices* (DfT, 2023)	*BEVs*	*PHEVs* (IEA, 2022)	*EVs*	*Public charging devices* (Statista, 2023)
2010	1,500	21	1,521	-	270	11	281	-
2011	2,600	28	2,628	-	1,100	26	1,126	-
2012	4,100	990	5,090	-	1,900	4,400	6,300	-
2013	6,200	2,000	8,200	-	4,200	24,000	28,200	-
2014	12,000	9,700	21,700	-	6,800	37,000	43,800	5,675
2015	21,000	27,000	48,000	2,283	9,400	78,000	87,400	7,860
2016	30,000	55,000	85,000	3,672	13,000	99,000	112,000	12,380
2017	42,000	87,000	129,000	5,111	21,000	98,000	119,000	16,043
2018	56,000	130,000	186,000	7,211	45,000	98,000	143,000	21,344
2019	91,000	160,000	251,000	10,309	110,000	96,000	206,000	29,025
2020	190,000	220,000	410,000	16,505	180,000	110,000	290,000	41,995
2021	380,000	330,000	710,000	20,775	250,000	140,000	390,000	54,000
2022	550,000	400,000	950,000	28,375	340,000	190,000	530,000	73,968

B | Summary of Actor Roles

The actor roles included in the tables of this Appendix were explained in Section 7.1.3. Table B.1 provides a summary of all interactions (sub-divided per actor role) present in case studies' feedback loop models, showing whether the interaction was included or not in each model. Lastly, Table B.2 shows which of the interactions were found in the refined version of the model of Geels and Ayoub (2023) (Figure 4.3), the version of the expanded feedback loop model based on literature (Figure 4.4), and the two final feedback loop models (Figure 7.1 and Figure 7.2).

The actor role of *promoting education* was not included in the final feedback loop diagrams (presented in Section 7.1.1), with the reasoning provided in Section 7.1.3. However, it did appear in the first version of the expanded feedback loop model, which was based on general literature alone. Therefore, it was included in the following tables.

Table B.1: Summary of all interactions present in this report's feedback loop models, showing on which model(s) they were included. The interactions are sub-divided according to the overarching actor roles explained in Section 7.1.3

Interaction label	**Wind energy**		**Electric vehicles**	
	UK (Figure 6.2)	*Portugal* (Figure 6.4)	*UK* (Figure 6.7)	*The Netherlands* (Figure 6.11)
Technology development				
Investment in R&D and production	✓	✓	✓	✓
Value	✓	✓	✓	✓
Research and test	✓	✓	✓	✓
Technology adoption				
Purchases	✓	✓	✓	✓
Revenue and profit	✓	✓	✓	✓
Further adoption	✓	✓	✓	✓
Expanded technology's visibility	✓	✓	✓	✓
Raising awareness				
Public awareness campaigns	✓	✓	✓	✓
Foster collaboration	✗	✗	✗	✗
Legitimising technology				
Strong policy plans and accompanying narratives	✓	✓	✓	✓
Solution to societal problems	✓	✓	✓	✓
Legitimacy	✓	✓	✓	✓
Public opinion	✓	✓	✓	✓
Providing financing incentives/options				
Loans	✓	✓	✓	✓
Capital grants	✓	✓	✓	✓

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Table B.1 – continued from previous page

Interaction label	**Wind energy** *UK* (Figure 6.2)	*Portugal* (Figure 6.4)	**Electric vehicles** *UK* (Figure 6.7)	*The Netherlands* (Figure 6.11)
Support new ventures	✓	✓	✓	✓
R&D subsidies	✓	✓	✓	✓
Purchase subsidies	✗	✓	✓	✓
Tax rebates	✗	✗	✓	✓
Feed-in tariffs	✓	✓	✗	✗
Funding	✓	✓	✓	✗
Long-term certainty	✓	✓	✗	✗
Financing solutions	✓	✓	✗	✗
Public financing departments or businesses	✓	✓	✗	✗
Establishing market-based mechanisms				
Tenders	✓	✓	✗	✗
Investing in infrastructure				
Investment in infrastructure	✓	✓	✓	✓
Establishing legislation				
Regulations and standards	✓	✓	✓	✓
(Binding) targets	✓	✓	✓	✓
Policies, goals and coalitions adjustments	✓	✓	✓	✓
Promoting education				
Training	✗	✗	✗	✗
Retraining programs	✗	✗	✓	✗
Promote education	✗	✗	✓	✓
Fostering collaboration				
Foster collaboration	✓	✓	✓	✓
Transferring knowledge				
Knowledge transfer	✓	✓	✓	✓
Expert professionals	✓	✓	✓	✓
Giving & receiving feedback				
Consultation	✓	✓	✓	✓
User feedback	✗	✗	✓	✓
Impact evaluations	✗	✗	✗	✗
Convey and interpret data	✗	✗	✗	✗
Lobbying				
Lobbying	✓	✓	✓	✓
Litigation and electioneering	✗	✗	✗	✗
Foster collaboration	✓	✓	✓	✓
Public opinion	✓	✓	✓	✓

Table B.2: Summary of all interactions present in this report's feedback loop models, showing on which model(s) they were included. The interactions are sub-divided according to the overarching actor roles as defined in Section 7.1.3

Interaction label	Geels & Ayoub (Figure 4.3)	Literature (Figure 4.4)	Wind energy (Figure 7.1)	Electric vehicles (Figure 7.2)
Technology development				
Investment in R&D and production	✓	✓	✓	✓
Value	✓	✓	✓	✓
Research and test	✗	✓	✓	✓
Technology adoption				
Purchases	✓	✓	✓	✓
Revenue and profit	✓	✓	✓	✓
Further adoption	✓	✓	✓	✓
Expanded technology's visibility	✓	✓	✓	✓
Raising awareness				
Public awareness campaigns	✗	✓	✓	✓
Foster collaboration	✗	✓	✗	✓
Legitimising technology				
Strong policy plans and accompanying narratives	✓	✓	✓	✓
Solution to societal problems	✓	✓	✓	✓
Legitimacy	✓	✓	✓	✓
Public opinion	✓	✓	✓	✓
Providing financing incentives/options				
Loans	✓	✓	✓	✓
Capital grants	✓	✓	✓	✓
Support new ventures	✗	✓	✗	✗
R&D subsidies	✓	✓	✓	✓
Purchase subsidies	✓	✓	✓	✓
Tax rebates	✗	✓	✗	✓
Feed-in tariffs	✗	✓	✓	✗
Funding	✗	✓	✓	✓
Long-term certainty	✗	✓	✓	✗
Financing solutions	✗	✓	✓	✗
Public financing departments or businesses	✗	✗	✓	✗
Establishing market-based mechanisms				
Tenders	✗	✓	✓	✗
Investing in infrastructure				
Investment in infrastructure	✓	✓	✓	✓
Establishing legislation				
Regulations and standards	✓	✓	✓	✓

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Table B.2 – continued from previous page

Interaction label	Geels & Ayoub (Figure 4.3)	General literature (Figure 4.4)	Wind energy (Figure 7.1)	Electric vehicles (Figure 7.2)
(Binding) targets	✗	✗	✓	✓
Policies, goals and coalitions adjustments	✓	✓	✓	✓
Promoting education[1]				
Training	✗	✓	✗	✗
Retraining programs	✗	✗	✗	✗
Promote education	✗	✓	✗	✗
Fostering collaboration				
Foster collaboration	✗	✓	✓	✓
Transferring knowledge				
Knowledge transfer	✗	✓	✓	✓
Expert professionals	✗	✓	✓	✓
Giving & receiving feedback				
Consultation	✗	✗	✓	✓
User feedback	✗	✗	✗	✓
Impact evaluations	✗	✓	✗	✗
Convey and interpret data	✗	✓	✗	✗
Lobbying				
Lobbying	✓	✓	✓	✓
Litigation and electioneering	✗	✓	✗	✗
Foster collaboration	✗	✓	✓	✓
Public opinion	✓	✓	✓	✓

C | Summary of Policies

Section C.1 complements the explanation provided in Section 4.3.1 about different types of policy instruments. Secondly, Section C.2 provides a summary of the policies found in each case study.

C.1. Policy Categorisation

In the framework of Geels and Ayoub (2023) the following policy instruments are included: loans, capital grants, R&D subsidies, infrastructure investment, regulations, standards, and purchase subsidies (see Figure 4.2). However, due to the plenitude of policy instruments, it is unlikely that these were the only ones at play. Perhaps additional policies were included in terms such as "stronger policy support" and "climate-related policy pressures", which do not say much. This thesis aimed to understand which policies were employed in the four case studies, as well as which ones were the most important. Specific policies differ when looking at different technologies and/or different countries. Thus, to compare the policies of each case study, policy instruments were categorised according to their objective.

Policies can be divided into three main groups: economic, regulatory, and information instruments (Dubois & Eyckmans, 2014; Rogge & Reichardt, 2016; van Calster, 2014; Worrell, 2014). These three policy types are explained below. Each instrument was further sub-divided into three categories, allowing the comparison of the policies employed in the different case studies according to their objective (e.g., feed-in-tariffs and contracts-for-difference are two instruments that have a similar goal).

Economic Instruments

Economic instruments are policy tools designed to compensate for externalities and can be employed to internalise environmental costs, applying the polluter-pays principle. Economic instruments enhance the capacity of governments to address environmental and development issues cost-effectively. These instruments aim to influence behaviour such that economic activities align with specific policy objectives. By providing financial incentives for environmentally improved behaviour or disincentives for harmful practices, governments can encourage technological innovation and influence consumption and production patterns. This is done through alleviating financial barriers, promoting investments, and making certain products more economically viable (Johansson et al., 2021; Panayotou, 1995; Roseland, 1996).

It was decided to divide economic instruments into three sub-categories: financial incentives, market-based mechanisms, and R&D support schemes. Examples of economic instruments falling under each category are provided in Table C.1. In particular, *financial incentives* aim to stimulate investment in renewable energy projects and promote the adoption of sustainable practices. Examples include purchase subsidies, feed-in tariffs, tax rebates, and green bonds (Cox, 2016). *Market-based mechanisms* leverage market forces to internalise the costs of environmental externalities and promote emissions reductions. Examples are carbon taxes, tenders, net metering, and emissions trading (Joskow & Schmalensee, 1998). *R&D support* aims to foster innovation and technological advancements through financial support for R&D and demonstration projects (Huergo & Moreno, 2014).

Table C.1: Examples of economic instruments per sub-category, and sources where more information can be found

Examples	**Source**
Financial incentives	
Investment subsidies or grants	(Gregersen & Johnson, 2010)
Purchase subsidies	(Besley & Persson, 2023; Jaffe & Stavins, 1994; Rogge & Reichardt, 2016; Zhang & He, 2013)
Renewable energy financing programs	(Q. Chai & Zhang, 2010)
Feed-in tariffs	(Gregersen & Johnson, 2010; Rogge & Reichardt, 2016; Zhang & He, 2013)
Tax credits, rebates and incentives	(Q. Chai & Zhang, 2010; Gregersen & Johnson, 2010; Jaffe & Stavins, 1994; Rogge & Reichardt, 2016)
Green bonds	(Newell & Simms, 2021; Zhang & He, 2013)
State equity assistance	(Rogge & Reichardt, 2016)
Sustainable public procurement	(Gregersen & Johnson, 2010; Rogge & Reichardt, 2016)
Market-based mechanisms	
Carbon taxes	(Besley & Persson, 2023; Rogge & Reichardt, 2016)
Emissions trading	(Gregersen & Johnson, 2010; Jaffe & Stavins, 1994; Rogge & Reichardt, 2016)
Tenders	(Metcalfe & Sasse, 2023)
Net metering or billing	(Gregersen & Johnson, 2010)
R&D support	
R&D incentives	(Jaffe & Stavins, 1994; Newell & Simms, 2021; Rogge & Reichardt, 2016; Zhang & He, 2013)
Financial and technical support for demonstration projects	(Gregersen & Johnson, 2010; Zhang & He, 2013)

Regulatory Instruments

Regulatory instruments are policy tools that involve the use of informal and formal orders, decrees, laws, regulations, and standards to achieve policy objectives. These instruments are typically mandated by government authorities and enforce compliance through legal and administrative measures (Astuti, Day, & Emery, 2019; Entsalo, Kalimo, Kautto, & Turunen, 2023). Three sub-categories were created: standards, strategic planning, and market facilitation. Examples of regulatory instruments falling under each category are provided in Table C.2. *Standards* ensure that products, practices, and operations meet specific requirements or guidelines. Examples include mandating products or practices, intellectual property rights, renewable portfolio standards, technology/performance standards, and product labelling (ISO, 2024). *Strategic planning* involves the setting of goals, targets, and long-term roadmaps to guide policy development and decision-making (Gregersen & Johnson, 2010; Newell & Simms, 2021). *Market facilitation* focuses on creating conducive environments for the development, growth, and integration of renewable energy markets and infrastructure. This is done via local market design/development, infrastructure provision, and grid access guarantees (Steinbach & Bunk, 2024).

Table C.2: Examples of regulatory instruments per sub-category, and sources where more information can be found

Examples	**Source**
Standards	
Mandate products or practices	(Gregersen & Johnson, 2010; Jaffe & Stavins, 1994; Rogge & Reichardt, 2016)
Application constraints	(Rogge & Reichardt, 2016)
Mandate environmental reporting	(Jaffe & Stavins, 1994)
Environmental liability law	(Rogge & Reichardt, 2016)
Intellectual property rights	(Gregersen & Johnson, 2010; Rogge & Reichardt, 2016)

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Table C.2 – continued from previous page

Examples	Source
Patent law	(Rogge & Reichardt, 2016)
Renewable portfolio standard	(Gregersen & Johnson, 2010)
Technology/Performance standard	(Gregersen & Johnson, 2010; Jaffe & Stavins, 1994; Rogge & Reichardt, 2016)
Product labelling	(Jaffe & Stavins, 1994)
Strategic planning	
(Binding) targets	(Q. Chai & Zhang, 2010; Gregersen & Johnson, 2010; Newell & Simms, 2021; Zhang & He, 2013)
Roadmap	(Gregersen & Johnson, 2010; Newell & Simms, 2021)
Market facilitation	
Local market design/development	(Newell & Simms, 2021; Rogge & Reichardt, 2016)
Infrastructure provision	(Rogge & Reichardt, 2016; The World Bank, 2023)
Priority feed-in	(Rogge & Reichardt, 2016)
Grid access guarantee	(Rogge & Reichardt, 2016)

Information Instruments

Information instruments intend to change individuals' behaviour by making sure they are better informed about the necessity or advantages of certain choices. To do so effectively, information campaigns should be customised to the target group, and fundamental information should be repeated often (Orset, 2021; Worrell, 2014). Information instruments were sub-divided into knowledge transfer, collaboration and networking, and outreach initiatives. Table C.3 shows examples for each. *Knowledge transfer* is designed to facilitate information, expertise, and skills exchange among stakeholders via e.g., professional and entrepreneurship trainings and scientific workshops (Kochenkova et al., 2015). *Collaboration and networking* incentives aim to facilitate partnerships, cooperation, and knowledge sharing among stakeholders, which is accomplished through public-private partnerships, cooperative RD&D programs, thematic meetings, and clusters (Q. Chai & Zhang, 2010; Lehmann, 2006). *Outreach* instruments aim to raise awareness, educate the public, and engage stakeholders. Examples include rating and labelling programs, public information campaigns, and organised public debates (Orset, 2021).

Table C.3: Examples of information instruments per sub-category, and sources where more information can be found

Examples	Source
Knowledge transfer	
Professional training and qualification	(Newell & Simms, 2021; Rogge & Reichardt, 2016)
Entrepreneurship training	(Kochenkova et al., 2015; Rogge & Reichardt, 2016)
Scientific workshops	(Kochenkova et al., 2015; Rogge & Reichardt, 2016)
Collaboration & networking	
Public-private partnerships	(Gregersen & Johnson, 2010; Lehmann, 2006)
Cooperative RD&D programmes	(Q. Chai & Zhang, 2010; Newell & Simms, 2021; Rogge & Reichardt, 2016)
Thematic meetings	(Rogge & Reichardt, 2016)
Clusters	(Rogge & Reichardt, 2016)
Outreach	
Rating and labelling programmes	(Rogge & Reichardt, 2016)
Public information campaigns	(Jaffe & Stavins, 1994; Orset, 2021; Rogge & Reichardt, 2016)
Public debates	(Rogge & Reichardt, 2016)

Therefore, many policy instruments exist to foster the diffusion of SETs. It is thus unlikely that there were not more relevant policies employed in the case studies analysed by Geels and Ayoub (2023).

C.2. Case Studies Policies

In this section, a summary of the policies found in each case study is provided, in the same order as the case studies appear in Chapter 6. The policies are allocated to the respective sub-category (explained in Section C.1). Furthermore, their implementation year and source are stated.

Wind Energy in the UK (2002 - 2014)

Table C.4 gives an overview of the policies employed between 2002 and 2014 that had the largest impact on the uptake of offshore wind energy in the UK. This summary was constructed based on the information in Section 6.1.

Table C.4: Policies in place during the enabling phase and part of the accelerating phase (2002 - 2014) of the deployment of offshore wind energy in the UK, as well as the year in which they were introduced and the source where this information can be obtained

Instrument type	Instruments employed	Year	Source
Economic instruments			
Financial incentives	Renewable Obligation Certificates	2002 (adjusted in 2009)	(Geels & Ayoub, 2023)
	Interim Connect and Manage	2009-2011	(Ofgem, 2013)
	Connect and Manage	2011	(Metcalfe & Sasse, 2023; Ofgem, 2013)
	Green Investment Bank	2012	(Green Investment Group, 2024)
	Final Investment Decision Enabling for Renewables (FiDeR)	2013-2014	(BVG Associates, 2021)
	Contracts for Difference	2014	(BVG Associates, 2021)
	Offshore Wind Capital Grant Scheme	2003	(IEA, 2014)
	Environmental Transformation Fund	2009-2011	(Kern et al., 2014)
	Offshore Wind Manufacturing Funding	2011-2015	(Kern et al., 2014)
Market-based mechanisms	EU ETS	2005	(European Commission, 2021)
	Crown Estate seabed leasing auctions	2003 and 2008	(Kern et al., 2014)
	Tenders for transmission licenses	2009	(Metcalfe & Sasse, 2023)
	Carbon Price Floor	2013	(HM Revenue & Customs, 2018)
R&D support	Offshore Wind Accelerator	2008-2014	(Kern et al., 2014)
Regulatory instruments			
Standards	Renewable Obligation	2002 (amended in 2009)	(Geels & Ayoub, 2023)
Strategic planning	EU targets	2007	(McNally, 2022)
	Climate Change Act	2008	(Metcalfe & Sasse, 2023)
	Renewable Energy Roadmap	2011	(DECC, 2011)
	Offshore Wind Industrial Strategy	2013	(BIS & DECC, 2013)
Market facilitation[1]	Interim Connect and Manage	2009-2011	(Ofgem, 2013)
	Connect and Manage	2011	(Metcalfe & Sasse, 2023; Ofgem, 2013)
Information instruments			
Knowledge transfer	Test and technical services	2003	(BVG Associates, 2021)
Collaboration & networking	Offshore Wind Cost Reduction Task Force	2011	(RenewableUK, 2012)
	Supply chain events	2001	(Kern et al., 2014)
Outreach	-	-	-

Wind Energy in Portugal (2000 - 2007)

The policies that mostly influenced the deployment of onshore wind energy in Portugal between 2000 and 2007 are summarised in Table C.5, according to the information provided in Section 6.2.

Table C.5: Policies in place during the enabling phase and part of the accelerating phase (2000 - 2007) of the deployment of offshore wind energy in Portugal, as well as the year in which they were introduced and the source where this information can be obtained

Instrument type	Instruments employed	Year	Source
Economic instruments			
Financial incentives	Feed-in tariffs	1995	(IRENA, 2013b)
	Incentive Scheme for Rational Use of Energy (SIRUE)	2001-2005	(IRENA, 2013b)
	PRIME/MAPE subsidy	2007	(IEA, 2008)
	Investments in (reinforcement of) the transmission and distribution grid	2000	(Agência LUSA, 2004; IEA, 2005, 2009a)
	Financing from Caixa BI	2006	(TVI Notícias, 2006)
	European Investment Bank	Since 1986	(EIB, 2007)
Market-based mechanisms	Tenders	2005	(IEA, 2009a)
R&D support	Grants given by the countries where companies had manufacturing facilities	-	(BMWi, 2020; IRENA, 2013a; MITECO, 2005)
	Partial funding of INETI	1977	(IEA, 2004b)
Regulatory instruments			
Standards	Simplification of license-granting process	2001	(IRENA, 2013b)
	Market liberalisation	2004	(IEA, 2004a)
Strategic planning	Renewables electricity generation share of 39% (later changed to 45%) by 2010	2001	(IEA, 2004a)
	3,750 MW of wind power until 2010	2003	(IEA, 2004b)
	5,100 MW of wind power until 2013	2005	(IEA, 2006a)
Market facilitation	Guaranteed grid access for Independent Power Producers	1999	(IRENA, 2013b)
Information instruments			
Knowledge transfer	-	-	-
Collaboration & networking	IEA R&D Wind Executive Committee	2003	(IEA, 2004b)
	Wind energy industrial cluster	2005	(J. R. Ferreira & Martins, 2009)
Outreach	-	-	-

Electric Vehicles in the UK (2015 - 2021)

A summary of the relevant policies to EV uptake in the UK between 2015 and 2021 is provided in Table C.6. An explanation of each policy is given throughout Section 6.3.

Table C.6: Policies in place during the enabling phase and part of the accelerating phase (2015 - 2021) of the deployment of EVs in the UK, as well as the year in which they were introduced and the source where this information can be obtained

Instrument type	Instruments employed	Year	Source
Economic instruments			
Financial incentives	Plug-in Car Grant	2011	(Geels & Turnheim, 2022)
	Vehicle Excise Duty (VED) rebates	2010	(Zapmap, 2023)
	Fuel Excise Duty (FED) rebates	-	(Zapmap, 2023)
	Company Car Tax rebates	2002	(Zapmap, 2023)
	Free parking	Ongoing	(Rietmann & Lieven, 2019)
	Electric Vehicle Homecharge Scheme (EVHS)	2014	(British Gas, 2024)
	Workplace Charging Scheme	2016	(OZEV, 2016b)
	On-street Residential Chargepoint Scheme (ORCS)	2016	(OZEV, 2016a)
	Go Ultra Low Scheme	2016	(OLEV, 2014)
	Further charging infrastructure investments	2017 and 2018	(BEIS, 2017, 2018)
Market-based mechanisms	-	-	-
R&D support	Faraday Battery Challenge	2017	(BEIS, 2017)
	Automotive Sector Deal	2018	(BEIS, 2018)
	Innovate UK	Ongoing	(Innovate UK, 2024)
	UK Research and Innovation	2018	(UK Research and Innovation, 2024a)
Regulatory instruments			
Standards	EU CO_2 emission standards	2009	(ICCT, 2014)
	Phase-out of petrol/diesel cars	2017 (adjusted in 2020)	(BEIS, 2017)
	Clean Air Zones	2019 and 2020	(Department for Environment, Food & Rural Affairs, 2020)
Strategic planning	Clean Growth Strategy	2017	(BEIS, 2017)
	Road to Zero Strategy	2018	(UK Government, 2018)
Market facilitation[2]	Electric Vehicle Homecharge Scheme (EVHS)	2014	(British Gas, 2024)
	Workplace Charging Scheme	2016	(OZEV, 2016b)
	On-street Residential Chargepoint Scheme (ORCS)	2016	(OZEV, 2016a)
	Go Ultra Low Scheme	2016	(Department for Transport & OZEV, 2020; Fleet News, 2016; OLEV, 2014)
	Further charging infrastructure investments	2017 and 2018	(BEIS, 2017, 2018)
Information instruments			
Knowledge transfer	Investment in education system	2018	(BEIS, 2018)
	National Retraining Scheme	2018	(BEIS, 2018)
Collaboration & networking	Faraday Battery Challenge	2017	(UK Research and Innovation, 2023)
	Automotive Sector Deal	2018	(BEIS, 2018)
Outreach	-	-	-

[2]Market creation/development was mainly done through the provision of a public charging infrastructure, which showed a clear investment from the UK government in creating a mass market for EVs (Geels & Ayoub, 2023).

Electric Vehicles in the Netherlands (2015 - 2021)

Table C.7 summarises the policies that targeted and affected the uptake of EVs in the Netherlands between 2015 and 2021, according to the description given in Section 6.4.

Table C.7: Policies in place during the enabling phase and part of the accelerating phase (2015 - 2021) of the deployment of EVs in the Netherlands, as well as the year in which they were introduced and the source where this information can be obtained

Instrument type	Instruments employed	Year	Source
Economic instruments			
Financial incentives	Climate Agreement (infrastructure)	2019	(Nederland Elektrisch, 2020)
	Green Deal (infrastructure)	2016	(Nederland Elektrisch, 2019)
	Purchase subsidy (SEPP)	2020	(RVO, 2022b)
	Free parking	Until 2018[3]	(Yellowbrick, 2018)
	Registration and circulation tax exemption	2011 (ended in 2016 for PHEVs)	(Deuten et al., 2020)
	Reduced addition to taxable income	2014	(Deuten et al., 2020)
Market-based mechanisms	-	-	-
R&D support	Research and Development Promotion Act (WBSO)	1994	(RVO, 2015)
	Region and Top Sectors (MIT)	2014	(RVO, 2023b)
	Demonstration of Energy and Climate Innovation (DEI+)	2014	(RVO, 2023a)
	Subsidy Scheme for Demonstration of Climate Technologies and Innovations in Transport (DKTI-Transport)	2017	(RVO, 2022a)
	Interreg	1990	(European Commission, 2020)
	LIFE	1992	(European Commission, 2022)
	Eurostars	2007	(RVO, 2011)
	Connecting Europe Facility (CEF) Transport	2014	(RVO, 2014)
Regulatory instruments			
Standards	EU CO_2 emission standards	2009	(ICCT, 2014)
	Low-emission zones (LEZs)	2015	(Auto Siero, 2021; IEA, 2023b)
Strategic planning	100% sale of zero-emission vehicles by 2030	2017	(Deuten et al., 2020)
	EU CO_2 emission targets for new fleets	2015	(Agency, 2016)
	Fit for 55	2021	(Nationale Agenda Laadinfrastructuur, 2022)
Market facilitation	Climate Agreement (infrastructure)	2019	(Nederland Elektrisch, 2020)
	Green Deal (infrastructure)	2016	(Nederland Elektrisch, 2019)
Information instruments			
Knowledge transfer	Formula E-team	2016	(Nederland Elektrisch, 2024a)
Collaboration & networking	Formula E-team	2016	(Nederland Elektrisch, 2024a)
	Dutch National Charging Infrastructure Agenda	2022	(Nationale Agenda Laadinfrastructuur, 2022)
Outreach	-	-	-

[3]Before 2018, when at a charging point EVs did not have to pay for parking in most cities (Yellowbrick, 2018). However, since this was different for each city it is hard to specify the first year in which EVs did not have to pay for parking.

D | Summary of Validation Interviews

In this chapter a summary is provided, per interviewee, of the interviews conducted as part of the validation process. While for most part the interviewees agreed with was presented to them, they also shared interesting insights and recommendations about certain points, which are described below.

D.1. Interviewee 1

Interviewee 1 is a manager at one of UK's Big Four consultancy firms, and has worked in the renewable energy sector. They contributed to the validation of the wind energy (Section 6.1) and the EV (Section 6.3) case studies in the UK. Furthermore, other general points were discussed with the interviewee.

When inquired about where consultancy firms would fit within the model, they agreed that it made sense to frame them as technology firms. This is because these companies often work on projects aimed at developing the technology or at defining the strategy of its implementation. Nonetheless, the interviewee mentioned that consultancy firms typically fit in different boxes.

The fact that the incumbents appeared very active in all case studies was discussed with the interviewee. They considered that generally the very large incumbents were risk averse. While that does not mean that large firms like Siemens do not innovate, according to the interviewee's experience in the UK the majority of innovations come from small and medium enterprises trying to set themselves up. This is then followed by commitment from the incumbents once the technology is more developed. For example, most people associate the large growth in EVs with Tesla, who put a lot of effort into developing and marketing the technology. However, since the beginning it was expected that once the large incumbents such as Mercedes and Volkswagen committed to EVs, they would overcome Tesla in many aspects, which was observed in reality. These insights were integrated into Chapter 7 and Chapter 8.

There was one detail concerning the role of incumbents in which the interviewee's opinion differed slightly from the case studies' findings. Based on intuition, interviewee 1 suggested that most incumbents wait for the tipping point before committing to a new technology. This did not agree with the data found in all case studies and therefore was not implemented.

D.1.1. Wind Energy in the UK

For the wind energy in the UK case study, interviewee 1 mentioned that for instance the TSB is currently very focused on collaboration agreements, providing a lot of data to other parties. In fact, many of the projects in which the interviewee has been involved stipulate that they must perform the data work in collaboration with a university. Furthermore, they stated that, apart from the academic and research institutes mentioned in the presentation, ORE Catapult is also involved in performing research.

Concerning trade associations, interviewee 1 highlighted the mutual relationship between these and policymakers. When the government is looking for feedback on policies, they perform a request for evidence, typically next to trade associations. This helps set-out policies that are implementable, such that time and money are not wasted. For instance, interviewee 1 mentioned that the switch from Renewable Obligation Certificates to Contracts for Difference was a consequence of feedback from the industry. At the time, the government wanted to bring the incentive to a halt since it was only meant to kick-start the industry, not maintain it. However, the industry players claimed they still needed support, from which the new system emerged. Therefore, the interviewee proposed having a feedback loop between policymakers and trade associations to show this mutual interaction.

They argued that a lot of the political influence and lobbying from technology firms towards policymakers goes through trade associations. This is because in this industry there are many small businesses that do not have the weight of a trade association. Thus, the latter act as the middle man. This observation was, however, already included in the description of the case studies, although perhaps it is not immediately clear from the feedback loop models. Besides, interviewee 1 pointed out that apart from the trade associations mentioned in the presentation there was also the Renewable Energy Association.

In terms of financial institutions, the interviewee confirmed the importance of the Green Investment Bank, and stated that currently the UK Infrastructure Bank is a big player in this field. Nonetheless, the latter was only established in 2021 (UK Infrastructure Bank, 2022).

They also mentioned that the Crown Estate (CE) is a very particular organisation since they are an independent private organisation set up by an active government. They report to the government as their main shareholder and most of the CE's revenue goes to the country's Treasury.

Moreover, they said that financial institutions could be linked directly with technology firms as they provide most firms require on loans, especially the smaller ones. However, I argued that these financing solutions toward technology firms have always been there. Therefore, they were probably not critical in triggering the positive tipping point and can be left out to avoid adding unnecessary complexity to the model. The interviewee agreed with this point.

Finally, interviewee 1 argued that academic and research institutes could link directly to the sustainable energy technology block. In the model presented to them these institutes interacted with technology firms who in turn interacted with the technology. However, academic and research institutes directly research and test new technologies. Nonetheless, they said that if the intention was to show how the investment flows then probably not having them link directly to the technology made sense. Still on academic and research institutes, the interviewee agreed that technology firms provided them training but they argued that direct R&D investment was also involved.

D.1.2. EVs in the UK

Again, interviewee 1 argued that there was investment from technology firms toward academic and research institutes. As an example they mentioned the Work Manufacturing Group at the Warwick Business School, which worked very closely with Jaguar, Land Rover, among other manufacturers. This collaboration included the Advanced Propulsion Centre as well. Such investments resulted in new buildings at engineering schools, some of which dedicated solely to EVs, for instance at the new engineering school of Coventry University. Furthermore, they argued that training in both directions was definitely involved. This was already captured by the interactions named *knowledge transfer*.

The interviewee agreed with not having a direct link between trade associations and adopters. They believe that trade associations undertake surveys of EV users, but so do technology firms, consultancies, and the government. Therefore, this does seem like standard practice and the interviewee agreed that it did not need its own arrow in the model. They noted that it differed from wind energy, in which adopters are typically companies and not individuals.

Interviewee 1 also highlighted the important role of infrastructure, as the lack of charging points is one of the main reasons for not adopting an EV according to them. They consider that there have been affordable EVs available for a long time already, and that the charging infrastructure was one of the main constraints for the technology's deployment. They noted that there is still some way to go. For instance, there are lamppost chargers on some streets, but those parking spots are often occupied by cars that are not plugged in. Another concern is the fact that the network does not have enough capacity to, e.g., change all the lamppost on a street to charging points.

Concerning the contribution of incumbents, they argued that the 2015 Diesel scandal was responsible both for the tipping point in adoption, and the commitment of incumbents, with the two latter occurring at a similar time. Their opinion was based on the fact that EVs depend heavily on behavioural aspects and that the Diesel scandal showed people that their car was not as environmentally friendly as they thought, making them realise they had to do something different. However, this opinion is not supported by the case study findings. Rather the analysis suggests that the Diesel scandal led technology firms to reorient shortly after, with the tipping point occurring roughly four years after, in 2015.

D.2. Interviewee 2 - Wind Energy in Portugal

Interviewee 2 validated the case study concerning wind energy in Portugal (Section 6.2). They work at a company focused on wind energy production as a project manager.

The interviewee mentioned that the stabilisation period after 2010 was not solely due to the economic crisis but also due to the inability of the electrical grid to accommodate the energy that could be generated in locations suitable for wind projects, which has remained insufficient up to today. In the case study it was mentioned that the tender process specified the preferred points on the grid for new projects. As discussed with interviewee 2, if the grid is not expanded, these points will eventually run out.

In terms of the actors involved, interviewee 2 acknowledged that project developers do sometimes sell parks that have been built. This is common when investment funds - which specialise in managing financial investments rather than in developing or building wind parks themselves - seek assets that are already operational. Consequently, they often hire other companies to handle the technical management of the parks on their behalf. In this case, the project developers would fit as *adopters*.

However, interviewee 2 highlighted that project developers do not always correspond to *adopters* as in "people who actually buy the technology". They mentioned that it was very common for project developers to take projects to the ready-to-build phase by acquiring land, conducting preliminary studies, engineering the designs, and obtaining the necessary permits. They then sell these ready-to-build projects already with the technology (e.g., wind turbines or solar panels) to the final owner. This is very common nowadays and occurs via milestone fee payments following a co-development logic.

Other actors to consider might be consulting firms (technical, energy, environmental, legal, etc.), providing reassurance to adopters for their investments, including validating the work done by project developers. Interviewee 2 mentioned that consultancy has always been important for validating the reliability of projects in due diligence processes for bank financing.

Concerning financial institutions, interviewee 2 made a specific comment about banks, saying that these can play a significant role in providing the capital that allows these projects to materialise. Banks have always been very interested in renewable energy projects, especially when their production can be predicted with considerable certainty in the medium- to long-term, and feed-in tariffs are involved. The production estimations are then typically validated via due diligence by consultants.

With respect to the wind atlas developed by INETI, the interviewee mentioned that it serves only to provide an initial perception of the wind potential and to identify suitable locations. It is still necessary to conduct wind measurement campaigns, with the installation of measurement towers (met masts), to reliably anticipate investment returns and obtain project financing.

In specific regarding policies, nowadays the use of what could be called *compensatory instruments* is widespread. Despite them being renewable energies, these technologies still have a significant impact on the environment, territory, and/or local communities. Thus, it is common for administrative entities (e.g., municipalities) to request a compensatory measure. At times, these measures are defined by law, such as compensations to municipalities. Nowadays, it is even common for promoters to suggest compensatory measures right away (tree planting, offering vehicles for fire prevention, habitat protection measures, among others). This is indeed observed in the wind energy in Portugal case study.

The interviewee commented that public incentives were not solely financial benefits. The tender process offered the opportunity for project promoters proposing technological clusters to install capacity in the country. This setup encouraged manufacturers to participate and establish factories in Portugal. By joining these clusters and winning the auctions, they not only had access to incentives but also had a market to sell their products in, which facilitated their investment in the country.

When it comes to the feed-in tariffs, they highlighted that these were not exactly a fixed rate per MWh, but were calculated with a complex formula. The latter involved indices associated with e.g., production hours. For instance, a wind park could have an average tariff of €80/MWh and another of €100/MWh. Hence, the feed-in tariff I specify in my case study should probably be referred to as “average tariff”.

Moreover, the feed-in tariffs were not strictly given for 15 years (after the revision of 2005). They were at most 15 years or until an accumulated production of a certain amount of GWh was reached. For instance, there were parks with good production whose feed-in tariff only lasted for 13 years. Therefore, the correct term should be “up to a maximum of 15 years”.

Concerning feedback loops 1 and 2, the interviewee noted that in the past years the cost per MW of installing wind farms has not decreased much, even though they are not sure how it was between 2000 and 2007. Since 2007, when the interviewee joined the industry, turbines have indeed become larger, with higher power and rotor diameters. This has allowed for the installation of more MW in smaller areas and increased production in locations with less wind, which might have been disregarded previously.

D.3. Interviewee 3 - EVs in the Netherlands

Interviewee 3 is a senior manager at one of the Netherlands’ Big Four accounting firms, and works in renewable energy projects. They helped validate the EVs in the Netherlands case study (Section 6.4).

One of the remarks they made concerned the importance of the infrastructure and accessibility in reaching the tipping point in EV adoption in the Netherlands. This is because, once the infrastructure provides sufficient coverage, the technology becomes usable and adaptation begins. Associated with infrastructure development they mentioned the role of national government and municipality-level policies. For instance, the environmental areas (*milieuzones*) within city centres proved to be a relevant incentive in the transition. On this note, they stressed the importance of polycentric efforts, i.e. having policymaking at different levels, in enabling positive tipping points (Geels et al., 2017).

Interviewee 3 pointed out that the Netherlands, lacking a domestic car industry, is an unexpected leader in electric vehicle adoption. Typically, one would anticipate robust government support and subsidies in countries with significant car manufacturing sectors. However, powerful lobbying efforts, particularly evident in Germany, have instead hindered progress in such countries, resulting in their lagging behind. This discrepancy highlights the irrationality of political influence on policy decisions.

When it comes to feedback loop 4, interviewee 3 mentioned that municipalities, particularly Amsterdam, were eager to establish a public charging network and demonstrated flexibility in the permitting process. Erecting these stations in public areas posed challenges, requiring adherence to a rigorous permitting procedure. The national government provided subsidies to municipalities for charger installation, enabling individuals without home chargers to request public ones. Additionally, an auction was held for fast charging spots near highways, which was overlooked by oil and gas companies but seized by Fastned at low cost. Fastned has since expanded into a major company, though confrontations with existing gas stations persist, as they cannot sell beverages, for instance.

In terms of private infrastructure investment, they also highlighted Tesla's innovative business model, performed in partnership with the Van der Valk hotels. Having chargers in the hotel's premises is beneficial for both parties. For Tesla, one of the advantages is that hotels are always closely located to highways. Interviewee 3 outlined that these collaborations helped make the tipping point realistic.

Concerning feedback loop 6 and the fact that framing EVs as offering a solution to societal problems legitimises the technology, interviewee 3 mentioned that one other very important factor is simply that owning an EV is 'cool'. For instance, even though Tesla does tick most of the ten types of innovation (Deloitte Digital, 2024), it also brings with it a unique experience that affects behavioural aspects.

Another aspect they saw as important to consider was the fact that in 2013 the Dutch Government set ambitious climate goals, yet certain aspects of the transition seemed unattainable at the time. For instance, decarbonising the steel industry posed significant challenges. However, progress could be swiftly achieved in sectors like solar, wind, and electric vehicles. These were areas ready for transition, whereas progress in other sectors lagged behind. This does not, nonetheless, imply that wind and EVs are "easy" sectors, as they faced significant challenges one or two decades ago, too. The difficulty lies in kick starting progress and establishing the necessary infrastructure. Additionally, interviewee 3 stated that subsidising early adopters is crucial. Choosing where to focus efforts is also challenging as making the wrong choice could result in delays spanning decades.

Lastly, they mentioned that general lessons from these case studies can be incredibly helpful and interesting for the industry. They highlighted that although comparing the case studies and trying to find patterns among them is perhaps this thesis' most difficult part, it is also the most interesting one.

D.4. Interviewee 4 - Final Feedback Loop Models

Interviewee 4 is a postdoctoral researcher at a Dutch technical university working closely to positive tipping points. Therefore, they validated the overall final feedback loop models (Section 7.1.1), as well as the conclusions about actor groups and actor roles (Section 7.1.2 and Section 7.1.3).

One point made by interviewee 4 concerned the definition of wider publics, especially when it comes to onshore wind. They mentioned there is a lot of literature on social acceptance of wind energy and renewable energy. That literature often makes a distinction between the general public and specific communities where the technology is located. They suggested this distinction could be integrated into this thesis' models. Besides, interviewee 4 said there was typically a difference in the level of acceptance of the general public. For instance, while the wider public might generally support wind energy, a local community might not. This difference is called the social gap.

Initially, interviewee 4 agreed that it made sense for financial institutions to have a larger impact for B2B than B2C technologies. The interviewee argued that, although it might not be as obvious as the role of large capital investments or debt provided to wind farm developers, financial institutions could still play a role in EV adoption. However, they said including this actor group on the EV case studies or not depended on the case studies' findings.

Concerning promoting education, I commented that perhaps creating these education programs did not have a direct impact on the deployment of the technologies in the time period analysed. The interviewee agreed that it was hard to be sure of the effect of this actor role and that they would also leave it out.

The interviewee pointed out that policymakers seemed to have a substantial role in most of the actor roles. They commented that oftentimes when people look at different systems policymakers come across as the most important actors, but that is not always the case. They are the ones that are in the public eye the whole time and so have the most explicit public goals and visions. However, sometimes systems are driven by other actors whose role is not so visible. For instance, global communities and wider publics can also play an important role in shaping the positions of policymakers.

Finally, interviewee 4 noted that three or two new feedback loops had been added to the model, pointing out these were 'smaller' feedbacks. They questioned whether there were any bigger feedback loops created by these additions. This comment was incorporated in Section 7.1.1 and Section 8.3.