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Next exit: Net-zero? Transition acceleration challenges in hard-to-abate industry sectors

The case of heavy-duty freight transport

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First, promiscuously plucking out fibers in clotted and dense events and practices, I try to follow the threads where they lead in order to track them and find their tangles and patterns crucial for staying with the trouble in real and particular places and times.

— Donna J. Haraway, Staying with the Trouble: Making Kin in the Chthulucene.

Abstract

Keywords: Net-zero transitions, hard-to-abate industry sectors, heavy-duty road freight, acceleration challenges, transition governance

Acknowledgements

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List of included papers

This thesis is based on the following five papers, referred to in the text by their Roman numerals.

Paper I. Ertelt, Sophie-Marie, forthcoming. ”Reinterpreting circularity? Understanding the contested directionalities of the Swedish heavy-duty vehicle sector towards the Circular Economy”. In *Sustainability transitions: multi-system dynamics and industrial transformation*. Book chapter to be published by the beginning of 2025.

Paper II. Ertelt, Sophie-Marie, & Kask, Johan, 2024. “Home field advantage: Examining incumbency reorientation dynamics in low-carbon transitions.” *Environmental Innovation and Societal Transitions*, *50*, 100802. https://doi.org/10.1016/j.eist.2023.100802

Paper III. Ertelt, Sophie-Marie, Breslin Dermot, Kask Johan, 2024. ”From carbon lock-in to climate neutrality? Exploring the decline-innovation nexus in the net-zero transition of the EU heavy-duty vehicle sector”. Advanced manuscript presented at the International Sustainability Transitions Conference 2024, Oslo, Norway.

Paper IV. Ertelt, Sophie-Marie, 2024. “Beyond predict and provide: Embracing sufficiency synergies in road freight electrification across the European Union”. *Energy Research & Social Science*, 111, 103498. https://doi.org/10.1016/j.erss.2024.103498

Paper V. Ertelt, Sophie-Marie, Rezvani, Zeinab, Klezl, Vojtech, Kask Johan, 2024. ”From policy mix to pavement: Exploring actor internal factors in zero-emission truck adoption”. Published as part of the special issue on “Behaviour in Transitions” in the *Journal of Cleaner Production*, p.143427. https://doi.org/10.1016/j.jclepro.2024.143427

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During the preparation of this thesis, I have made use of the generative AI tools, Grammarly and ChatGPT to assist me with grammar and spelling corrections as well as to improve language, flow, and readability. After using these tools, I have reviewed and edited the content as needed and I take full responsibility for the content of the whole thesis

Abbreviations

ACEA	European Automobile Manufacturers' Association
AID	Adoption Intention Delay
AFIR	Alternative Fuels Infrastructure Regulation
AR	Anticipated Regret
BEV	Battery Electric Vehicle
BESS	Battery Energy Storage System
BET	Battery Electric Truck
CCS	Carbon Capture and Storage
CE	Circular Economy
CNG	Compressed Natural Gas
CO2	Carbon Dioxide
DT	Deep Transition
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
ERS	Electric Road System
ERSV	Electric Road System Vehicle
EU	European Union
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
HDV	Heavy-Duty Vehicle
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
LNG	Liquefied Natural Gas
MCS	Megawatt Charging System
MLP	Multi-level Perspective
NGO	Non-Governmental Organization
OEM	Original Equipment Manufacturer
PHEV	Plug-in Hybrid Electric Vehicle
PRT	Perceived Rate of Technology
PTN	Perceived Technology Neutrality
RED	Renewable Energy Directive
RD&D	Research, Development and Demonstration
R&D	Research and Development
TCO	Total Cost of Ownership
SCR	Selective Catalytic Reduction
SNA	Social Network Analysis
ZEV	Zero-Emission Vehicle

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All figures are the author's own illustrations unless stated otherwise.

1. Introduction

This chapter sets the stage for the research presented in this thesis by providing an in-depth introduction to the research context and the empirical case under investigation. It discusses the key issues faced by hard-to-abate industry sectors striving for net-zero emissions, focusing on heavy-duty freight transport and its transition acceleration challenges. The chapter further outlines the research aim(s) and provides an overview of the dissertation's structure and content.

1.1 The age of net-zero

Limiting warming to 1.5°C implies reaching net zero CO2 emissions globally around 2050. (IPCC, 2018, p. 33)

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A seemingly straightforward sentence of thirteen words that delivered a clear message and marked the starting gun of the global race to net zero. In 2018, three years after the adoption of the Paris Agreement, which aimed to limit global temperature increase to well below 2°C (UNFCCC, 2015), the Intergovernmental Panel on Climate Change published a *Special Report on Global Warming of 1.5°C* (SR15) which included mitigation pathway models that highlighted with great confidence that to achieve such global temperature increase target and prevent the most severe impacts, global carbon dioxide (CO2) emissions must be reduced to net-zero by around 2050 (Allen et al., 2022). In the context of climate change mitigation, net-zero emission refers to the balance between the amount of greenhouse gases emitted into the atmosphere and the amount removed, ensuring that the net addition to atmospheric concentrations is zero (Fankhauser et al., 2022). This is not limited to CO2 emissions but also includes other greenhouse gases (GHGs), such as methane or nitrous oxide (Rogelj et al., 2021). Research on the necessity to reduce global emissions to net zero to halt global warming already emerged in the late 2000s (e.g., see Matthews and Caldeira, 2008; Solomon et al., 2009). The "unifying and galvanising power of the net-zero narrative" (Fankhauser et al., 2022, p. 17), nevertheless, only fully unfolded after the publication of the SR15 report. As highlighted in Figure 1, within just over two years of its publication, the number of countries with net-zero targets rose from only a handful to over 120 (Höhne et al., 2021). In 2023, according to the analysis of Net Zero Tracker (2023), 149 nations, 145 states or regions, 252 cities, and 929 companies from the Forbes 2000 have set net-zero targets.

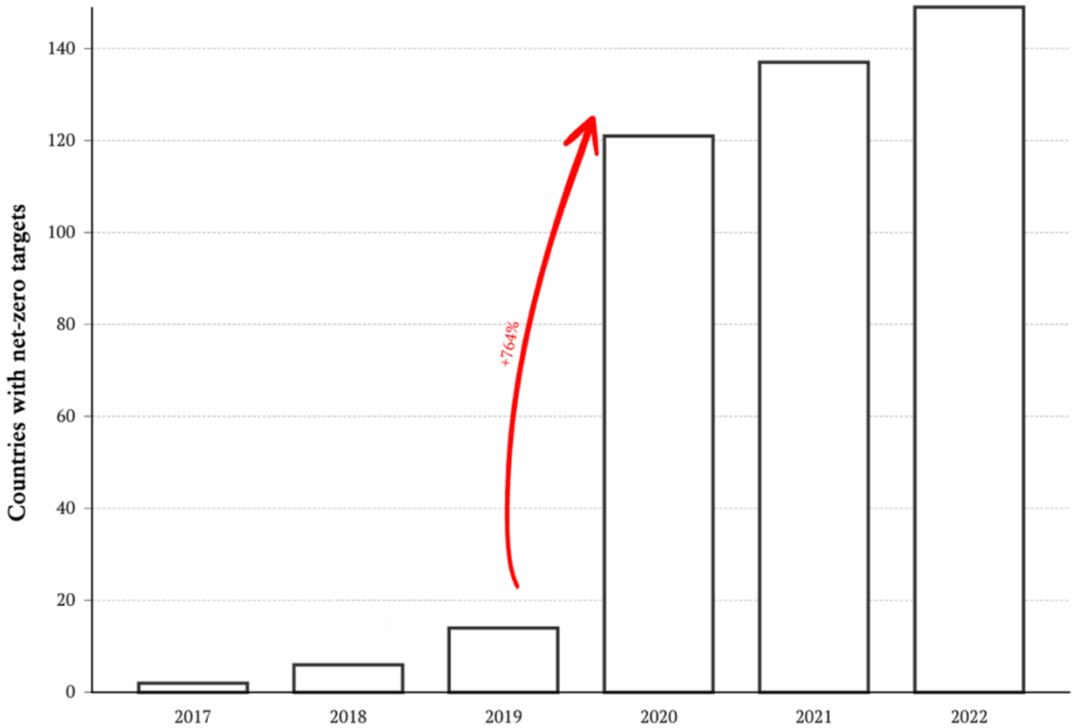

Figure 1 Number of countries with net-zero targets 2017-2022. Based on Net Zero Tracker (2023) and Climate action tracker (2023).

Achieving such targets, however, will require a series of interrelated and complementary *net-zero transitions*–fundamental transformations of current production, distribution and consumption systems–across energy, transportation, agriculture, housing and other sectors globally to reduce their emissions to net-zero (Markard and Rosenbloom, 2022; Meadowcroft and Rosenbloom, 2023). Net-zero transitions, thus, are *highly disruptive* in nature because they entail far-reaching changes to existing socio-technical systems–configurations of interconnected social and technical elements such as technologies, infrastructures, institutions, and cultural norms that together fulfil specific societal functions (Geels, 2004; Geels and Turnheim, 2022)–including the development of new products, business models, fundamental alterations to existing technological and institutional structures, as well as a sociocultural shift in the perceptions of consumers regarding how certain societal functions can be fulfilled (Andersen et al., 2023a; Andersen and Geels, 2023). While some social or technological innovations to eliminate emissions are already seeing significant uptake (e.g., repair cafés or solar photovoltaic), (Breyer et al., 2017; Spekkink et al., 2022), others are still in their early phases of development or simply do not exist yet (Geels et al., 2017; Markard and Rosenbloom, 2022). Consequently, net-zero transitions involve considerable amounts of *uncertainty* but are also *none-linear* as the rate of innovation development and diffusion is often hard to forecast and may go through cycles of hype and disappointment (van Lente et al., 2013), unforeseen market developments such as the rapidly falling battery cell prices which allowed for much faster diffusion of associated technologies (Kittner et al., 2017) or might face increasing public or industry pushback (LaPatin et al., 2023).

Given this high level of disruptiveness and uncertainty, net-zero transitions are also *highly contested multi-actor processes* involving a large variety of different societal actors, including the wider public, policymakers, firms, industry associations, special-interest groups, universities and non-governmental organisations (NGOs) (Geels et al., 2017; Meadowcroft and Rosenbloom, 2023). Each of these actors may hold vastly different views on the feasibility of different decarbonisation strategies, leading to contestations, public debates, conflicts and power struggles of actors over desired future net-zero transition trajectories (Rogge and Goedeking, 2024; Sovacool, 2017). Lastly, because the proposed long-term benefits of climate change mitigation might lack attractiveness to both organisations and consumers as their benefits are often perceived as distant compared to immediate costs and sacrifices (Geels et al., 2017) *net-zero transition governance* broadly understood as the design and implementation of coherent policy mixes–sets of regulations, standards, taxes, and subsidies–in line with net-zero targets is a crucial component for successful emission reductions (Meadowcroft and Rosenbloom, 2023).

1.2 Hard-to-abate industry sectors on the quest to net-zero

While the above-outlined characteristics of net-zero transitions pose significant challenges for progress across all societal sectors (Andersen et al., 2023a; Fankhauser et al., 2022), a specific cohort of sectors stands out due to their exceptionally high emissions yet inherent difficulties in reducing said emission footprint (Kumar et al., 2024). So-called difficult-to-decarbonise or hard-to-abate industry sectors, including heavy-duty trucking, shipping, aviation, iron and steel, as well as chemicals and petrochemicals, currently represent sectors in which progress towards net-zero is the slowest (in terms of total emission reduction numbers) (IRENA, 2024). Given the fact that collectively, these sectors account for a quarter of the world's total energy consumption and approximately 20-30% of global CO2 emissions, (IEA, 2023), their deep decarbonisation thus can be considered critical to limit global warming in line with the Paris Agreement (Sharmina et al., 2021). However, these sectors face a specific set of problems that so far have limited their ability to contribute significantly to reaching net-zero emissions globally:

(1) *Path dependency and carbon lock-in*. A significant problem is the presence of path dependencies–the self-reinforcing dynamics of historical investments in infrastructure and technologies locking sectors into specific trajectories–that constrain future decarbonisation possibilities (Arthur, 1994; Kushnir et al., 2020; Urban et al., 2024). Hard-to-abate industry sectors are characterised by assets with long lifetimes, creating a form of inertia against rapid decarbonisation and learning effects that arise from years of experience and accumulated knowledge further

reinforce the dependability on carbon-intensive technologies (Åhman, 2020; Sydow et al., 2021). Network externalities and complementary effects intensify these dynamics (Apajalahti and Kungl, 2022a; Arthur, 1988) because when a specific type of infrastructure or technology becomes widespread, its value increases with each additional user and through the development of compatible technologies, services and products (Apajalahti and Kungl, 2022a; Arthur, 1988, 1994). The resulting interdependencies favour incremental innovation and optimisation of carbon-intensive technologies rather than shifts to radical low-carbon alternatives (Janipour et al., 2020; Klitkou et al., 2015), thus making alternative solutions seem less attractive (Arthur, 1989; Schreyögg and Sydow, 2010) or even marginalised (Klitkou et al., 2015). These dynamics solidify the status quo, entrench carbon-intensive technologies and result in carbon lock-in (Unruh, 2002, 2000), making significant progress towards net zero a challenging proposition (Löfgren and Rootzén, 2021; Sharmina et al., 2021).

(2) *Economic, technological and political barriers*. Substantial economic barriers often impede transitioning to net-zero operations in hard-to-abate sectors: On the one hand, industry actors in these sectors are generally faced with long investment cycles, high initial capital costs for implementing new technologies and elevated operational expenditures for maintaining them (Bergek et al., 2023; Kushnir et al., 2020; Rissman et al., 2020) , and the return on investment is often long-term and uncertain (Bataille et al., 2018; Sandén and Azar, 2005); which may discourage established industry actors from initiating the search path towards less carbon-intensive practices. On the other hand, net-zero initiatives in these sectors are notoriously underfunded, as all hard-to-abate sectors together received less than 1% of all global climate finance in 2023 (Buchner et al., 2023). Additionally, technological constraints represent a substantial barrier to rapid decarbonisation: Hard-to-abate sectors frequently face an innovation gap, wherein low-carbon technologies that can replace their carbon-intensive counterparts are either in their infancy or virtually non-existent (Kumar et al., 2024). As a result, many net-zero strategies for hard-to-abate sectors rely on the future promise of offsetting emissions with the help of carbon capture, utilisation, and removal technologies to eliminate emissions (Sharmina et al., 2021). Lastly, given their high societal importance, current regulatory and policy frameworks are often lacking when mandating industry actors in hard-to-abate sectors to transition toward net-zero trajectories (Bergek et al., 2023; Janipour et al., 2020). Hard-to-abate industry sectors can be considered the backbone of national economies because they provide essential materials such as steel, cement, and chemicals that underpin infrastructure development and manufacturing (Janipour et al., 2020; Nykamp et al., 2023). Additionally, heavy transport and aviation are vital for global trade and connectivity

(Liu et al., 2023; Martin et al., 2023). These industries also employ a substantial number of workers, creating economic stability and social benefits, which together lowers the political will to implement disruptive policies (Urban et al., 2024)

(3) *Cemented position of incumbent actors*. Hard-to-abate industries are dominated by incumbents–established companies or organisations with long-standing presence, substantial market share, extensive infrastructure, and established relationships with suppliers, customers, and regulators–that frequently have vested interests in maintaining their privileged position and thus might use their power to defend prevailing carbon intensive arrangements (Galeano Galvan et al., 2020; Johnstone et al., 2017; Turnheim and Sovacool, 2020). These industry actors often resist any change that threatens the status quo of their operations, and their considerable influence can shape regulatory landscapes and sway public opinion in their favour, thus significantly influencing the speed and scope of decarbonisation efforts (Geels, 2014; Penna and Geels, 2015; Roberts et al., 2018; Turnheim and Sovacool, 2020). Adding to that, incumbents are frequently risk-averse and rather conservative in their search mechanism for low-carbon alternatives (Johnstone et al., 2017; Stirling, 2019). However, their control over critical resources and political influence makes it almost impossible for newcomers to challenge their entrenched positions and successfully enter these sectors with low-carbon innovations (Darnhofer et al., 2019; Hess, 2016). Despite their capability to resist change, defend carbon-intensive arrangements and slow down transition processes (Geels, 2014; Penna and Geels, 2015; Sovacool et al., 2017), their substantial resources and industry knowledge nevertheless position incumbents as potential leaders in the quest for net zero (van Mossel et al., 2018).

Despite these problems in recent years, the development of low-carbon innovations to decarbonise hard-to-abate sectors has seen significant progress: For example, green hydrogen is being developed as a clean energy source for the steel industry, and the aviation sector is exploring sustainable aviation fuels and electric aircraft, while the shipping industry is investing in battery-powered vessels to minimise their carbon footprint (Sharmina et al., 2021; Watari and McLellan, 2024; Yaşar Dinçer et al., 2024). Together with mounting social and political pressure to align with net-zero targets, this has led to an increased momentum for the net-zero transitions of these sectors (IRENA, 2024).

1.3 The case of heavy-duty road freight transport

The empirical focus of this thesis, and the hard-to-abate sector in which the pace towards net zero has picked up the most among the five sectors discussed above, is *heavy-duty road freight transport* (Aryanpur and Rogan, 2024; Borlaug et al., 2021; IRENA, 2024). Road freight transport—moving goods in heavy-duty trucks[1] via roads across countries and continents—plays a crucial role in facilitating global trade and economic activities. Fluctuations in national gross domestic products are often mirrored by changes in road freight activity, which has led to the assumption that road freight activity and economic growth are closely interconnected (Chovancová et al., 2023; McKinnon, 2007). In terms of industry characteristics, European heavy-duty road freight is dominated by seven legacy original equipment manufacturers (OEMs), namely DAF, IVECO, MAN, Volvo Trucks, Renault Trucks and Scania, who together hold over 95% of the total European market share of the heavy-duty truck market (ICCT, 2024). Similarly, about 95% of these trucks are diesel-powered (ACEA, 2024b), and European legacy OEMs have a long-standing history of incrementally improving the associated powertrain technologies (Berggren et al., 2015).

The market structure of the user side of these trucks, however, is far more heterogeneous, primarily composed of very small companies that typically operate fewer than ten trucks in their fleet. These small operators are often involved in short-haul and regional transportation, catering to local markets. Additionally, independent owner-operators who own and operate just one or a few trucks also constitute a significant segment. They frequently handle specialised or niche routes and cargo, offering personalised services that larger companies might not be able to provide. Additionally, there are larger logistics companies that manage extensive fleets, typically comprising hundreds or thousands of trucks. These companies are heavily involved in long-haul freight operations, providing comprehensive logistics solutions across multiple countries. The movement of heavy-duty trucks at local, national and European-wide levels is facilitated by a large amount of fixed physical infrastructure tangible assets such as highways and refuelling stations and is governed by a variety of laws, including environmental regulations, safety standards, and agreements on cross-border transportation. Figure 2 gives a non-exhaustive overview of the different elements that together form the current socio-technical configuration of heavy-duty road freight transport.

[1]Heavy-duty trucks are used in this thesis as an umbrella term for medium trucks (3.5-15 tonnes) and heavy trucks (> 15 tonnes).

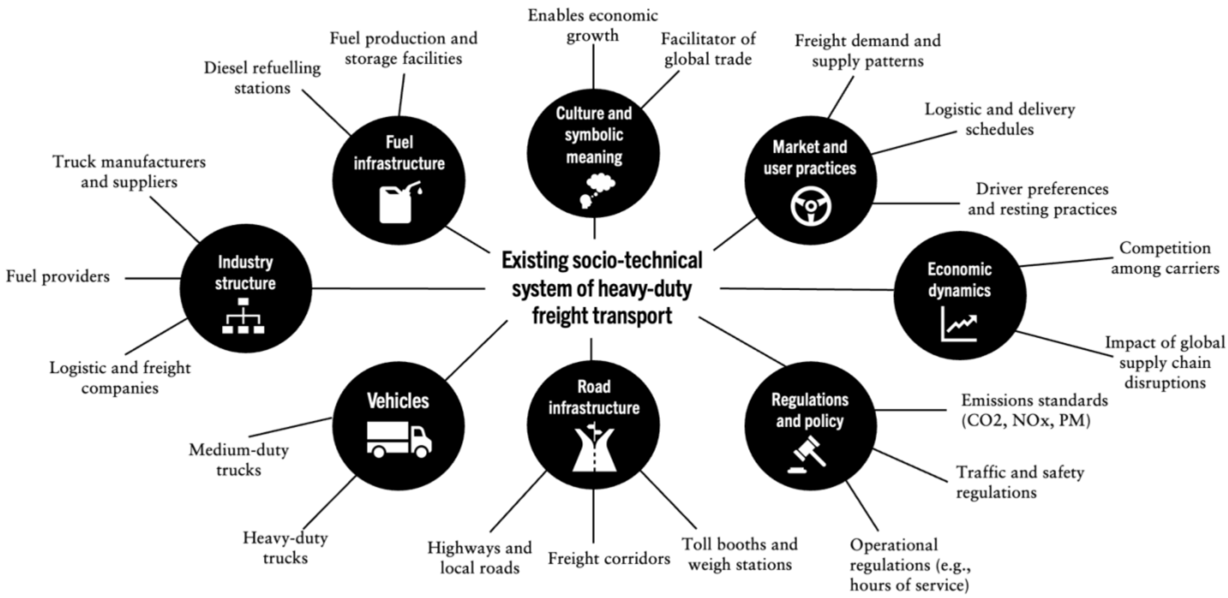

Figure 2 Schematic representation of the different elements that make up the socio-technical configuration of heavy-duty road freight transport, substantially adapted from Geels (2005).

The volume of goods transported via heavy-duty trucks already today amounts to over 13.5 billion tonnes annually in the European Union (EU), which is a 10 % increase compared to ten years earlier (Eurostat, 2024), and demand is forecasted to double by 2050 (ITF, 2023). The high economic importance and high demand for heavy-duty road freight transport follow an overwhelmingly high emission profile: Although heavy-duty trucks comprise less than 5% of the vehicles on European roads, they account for roughly 25% of road transport CO2 emissions and around 2–4% of the EU's total emissions (Plötz et al., 2023; Shoman et al., 2023). Heavy-duty trucks are envisioned to be one of the primary sources of residual emissions closer to 2050, therefore presenting a challenge to the net-zero ambitions of the EU (Creutzig et al., 2015; Luderer et al., 2018). While CO2 emissions have generally declined across various sectors in the EU, emissions from heavy-duty trucks, as illustrated in Figure 3, have continued to increase over the past thirty years (1990–2022), except for a temporary decrease in 2020 due to the COVID-19 pandemic (EEA, 2022). The red dotted line in Figure 3 highlights the steep emission decrease required to reach net zero; however, it only serves illustrative purposes as the exact emission reduction pathway and how many million tonnes may still be emitted in 2050 under the current policy scenario remains a debated topic (for different projections see Mulholland and Rodríguez, 2022 or T&E, 2023a).

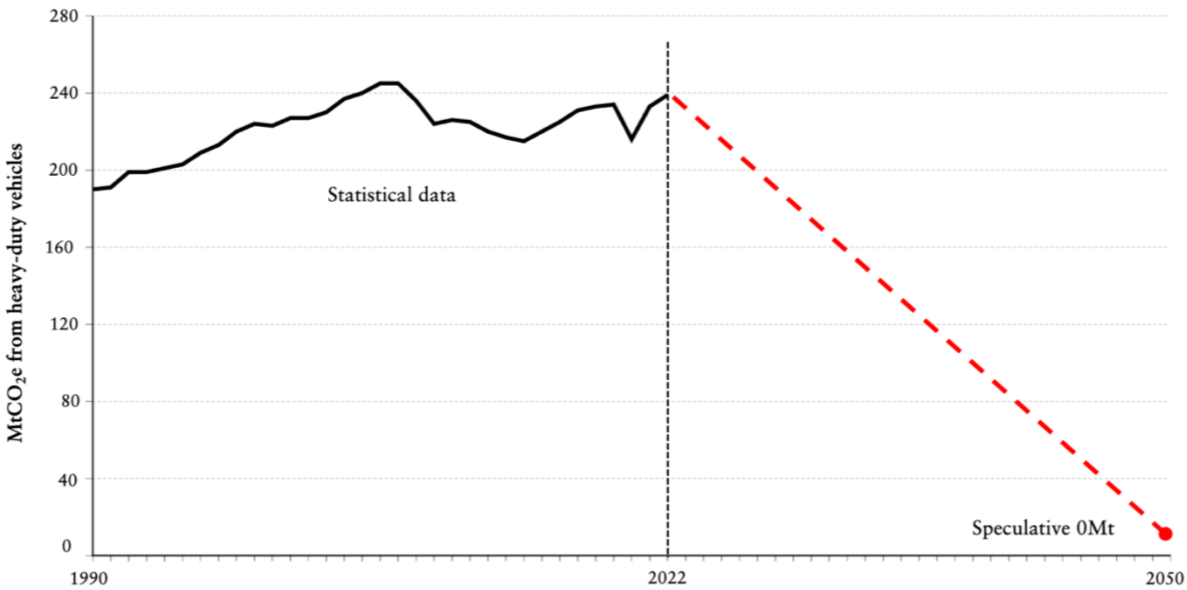

Figure 3 Trends in CO_2 emissions from heavy-duty vehicles in the EU (including the UK), 1990-2022 based on (T&E, 2024) and a speculative net-zero target 2050.

Despite this countertrend, the EU has a variety of emission reduction goals for heavy-duty road transport in place: The European Commission's regulations mandate a 15% reduction in CO2 emissions from new trucks by 2025 and a 30% reduction by 2030, relative to 2019 levels. Further proposed revisions, which will be decided on in 2025, aim to extend these targets to a 45% reduction by 2030, 65% by 2035, and 90% by 2040 (ACEA, 2023; European Commission, 2023a).

The improved energy efficiency of prevailing diesel-powered internal combustion engines (ICEs) in combination with a modal shift from road to rail, however, is not considered a sufficient decarbonisation strategy (Sharmina et al., 2021; Tsemekidi Tzeiranaki et al., 2023). Therefore, to reach the EU targets, several low-carbon alternatives have been developed that broadly can be categorised into drivetrain switches–changing the trucks' propulsion system–on the one hand and fuel source swaps–using renewable fuels instead of diesel in traditional ICEs–on the other hand. Potential drive train switches include battery-electric vehicles (BEVs), which rely on batteries and require the development of a charging infrastructure network, and hydrogen fuel cell vehicles (FCEVs), which use fuel cells and hydrogen, necessitating the roll-out of a hydrogen refuelling station network (Aryanpur and Rogan, 2024; Seemungal et al., 2021). Plug-in hybrid electric vehicles (PHEVs) are somewhat of a mix of both categories because they combine batteries with diesel engines and can potentially use renewable fuels, yet also require charging infrastructure. On the other hand, fuel source swaps include ICE vehicles such as hydrogen combustion engine vehicles and gas trucks running on biogas or natural gas or ICE vehicles powered by synthetic fuels such as e-fuels (Axsen et al., 2020; Mulholland et al., 2018).

The EU supports the diffusion of these low and zero-emission vehicles under the “Fit for 55” package, which aims to reduce net GHG emissions by at least 55% by 2030 compared to 1990 (European Commission, 2023b). Central to this effort is the Alternative Fuels Infrastructure Regulation (AFIR), which mandates the development of extensive refuelling and recharging networks for alternative fuels such as electricity, hydrogen, and biofuels, ensuring the necessary infrastructure is in place to support the widespread adoption of these technologies (European Commission, 2023c). Additionally, the Renewable Energy Directive (RED II) sets ambitious targets for renewable energy in transport, requiring at least 14% of the energy consumed in road transport to come from renewable sources by 2030 (European Commission, 2018) , and the revision of the Weights and Dimensions Directive allows for modifications in vehicle design to accommodate the additional weight of electric batteries, which is critical for the deployment of electric trucks (European Commission, 2022). To support these regulatory measures, the Horizon Europe program allocates significant funding to research and innovation projects focused on advanced batteries, hydrogen technologies, and sustainable mobility solutions (T&E, 2019). Each EU member state complements these measures with their own financial and non-financial incentives, such as vehicle subsidies or tax exemption, (partial) funding for related infrastructures and research, development and demonstration (RD&D) or low emissions zones to stimulate the widespread adoption of low and zero-emission vehicles (ACEA, 2024a).

Which one of the above-described technologies can be considered the most viable in terms of technological feasibility, energy efficiency and emission elimination potential or the most desirable in terms of total societal cost has been the subject of extensive public, political, and expert debates in recent years (Schreiber et al., 2023). This debate is primarily brought about by the fact that no “silver bullet” exists to reach the net-zero targets of the sector, but rather, each option comes with distinct advantages and drawbacks: BEVs are highly efficient and produce zero tailpipe emissions but have a shorter driving range, are heavier due to the added battery weight compared to their ICE counterparts and require sufficient renewable energy production, increased grid capacity and extensive charging infrastructure (Link et al., 2024; Nykvist and Olsson, 2021). FCEVs offer longer ranges and quick refuelling times but are less efficient and require a comprehensive green hydrogen production, storage, distribution and refuelling infrastructure (Link et al., 2024; Plötz, 2022). Hydrogen or e-fuel ICE vehicles, while offering immediate emissions reductions for existing trucks, are highly inefficient due to the large amounts of electricity required for their production (T&E, 2022a, 2023b). Biogas presents a renewable fuel alternative but is limited in availability and scalability and still produces some emissions (Shirizadeh et al., 2024). Similarly, PHEVs provide transitional solutions that reduce emissions but continue to rely on fossil fuels, limiting their long-term emission reduction potential and net-zero compatibility.

While this debate is likely not yet fully settled, electrification, more specifically BEVs, has nevertheless emerged as the most promising technology to decarbonise heavy-duty road freight, gaining significant momentum in the last three years in terms of market availability, market share and adoption rates (ICCT, 2024; Liimatainen et al., 2019; Shoman et al., 2023). Starting with a handful of test vehicles and demonstration projects by selected vehicle manufacturers in the late 2010s (Werner and Onufrey, 2022), every major European OEM today offers fully electric truck models (CALSTART, 2024), and over 5000 new BEVs were registered in the EU at the end of the 2023 reporting period as highlighted in Figure 4 (ACEA, 2024b).

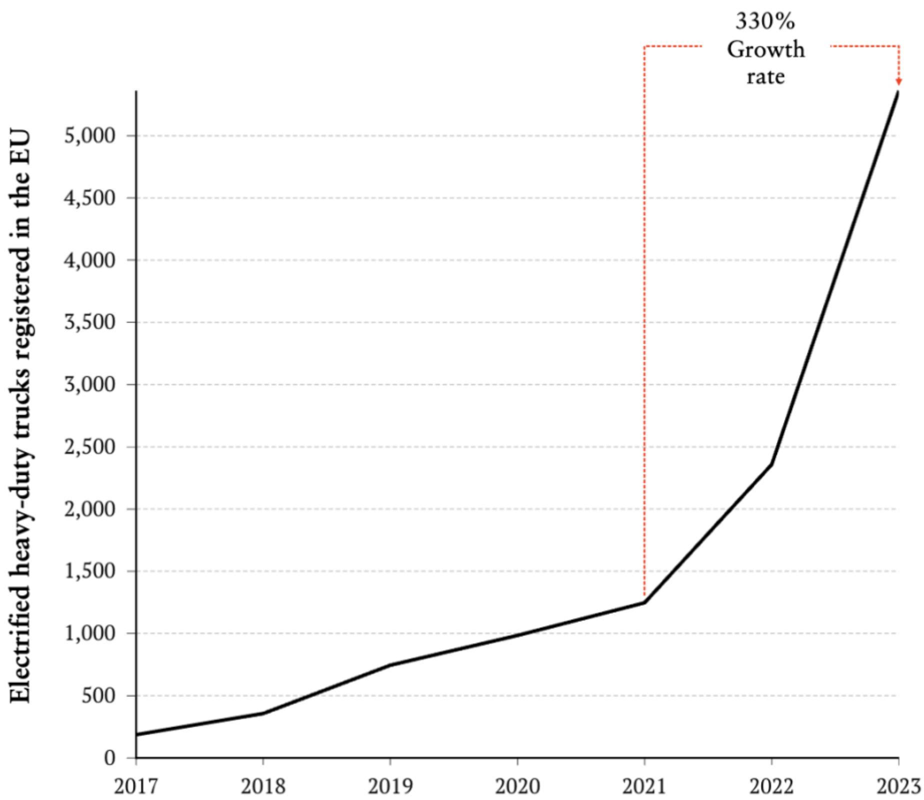

Figure 4 Electrified heavy-duty truck registration numbers in the EU 2017-2023 based on the yearly registration statistics of the European Automobile Manufacturers Association (ACEA).

This trend has been driven by significant advancements in battery efficiency, energy density, and cost reduction (Kittner et al., 2017; Link et al., 2024), which has made electric trucks increasingly competitive with traditional diesel vehicles (T&E, 2022b). Additionally, substantial investments in the development of the European charging infrastructure network by both public and private actors (Shoman et al., 2023) and increasing consumer demand for green freight transport options (Kirschstein et al., 2022) together have contributed to the increased adoption of BEVs in the EU.

1.4 Acceleration challenges of net-zero transitions

Previous research has highlighted that (net-zero) transitions unfold in a non-linear way in distinct phases, starting with *emergence* followed by *acceleration* and eventually *stabilisation* (Kanger and Schot, 2016; Markard and Rosenbloom, 2022; Meadowcroft and Rosenbloom, 2023; Rotmans et al., 2001). In the emergence or pre-development phase, several competing low-carbon innovations may exist, and early efforts focus on R&D, pilot projects, and initial trials to explore and demonstrate potential solutions with strong policy support. As described above, for heavy-duty freight transport, this phase was marked by legacy OEMS conducting R&D to develop viable decarbonisation technologies, focusing on improving battery performance and range and testing different charging infrastructures. Strong policy support, such as grants for R&D and pilot programs, was essential to encourage these initial efforts. During the acceleration phase, one or multiple low-carbon innovations gain momentum through large-scale deployment, cost reduction, and increased functionality, and this leads to broader reconfigurations of the prevailing socio-technical elements, i.e., changes of a systems architecture, driven by supportive policies such as subsidies, public investments, and regulatory frameworks that remove barriers to adoption (Markard, 2018; Turnheim et al., 2018).

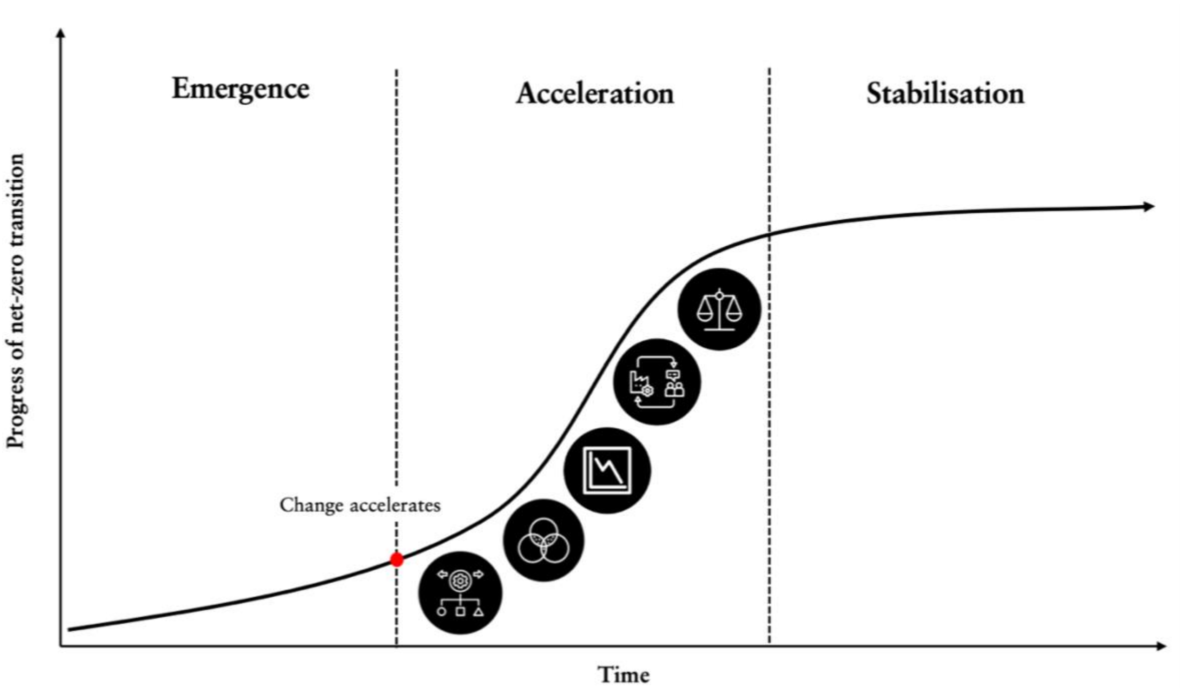

Figure 5 Three phases of net-zero transitions, including key acceleration phase challenges.

Now that the net-zero transition of heavy-duty road freight transport has started to progress past the emergence phase, signalled by rapidly increasing vehicle sales of battery electric trucks (BETs) (see Figure 4) however, previous contributions to the transition literature have conceptualised a set of *acceleration challenges* (Markard et al., 2020; Rogge and

Goedeking, 2024) that may impede the increased diffusion of low-carbon innovations such as BEVs:

(1) *Whole systems change*. The increased diffusion of a single low-carbon innovation is insufficient to enable net-zero transitions because such transitions require comprehensive transformations across entire (and often multiple) systems (Markard and Rosenbloom, 2022; Meadowcroft and Rosenbloom, 2023). Consequently, net-zero transitions may stall if the increased diffusion of a low-carbon innovation fails to trigger the development and alignment of complementary innovations such as enabling technologies, infrastructure, and changes in prevailing business models as well as market and regulatory frameworks (Markard et al., 2020). This process, referred to as whole systems change, thus involves multiple complementary innovations and change processes working together to fundamentally transform the architecture of systems (Geels, 2018; McMeekin et al., 2019; Turnheim et al., 2018).

(2) *Multi-system dynamics*. Net-zero transitions give an impetus for increased interactions, interdependencies and couplings between multiple different socio-technical systems such as transport and energy (Andersen and Geels, 2023); for example, the accelerated diffusion of BEVs demands more electricity and charging infrastructure but also relies on material input from the mining sector. These dynamics are crucial for net-zero transitions because changes in one system can significantly depend on and impact others, hence requiring coordinated efforts and integrated strategies across multiple sectors (Andersen et al., 2023b). Understanding and managing these dynamics is essential to ensure that innovations and policies in one system do not create conflicts, bottlenecks, resource competition, or inefficiencies in another, thereby slowing down net-zero progress (Markard and Rosenbloom, 2022).

(3) *Decline and resistance.* Accelerating progress towards net-zero targets does not just require the increased diffusion of low-carbon innovation but also necessitates the destabilisation, deliberate decline and phase-out of carbon-intensive technologies (Rosenbloom and Rinscheid, 2020; Turnheim, 2022; Turnheim and Geels, 2012). In the face of decline, however, incumbents with significant vested interests in the continuation of carbon-intensive technologies might use their advantageous power positions (in terms of control over resources, economic assets, and political lobbying capabilities) to slow down, oppose or build resistance towards net-zero transitions (Geels, 2014; Penna and Geels, 2015; Roberts et al., 2018; Turnheim and Sovacool, 2020).

(4) *Consumer practises and demand patterns.* The widespread diffusion of low-carbon innovations often requires significant changes in consumer habits, routines, and practices (Shove and Walker, 2010). However, such changes might face resistance from consumers who are accustomed to their current carbon-intensive routines and may find new practices that are part of the adoption of low-carbon innovation inconvenient or challenging (e.g., prolonged waiting times to charge electric vehicles) (Rogge and Goedeking, 2024). Furthermore, it is essential to rethink how society consumes goods and services to support emission elimination (Alfredsson et al., 2018). This involves altering deeply ingrained practices and cultural norms that drive consumption and demand patterns for critical resources such as energy (Barrett et al., 2021).

(5) *Governance*. Meeting net-zero targets at the required speed might require a move away from a neo-liberal policy paradigm, characterised by minimal government intervention, deregulation, and market-driven approaches (Novy and Hammer, 2007; Tödtling and Trippl, 2021), towards a more interventionist strategy where governments and policymakers play a more decisive role in shaping markets, stimulating innovation, launching large-scale initiatives, building infrastructure, and regulating businesses (Roberts and Geels, 2019). Such a paradigm shift is difficult, however, because it requires governments to challenge established market dynamics, thus potentially causing economic disruptions and risking political pushback from incumbents (Markard et al., 2020).

While a range of individual studies on the net-zero transitions in hard-to-abate industry sectors exists (e.g., see Bergek et al., 2023; Berggren et al., 2015; Christley et al., 2024; Urban et al., 2024) a comprehensive examination of how these sectors, specifically heavy-duty road freight transport, navigate the above-described transition acceleration challenges once they progress past the emergence phase is largely absent from current literature. Adding to that, given the specific characteristics of hard-to-abate industry sectors, the applicability of these "archetype" acceleration challenges and whether or not additional challenges may arise for these sectors remain unclear.

1.5 Research aim

As motivated in the first part of this introduction, the vast emission profile of heavy-duty road freight transport and the lack of concrete knowledge on the underlying dynamics of the acceleration phase of its ongoing decarbonisation efforts calls for a deeper understanding of the real-world challenges that may impede its accelerated progress towards net-zero. Consequently, the empirical aim of this thesis is to:

(1) **Enhance the knowledge state on transition acceleration challenges of heavy-duty road freight transport.**

On a more theoretical note, previous research has acknowledged that the acceleration phase of net-zero transition is analytically more complex compared to the earlier emergence phase (Markard, 2018). This new phase's inherently different features and dynamics challenge prevailing frameworks within the socio-technical literature and "warrant a new reflection concerning the appropriateness of current analytical approaches" (Turnheim et al., 2018, p. 158). I would argue this reflection is especially crucial when engaging with hard-to-abate industry sectors whose emergence phase already has not been portrayed by more classical transition dynamics , such as radical innovations emerging outside of prevailing systems as alternatives and in direct competition to existing socio-technical configurations, grow gradually and eventually break through to the system-level to overthrow incumbent arrangements. Instead, in the emergence phase in hard-to-abate industry sectors, incumbent actors, well equipped with their significant monetary, political and social power, have frequently contributed to the early establishment of specific visions and directions for decarbonisation of their respective sectors and are increasingly at the forefront of developing, testing and commercialising low-carbon innovations (Berggren et al., 2015; Christley et al., 2024; Stalmokaitė and Hassler, 2020; Urban et al., 2024; Werner et al., 2022); thus are driving change from within. However, such *endogenous change processes*– an umbrella term that is introduced in this thesis to describe transition dynamics such transformative change from within a system through the reconfiguration of prevailing socio-technical configurations and incumbent actors as strategic drivers of these processes– remain an under-theorised area of investigation in transition research more broadly (Kungl, 2024; Steen and Weaver, 2017; Turnheim and Sovacool, 2020). I would argue this is even more so the case for the acceleration phase. Given the above, it becomes clear that studying transition acceleration challenges in hard-to-abate industry sectors also requires new and expanded analytical tools to better understand the potentially different and novel dynamics at play. Therefore, the theoretical aim of this thesis is to:

(2) **Contribute to an increased conceptual understanding of endogenous change processes.**

To fulfil this aim, the thesis builds on theoretical approaches and concepts from the field of organisational studies[2] and integrates them into existing transition frameworks. This field's theoretical ability to explain how social, cultural, and political environments, as well as historical decisions, shape organisational actions and larger outcomes at the system level

[2]In this thesis, organisational studies is broadly understood as the interdisciplinary examination of how organizations function, evolve, and impact society through the integration of theories and methods from sociology, psychology, management, and related fields.

while also acknowledging that organisations nevertheless have the ability to actively shape and transform these environments through strategic actions provides valuable insights into how existing socio-technical systems can be reconfigured (for previous applications see e.g., Apajalahti and Kungl, 2022; Fuenfschilling and Truffer, 2014; Magnusson and Werner, 2023; van Mossel et al., 2018; Yap and Truffer, 2019). Hence, offering a variety of analytical tools that have enabled the research of this thesis to develop a deeper understanding of the conditions for and mechanisms behind accelerated transformative change from within hard-to-abate industry sectors. Chapter 2 provides a detailed overview of the theoretical approaches and concepts from organisational studies utilised in this thesis.

1.6 Overview of the papers

This thesis was written in an article-compilation format and, thus, builds on five individual research papers, four of empirical (Paper I-II & V) and one of conceptual nature (Paper IV), that each investigate one "archetype" transition acceleration challenges (as outlined by Markard et al. 2020).

Paper I examines the challenge of *whole systems change* through an in-depth analysis of how Circular Economy (CE) principles such as reduce, reuse, recycle, and recover are diffused and lead to interconnected changes across different sectors in the Swedish HDV value chain, including transport, energy and waste. In the paper, I develop an analytical framework to more explicitly theorise how overarching CE principles are diffused–interpreted and implemented–differently across various systems by integrating insights from institutional theory. I suggest that the diffusion of CE principles is influenced by the compatibility of these principles with existing practices within different sectors. This interpretative flexibility allows sectors to adapt CE principles to their specific contexts, leading to sector-specific implementations. In the framework, I also emphasise the role of adaptive tensions and conflicts that arise from potentially divergent interpretations of CE principles amongst systems of the same value chain, which can impact both the speed and pace of a transition towards more circular practices.[3] Applying this framework to the case of the emerging Swedish circular HDV value chain reveals how different sectors prioritise CE principles based on their alignment with existing practices, indicating that sectors adopt CE principles in ways that best fit their operational contexts and historical practices. Additionally, CE principles are interpreted and implemented differently across sectors, leading to a variety of practices under the same CE framework. This flexibility allows each sector to adapt the principles to its specific needs and constraints, which can enhance the practical applicability of CE strategies but also lead to varied and fragmented

[3]While net-zero transitions and circular economy transitions are distinctively different phenomena, focusing respectively on eliminating GHG emissions and improving resource efficiency, they are treated as somewhat interrelated in this thesis. That is due to the fact that circular economy practices are crucial for net-zero transitions as they reduce resource consumption and waste, thereby decreasing the overall carbon footprint and supporting the emission reduction goals essential for achieving net-zero transitions.

implementations. The analysis further identifies three specific adaptive tensions and conflicts arising from these divergent sectoral priorities that, if unresolved, may delay the transition towards a CE. Overall, the study's findings highlight that while CE principles hold the potential for enabling transformative change across a range of sectors, their diffusion is marked by interpretative flexibility and selective prioritisation across said sectors. This selective prioritisation can lead to incremental changes rather than transformative ones, thus potentially reproducing existing production and consumption patterns rather than fundamentally altering them.

Paper II focuses on the *multi-system dynamics* of heavy-duty road freight electrification and proposes a conceptual framework to assess how different interaction types–*inter-system* and *inter-system* interactions–as well as interaction natures–*symbiotic*, *competitive* and *antagonistic* interactions–among different incumbent actors' shape system reconfiguration processes. This framework is applied to Sweden's road freight electrification initiative, the Electrification Pledges, to analyse incumbent actor reorientation activities, interactions, and potential tensions that may arise in this process across the transport, energy, as well as information and communication systems. The paper's findings reveal how incumbent reorientations that underlie system reconfigurations occur through new interaction patterns within and across systems. Across the investigated regime dimensions, the interaction patterns and actor involvement differ, leading to diverse positions and varying role constellations that are characterised by fruitful collaboration as well as competition over technological solutions and power imbalances over regulatory decisions. Additionally, the study identifies three main inhibitors of accelerated system reconfigurations: insufficient involvement of key actors, declining commitment to reorientation activities by incumbents, and market competition that impedes the swift diffusion of low-carbon innovation. For policymakers, the paper's findings highlight the need to move beyond single-system-focused policy instruments towards multi-system transition governance approaches that can foster and govern interaction patterns among formerly independent systems essential for accelerated net-zero transitions.

Paper III explores the *decline and resistance* in the European Heavy-duty vehicle (HDV) sector by investigating the relationship between the decline of carbon-intensive technologies and the diffusion of low-carbon innovations. The paper uses path constitution theory to examine the timing, sequencing and interactions of innovation and decline through a thirty-year longitudinal case study of the sector. The main findings of the study reveal that once a threshold of path destabilisation is reached, innovation and decline become mutually reinforcing, creating feedback loops that accelerate the net-zero transition. The analysis shows that as battery-electric truck (BET) technology advanced, the reinforcing mechanisms for ICE technologies, such as economies of scale and network effects, began to weaken. Conversely, new reinforcing mechanisms for BETs emerged, such as improved infrastructure, increased market acceptance, and regulatory support. This created a self-reinforcing cycle where the decline of ICE technologies accelerated the adoption of BETs, and the growth of BETs further undermined the viability of ICE technologies. The interplay between decline and innovation thus becomes a critical driver for the industry's transition towards net-zero emissions. Overall, the transition process in the HVD sector follows that of a punctuated equilibrium, where long periods of stability are interrupted by rapid changes in technology and market structure. The study additionally conceptualises seven specific conditions that facilitated this punctuated equilibrium in the studied case and provides concrete policy recommendations on how to leverage these conditions.

Paper IV addresses the challenge of *changing demand patterns* by problematising how the current planning process for electrification–predict and provide (P&P)–by merely forecasting future transport volumes and constructing the necessary charging infrastructure, risks to reduce the transformative potential of the net-zero transition of electrified heavy-duty freight transport to a simple technological swap with limited emission reduction capacity. In the paper, I argue that electrification of the freight vehicle stock alone is insufficient to achieve net-zero emissions because this would not address the fundamental drivers of transport demand, such as ever-increasing freight volumes and inefficient logistics and other intrinsic problems such as emissions from road abrasion. As an alternative to P&P, I develop a sufficiency-oriented planning approach that focuses on reducing overall transport demand and optimising logistics to align with ecological constraints and societal needs. This approach involves questioning and reducing the necessity for freight transport by localising production and distribution, encouraging local consumption, and promoting efficient logistics practices to decrease overall transport volumes. It emphasises the efficient use of existing infrastructure and the integration of new developments with localised renewable energy sources, promoting the strategic positioning of charging points and infrastructure enhancements that align with the prevailing architecture of the energy system. Furthermore, it calls for a comprehensive assessment of the environmental impact across the entire lifecycle of freight vehicles, including ethical sourcing of critical raw materials, sustainable manufacturing practices, and effective recycling and disposal methods to minimise the environmental footprint. Implementing circular economy principles is also vital, involving strategies such as retrofitting existing vehicles, adopting modular designs for easy upgrading and recycling, and optimising logistics to ensure maximum efficiency and resource use. By incorporating these different pillars, sufficiency-oriented planning offers a more holistic approach to electrifying heavy-duty road freight transport, which could address both the technological and systemic challenges to achieve meaningful emissions reductions and support the broader decarbonisation goals of the EU.

Lastly, **Paper V** investigates the *governance challenges* that arise from the neo-liberal governance principle of regulating and guiding technological development and innovation in a technology-neutral way. The study is based on a national survey of Swedish transport operations managers of haulier companies and examines the impact of their perceptions of the prevailing policy mix on the willingness to adopt ZEVs. More specifically, it explores how perceived technology neutrality of the prevailing policy mix, anticipated regret over adopting the wrong ZEV technology prematurely, and perceived rate of technological change influence managers' decisions to delay ZEV adoption. Key results of this study include a strong correlation between managers' perceptions of a technology-neutral policy mix and their decision to delay ZEV adoption: Managers who perceived the policy mix as highly technology-neutral expressed more anticipated regret about premature adoption, influencing the decision to postpone ZEV adoption. The findings of the paper further confirm that anticipated regret mediates the relationship between perceived technology neutrality and adoption delay in the sense that higher anticipated regret was associated with a greater likelihood of delaying ZEV adoption. Additionally, managers' perceptions of rapid technological change further increased anticipated regret, amplifying the delay in ZEV adoption. Nevertheless, positive attitudes towards ZEV characteristics and prior organisational experience with ZEVs were found to lower anticipated regret, thus reducing the likelihood of adoption delay. Overall, the results of this paper highlight that while technology-neutral policies aim to foster a level playing field for different technologies that could enable decarbonisation, they may inadvertently slow down the adoption of low-carbon innovation due to increased uncertainty and anticipated regret among decision-makers. The paper, thus, calls for a re-evaluation of using technology neutrality as a design principle for net-zero policy mixes to avoid delaying urgently needed emission reductions.

Table 1 gives an overview of the publication statuses and outlines the author's contributions to each paper. Throughout my PhD process, the development of these papers has significantly benefitted from the input I received on earlier versions of their manuscripts that were presented at the annual "International Sustainability Transition Conferences," biannual Conferences of the "Swedish Research School of Management and IT," and two participations in the "Exploring multi-system phenomena in net-zero transitions" workshops.

Table 1 Overview of papers, publication statuses and author contributions.

Paper no	Title of the paper	Author(s)	Publication status	Author contribution
I	Reinterpreting circularity? Understanding the contested directionalities of the Swedish heavy-duty vehicle sector towards the Circular Economy	Sophie-Marie Ertelt	Under review as part of the book *Sustainability transitions: multi-system dynamics and industrial transformation*	Sole authorship
II	Home field advantage: Examining incumbency reorientation dynamics in low-carbon transitions	Co-authored with Johan Kask	Published in *Environmental Innovation and Societal Transitions*	**Sophie-Marie** Ertelt was responsible for the study design, research instrument development, data collection, data analysis, data visualization and the writing of the original as well as the revised manuscripts. **Johan Kask** provided substantial input for the development of the conceptual framework as well as the writing of the original manuscript and its several rounds of revision.
III	From carbon lock-in to climate neutrality? Exploring the decline-innovation nexus in the net-zero transition of the EU heavy-duty vehicle sector	Co-authored with Dermot Breslin and Johan Kask	In preparation for submission	**Sophie-Marie** Ertelt was responsible for the study design, research instrument development, data collection, data analysis and writing of the original manuscript. **Dermot Breslin** and **Johan Kask** provided substantial input for the development of the conceptual framework as well as the writing of the original manuscript.
IV	Beyond predict and provide: Embracing sufficiency synergies in road freight	Sophie-Marie Ertelt	Published in *Energy Research & Social Science*	Sole authorship

	electrification across the European Union			
V	From policy mix to pavement: Exploring actor internal factors in zero-emission truck adoption	Co-authored with Zeinab Rezvani, Vojtech Klezl and Johan Kask	Published in the *Journal of Cleaner Production*	**Sophie-Marie Ertelt** was responsible for the study design, research instrument development, data collection, data analysis, data visualization and the writing of the original as well as the revised manuscript. **Zeinab Rezvani** and **Vojtech Klezl** provided substantial input during the development of the research instrument, data analysis and writing, as well as revision of the manuscript. **Johan Kask** provided substantial input during the revision of the manuscript.

1.7 Outline of the thesis

The rest of this thesis is structured as follows: After this introduction (**Chapter 1**), **Chapter 2** provides the theoretical background to my research by outlining the conceptual building blocks of a socio-technical perspective on net-zero transitions and proposing how this perspective`s explanatory power of net-zero transition dynamics can be further refined with insights from institutional and path constitution theory as well as behavioural and psychological organisational research. **Chapter 3** outlines my methodological approach, including a discussion of this thesis' underlying research paradigm(s) and logical reasoning, as well as a transparent explanation of how the data was collected and analysed. **Chapters 4-8** present the research papers of this compilation thesis. **Chapter 9** introduces three additional transition acceleration challenge types that emerged throughout the research process of this thesis yet were not dedicated a full paper. Finally, **Chapter 10** concludes this thesis by summarising the central theoretical, methodological and empirical contributions of this research, discussing the implications of my findings for managers and policymakers, as well as reflecting on limitations and presenting avenues for future research on net-zero transitions in hard-to-abate industry sectors.

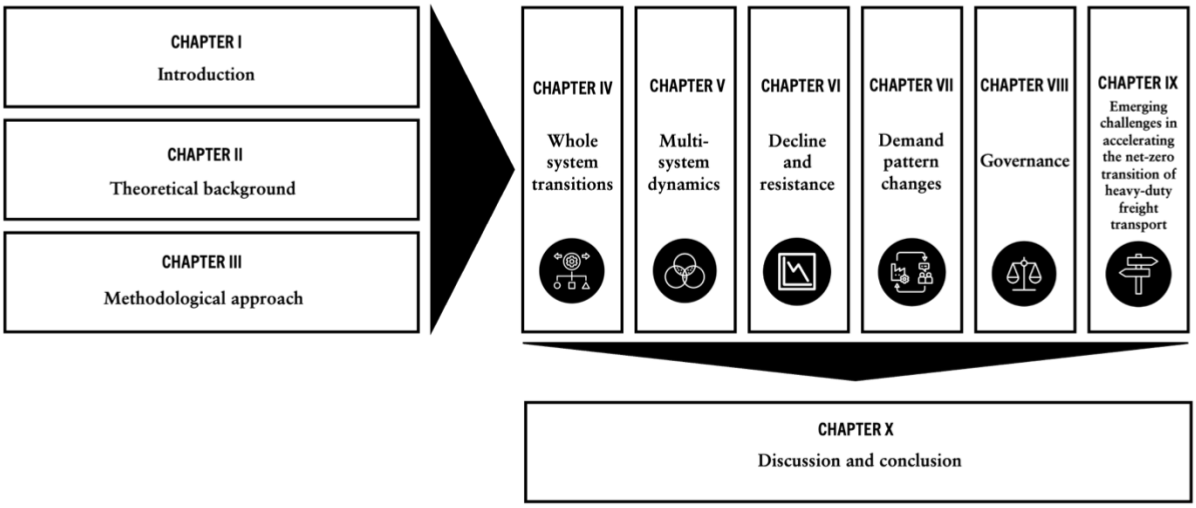

Figure 6 Structure of the thesis.

1.8 A note on terminology

Sustainability. While this thesis is positioned within the research field of sustainability transitions, after some critical reflections on whether or not the empirical cases of this dissertation would constitute a "true" sustainability transition to me as a researcher, I have decided that sustainability in the context of my thesis is not an appropriate terminology. I would argue that the sources of unsustainability (Susur and Karakaya, 2021) of heavy-duty freight transport are currently only addressed superficially and that prevailing transition trajectories have a limited "ability to meet the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, G.H., 1987). While internal ICE-powered vehicles undoubtedly represent a source of CO2 emissions and NOX pollution, the underlying driver that has led to the continuous increase of the negative impacts of road freight transport is the fact that economic growth today is still strongly coupled with transport growth (Chovancová et al., 2023; McKinnon, 2007). Hence, the continuous increase in demand for transport services and the resulting rise of vehicles on the road represents a source of unsustainability that cannot be addressed by drivetrain switch or fuel source substitution. Such a "carbon-tunnel vision" that only focuses on one limited aspect of environmental sustainability, i.e., decarbonisation (Lazarevic and Martin, 2016), is problematic because it fails to acknowledge negative social and environmental implications that may arise from the wide-scale electrification of heavy-duty vehicles. Problem-shifting effects, for example, might occur while mining earth metals required to produce vehicle batteries, including increased local pollution, corruption and child labour (Jannesar Niri et al., 2024; Marín and Goya, 2021). Also, under the current growth prognosis that forecasts an increase in transport demand of up to 50% over the next 15 years, it is questionable whether mere electrification of the European HDV stock will be even enough to reach net-zero targets. Previous studies at a global level indicate this would require a reduction in freight transport demand and entail a shift to less transport-intensive economic growth through different localisation of production (Ghisolfi et al., 2024). However, more holistic approaches to sustainable freight transport that can account for problem-shifting effects and challenge existing growth imperatives are only explicitly explored in Paper IV. Thus, I avoid the term sustainability throughout most of this thesis and have delineated the field of study to which my PhD research contributes to as net-zero transitions.

Low-carbon vs net-zero transition. The attentive reader will notice that throughout the five papers (Chapters 4-8), varying terminologies are utilised to describe the fundamental transformations of current production, distribution and consumption systems required to meet the climate change mitigation targets of the Paris Agreement. This is primarily the case because different publication outlets and reviewers that guided the publication process had divergent opinions about which term is the more appropriate to use in the context of heavy-duty freight decarbonisation. Strictly speaking, low-carbon transitions refer to a reduction of CO2 emissions through social and technological innovation, aiming for a significant but not complete elimination of emissions. Meanwhile, net-zero transitions encompass not only the reduction of CO2 emissions to the lowest possible levels but also include other GHG emissions and mechanisms to offset any remaining emissions, such as CCS or reforestation. Despite their differences, low-carbon and net-zero transitions undoubtedly share a common normative directionality; both focused on mitigating negative climate change impacts and keeping global warming at bay. While I acknowledge the subtitle yet important differences between the two terms, I would argue that only time will be able to tell us whether the current dynamics in the heavy-duty road freight sector will amount to a low-carbon or net-zero transition. Nevertheless, for conceptual coherency, I only refer to net-zero transition throughout the main chapters of this kappa (Chapters 1-3;9;10).

Socio-technical system, subsystem, regime and sector. The application of the system, regime, and sector concepts in the transition literature is diverse and somewhat incoherent (Andersen et al., 2024; Geels and Turnheim, 2022; Markard and Truffer, 2008; Steen and Weaver, 2017). Throughout the five papers, I have undoubtedly struggled to stay clear of such pitfalls, and a keen reader with attention to detail may spot conceptual inconsistencies. Instead of providing a superficial excuse, I see these inconsistencies as indicative of the learning process and development that this academic journey has represented to me. Nevertheless, in an attempt to detangle these different concepts, Chapters 2, 9, and 10 make a clear conceptual differentiation between (1) a socio-technical system which refers to the interconnected configurations of technologies, actors, social networks, institutions, and material artefacts which together to (re)produce and maintain specific societal functions (Geels, 2004, 2002); (2) a (socio-technical) regime which encompasses the dominant set of rules norms, and practices that guide and constrain the behaviour of actors within a socio-technical system and thus, contribute to its stability (Geels, 2004; Geels, 2005; Schot and Kanger, 2018); (3) a subsystem refers to a smaller, self-contained unit within a larger socio-technical system that focuses on a specific aspect of a societal function. Sub-systems can operate independently to some extent but are interconnected with other sub-systems within the broader socio-technical system (Geels and Turnheim, 2022). For example, road freight transport can be considered a sub-system, which is part of the larger transport system that also includes private passenger vehicles, rail and air transport, as well as cycling, etc. (Geels et al., 2017); and lastly (4) a sector refers to a broader area of economic activity distinguish by its production, distribution, or consumption of goods or services, and associated technologies, institutions, and actors (Andersen et al., 2024; Mäkitie et al., 2022). A sector can contain multiple socio-technical (sub)systems and regimes, and it is often characterised by distinct input-output relationships with other sectors, market structures, regulatory frameworks, and patterns of innovation.

2. Theoretical background

Overall, this thesis draws on concepts and frameworks from the field of sustainability transition research (Köhler et al., 2019; Loorbach et al., 2017; Markard et al., 2012). This interdisciplinary field mobilises insights from innovation research, environmental studies, and sustainability sciences to study so-called sustainability transitions, "long-term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption" (Markard et al., 2012, p. 956). The principal ambition of transition scholars is to increase the knowledge of the underlying change mechanisms of transitions, investigate ways to anticipate and adapt to potentially undesirable transitions, such as ecosystem collapse in oceans due to ocean acidification, and explore barriers and possibilities to accelerate the ongoing transitions (Köhler et al., 2019; Loorbach et al., 2017). Hence, most key strands of transition studies have in common that their primary aim is to examine the interplay between stability and change on a systemic level to better understand the resulting progress or stagnation of transition dynamics (Loorbach et al., 2017; Silva and Stocker, 2018).

In addition to sustainability transition research, the work presented in this thesis further integrates ideas and concepts from organisational studies to investigate transition acceleration challenges of heavy-duty road freight. Organisational studies (sometimes also referred to as organisation studies or organisation science) is a multidisciplinary field that broadly focuses on the structures, processes, and behaviours within and across organisations and has, in the past, generated valuable insights into how these entities function and adapt in response to both internal and external pressures. Insights from this field are crucial for transition research as they help to unpack the complexities of organisational change, particularly how firms navigate the challenges posed by net-zero transitions (Magnusson and Werner, 2023; van Mossel et al., 2018). Specifically, this thesis draws on three key strands of work within organisational studies: organisational institutionalism, path constitution theories, and behavioural and psychological organisational research. Organisational institutionalism (Fligstein and McAdam, 2015; Hoffman, 1999; Scott, 2001; Wooten and Hoffman, 2016) provides a robust theoretical underpinning to increase our conceptual understanding of endogenous regime change and meta-rule diffusion. Its application in this thesis focuses on how institutional logics, norms, and practices within established regimes influence the dynamics of change from within. Thus aiding an analysis of how entrenched socio-technical configurations either resist or adapt to net-zero initiatives, highlighting the internal processes, conflicts and tensions that drive or hinder net-zero transitions. Path constitution theories (Stache and Sydow, 2023; Sydow et al., 2009, 2012a, 2021) offer insights into how historical decisions and established routines create self-reinforcing dynamics that can lead to carbon lock-in and path dependency, making it difficult for organisations to pivot toward new low-carbon alternatives. These theories also explore how new paths can emerge and old ones can be destabilised, offering insights into the complex processes and interrelationships of continuity, decline and change within industries. Finally, behavioural and psychological organisational research (Ajzen, 1991; Cyert and March 2006; Rogers, 2003; Simon, 1947) focuses on the individual level, examining how cognitive biases, emotions, and social dynamics influence decision-making within firms. This research highlights the importance of considering individual actor-internal factors of decision-makers in organisations, such as perceptions and emotions, in influencing innovation adoption, providing a deeper understanding of the human elements that drive or hinder the accelerated market adoption of low-carbon alternatives. The application of these perspectives and how they extend existing understandings of net-zero transition dynamics is explained in depth in the following sub-chapters.

2.1 A socio-technical reconfiguration perspective on net-zero transitions

The work presented in this thesis builds on socio-technical reconfiguration approaches (Geels, 2018a; Geels and Turnheim, 2022; McMeekin et al., 2019)–an analytical perspective that focuses on the possibilities of endogenous change processes in existing socio-technical systems–to analyse and understand net-zero transition dynamics in hard-to-abate industry sectors. Albeit already acknowledged in seminal works as a potential pathway of how a transition may unfold (Geels and Schot, 2007), the dynamics of how the architecture of an existing socio-technical system may be reconfigured from within through the reorientation of incumbent actors toward radical innovations has only gained analytical interest more recently in the context of investigating low-carbon and net-zero transitions (Geels, 2018a, 2018b; Geels and Turnheim, 2022; Turnheim et al., 2018). The main strength of a system reconfiguration perspective is that it allows one to move beyond more widely established perspectives on how a transition may unfold, i.e., a singular radical innovation emerges outside of and overthrows an existing socio-technical system and its change-resistant incumbents (Turnheim and Sovacool, 2020) towards understanding the opportunities for renewal of and changes to prevailing socio-technical configurations (Geels, 2018b; McMeekin et al., 2019). Table x summarises the alternative perspectives on different transition dynamics that this thesis is grounded in and contrasts them with more established perspectives.

Table 2 Different perspectives on transition dynamics. Expanded based on Turnheim and Sovacool, 2020.

Aspect	Prevailing perspective[4]	Alternative perspective
Change and stability	Emergent change given inherent stability	Stability and continuity in spite of change efforts
New and old	Novel socio-technical configurations emerge as alternative to existing configurations	Existing socio-technical configurations also have potential for renewal
External and internal	Radical change comes from the outside	Radical change may also come from the inside
Bottom-up and top-down	Alternatives emerge from below through gradual dynamics	Strategically guided and directed search paths are also possible
Incremental and radical	Radical innovations are the primary drivers of transitions	Incremental innovations within existing systems can also contribute significantly to transitions
Homogeneous and heterogeneous	Transitions are driven by homogeneous actor networks with aligned interests	Diverse and sometimes conflicting actor groups can drive different aspects of a transition
Static and dynamic	Existing regimes are static and require external disruption for change	Existing regimes are semi-coherent and contain internal dynamics that can lead to change
Path pependency and path creation	Prevailing socio-technical configurations are constrained by existing paths and historical legacies	New paths can be created through strategic actions and innovative practices that break away from historical dependencies and lock-ins
Alignment and tensions	After an innovation breakthrough, regimes realign and eventually stabilise	Transition processes can result in regime tensions that create conflicts and contestations, often leading to proolonged peroids of instability and competing pathways
Incumbent actor agency	Incumbent actors resist change and maintain the status quo	Incumbent actors can adapt their strategies and drive change through reorientation
Single- and multi-system	Socio-technical systems change independently and in isolation	Inter-system interactions and cross-system dependencies shape transition trajectories

[4]Please note that the content under thus column is highly stylised. Many scholars in recent years have called for and contributed to a much more nuanced perspective on transition dynamics.

This alternative perspective outlined in Table 2 is particularly useful in the empirical context of hard-to-abate industry sectors in which radical innovations emerging from outside existing systems would face significant breakthrough barriers such as high capital costs, long-lived assets, and complex stakeholder networks dominated by a handful of powerful firms. Instead, previous research has already highlighted how incumbent actors play a significant role in developing decarbonisation strategies, pioneering R&D efforts for low-carbon alternatives and investing in complementary infrastructure and technologies, thus, are actively reconfiguring sectors such as maritime shipping, aviation and heavy-duty transport from within (Bergek et al., 2023; Christley et al., 2024; Urban et al., 2024; Werner et al., 2022).

2.2 Endogenous regime change processes

Central to system reconfigurations are regime-level processes (Geels, 2018b). In this thesis, the socio-technical regime (hereafter regime) is understood as "the deep structure that accounts for the stability of an existing socio-technical system. It refers to the semi-coherent set of rules that orient and coordinate the activities of the social groups that reproduce the various elements of socio-technical systems" (Geels, 2011, p. 5). Two specific aspects of this definition warrant further unpacking: (1) The concept of *regime rules* refers to "humanly devised constraints that structure human action, leading to regular patterns of practice" (Schot and Kanger, 2018, p. 1053 drawing on North, 1990) that drive the evolution and potential transformation of socio-technical systems over time. Rules[5], however, are not autonomous entities but rather are bundled up in rule-sets which evolve along five distinct regime dimensions, namely technology, science, policy, markets and user practices as well as socio-cultural (Geels, 2004; Ghosh and Schot, 2019; Smith and Raven, 2012).

Figure 7 illustrates the five different regime dimensions and their corresponding rule-sets. For the technology dimension, examples of such rules include technical standards, product specifications, and functional requirements. Together, these form a rule-set that guides technological advancements and product development, such as the expected capital returns rate influencing R&D investments. The science dimension encompasses rules related to formal research ethics, professional boundaries, and established research paradigms. Together, this rule-set ensures rigorous knowledge production and dissemination, such as review procedures for publication and academic norms. Within the policy dimension, rules include administrative regulations, formal technology regulations, and subsidy programs. These shape policy effectiveness and goals, such as interaction patterns between industry and government and institutional commitments. Examples of rules of the markets and user

[5]The seminal work of Geels (2004) makes a differentiation between regulative rules (e.g., laws, regulations and standards), cognitive rules (e.g., belief systems, guiding principles, and heuristics) and normative rules (e.g., role relationships, values and behavioural norms) for simplicity such an explicit differentiation is not adopted throughout this thesis.

practice dimension that together shape market dynamics and user behaviour include market construction laws, property rights, and competition rules. Lastly, rules belonging to the socio-cultural dimension structure information spread and cultural symbol production, thus influencing technology adoption and use, including cultural values attached to said technology.

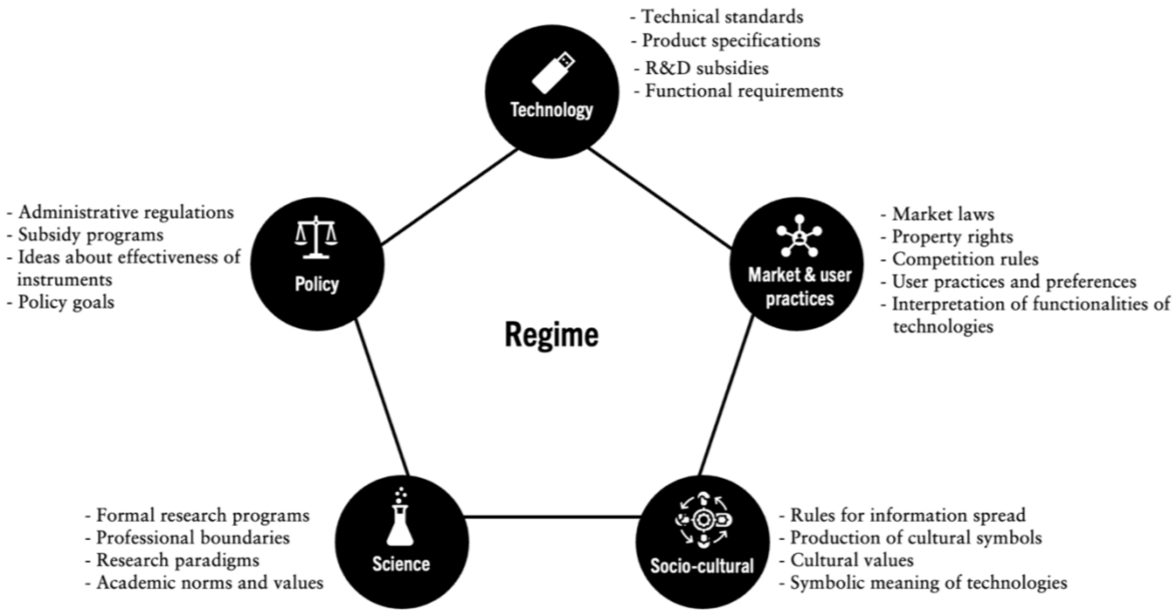

Figure 7 The five regime dimensions and their corresponding rule-sets are meta-coordinated through the regime. Substantially adapted from Geels (2004).

These different rule-sets of the five dimensions are interconnected and interrelated in the sense that changes in one dimension can influence and shape the rules in the others (Geels, 2004; Ghosh and Schot, 2019). For example, technological advancements can lead to new research paradigms (science dimension), which may prompt new regulations (policy dimension). These regulations can alter cultural perceptions (socio-cultural dimension) and reshape market dynamics and user practices. This alignment process of the different rule-sets that govern the different dimensions is meta-coordinated through the regime to ensure that the various rule-sets reinforce each other and work together cohesively, thereby facilitating the dynamically stable evolution of the prevailing socio-technical configurations (Geels, 2004; Ghosh and Schot, 2019). Dynamically stable in this context refers to a system's ability to reproduce its overall structure and functionality over time while allowing for gradual modifications in response to internal and external pressures (Geels, 2018a; Geels and Kemp, 2007; Geels and Schot, 2007). Thus, throughout the work presented in this thesis the regime is considered the primary source of stability of a socio-technical system while at the same time also providing opportunities for system reconfigurations. It further follows a rule-based logic of change, which assumes that system reconfigurations are driven by the emergence of new rules that, in interaction with actors and technologies which adapt to and reinforce these new rules, lead to changes in the prevailing socio-technical configurations.

Nonetheless, the rule-sets of the five regime dimensions are never fully aligned, and therefore, regimes are characterised by (2) *semi-coherence*. Semi-coherence implies that while there is a general alignment and coordination among the rule-sets across different dimensions, the complete consensus among actors from varying backgrounds and belief systems that enact these rule-sets is unlikely, and thus there are also incoherencies and mismatches between different rules (Fuenfschilling and Truffer, 2014; Geels, 2002). However, this semi-coherent nature of the regime also allows for the potential of regime tensions, as the partial misalignment can lead to conflicts and frictions between different actors and dimensions (Geels, 2004). Based on the above, one of the core assumptions made in this thesis is that during periods of net-zero system reconfigurations, regime tensions are more pronounced because the integration of low-carbon innovations requires continuous adjustments across all dimensions yet might initially be characterised by misalignment; such as when technological advancements outpace regulatory adaptations or when market demands clash with socio-cultural values. Additionally, regime tensions influence the speed of net-zero system reconfigurations as they can accelerate change by exposing critical areas of misalignment, thereby creating pressure for rule-set adaptations to address said misalignment to ensure the system's functionality and stability. At the same time, these tensions can slow down the pace of reconfiguration processes if not resolved, as they may lead to conflicts and prolonged negotiations among actor groups with differing interests, complicating the emergence of a new stable configuration. Consequently, I argue that regime tensions can be considered a concept of importance that deserves analytical attention to understand net-zero transition dynamics better. However, the previous conceptualisation of regimes "tend to leave out tensions and misalignments" (Jørgensen, 2012, p. 999), and internal regime dynamics more broadly have been given less scholarly attention thus, remain somewhat black-boxed and under-theorised (Fuenfschilling and Truffer, 2014; Runhaar et al., 2020; Steen and Weaver, 2017).

2.2.1 Regime tensions through the lens of organisational institutionalism

To open up this black box and enable a deeper conceptual understanding of the underlying mechanisms that contribute to the key characteristics of the regime, such as its dynamic stability, semi-coherence and internal tensions, the work presented in this thesis draws on several ideas and concepts from institutional theory. Institutional theory (Powell and DiMaggio, 1991; Scott, 2001; Thornton et al., 2012) as such can be considered one of the foundational theoretical strands upon which popular transition frameworks have been developed (Geels, 2020, 2010) and have been utilised by several scholars to enable the analysis of endogenous regime change (e.g., see Hacker and Binz, 2021; Fuenfschilling and Truffer, 2014; Friedrich et al., 2023). However, compared to previous contributions that draw more explicitly on neo-institutional theory, the conceptualisations of stability and change within prevailing regimes presented in this sub-chapter, in addition, build on organisational institutionalism.

Organisational institutionalism also originates from the broader field of institutional theory but focuses on how institutions– regulative, normative and cultural-cognitive structures that provide collective meaning to social behaviour (Scott, 2001)–influence organisations[6] and how, in turn, organisations respond to and enact these influences (Greenwood et al., 2008). Organisational institutionalism particularly emphasises the role of *organisational fields*, *field logics* and *inter-organisational relations* in understanding organisational behaviour and its influence on the evolution and transformation of industries (Beckert, 2010; Wooten and Hoffman, 2016). In the context of this thesis, organisational fields are defined as relational spaces in which sets of interacting actors, such as economic organisations, government entities, and interest groups, engage in interrelated activities within a particular industry sector (Fligstein and McAdam, 2015; Hoffman, 1999; Scott, 2001). The behaviour and interactions of actors within a specific organisational field are guided by field logics[7] understood here as a combination of technologies, shared beliefs, practices, rules, and norms (Thornton et al., 2012). Despite the presence of these field logics, the structure of organisational fields, however, is not static but inherently dynamic due to the continuous interactions and strategic jockeying for advantageous positions (in terms of economic, political or socio-cultural power) of their actors (Hoffman, 1999; Wooten and Hoffman, 2016). Thus, a "constant low-level contention and incremental change are the norm in fields" (Fligstein and McAdam, 2015, p. 3) driven by actors that constantly negotiate and reinterpret field logics to address emerging opportunities and challenges. However, fixed regulative frameworks (Fligstein, 2001), institutionalised norms, technological stability (Scott, 2008), as well as interdependence and cohesion among field actors (Davis et al., 2005) nevertheless provide sources of relative stability for organisational fields.

More significant field restructuring processes, on the other hand, are the result of the creation of new field rules in response to changing field conditions (e.g., the introduction of new environmental laws or technological advancements) (Brint and Karabel, 1991) or the exit/entry of actor(s) that causes changes in existing interaction patterns (Barnett and Carroll, 1993; Hoffman, 1999; Scott, 2000). Reconfiguration processes and the resulting new field structure, nevertheless, are only accepted and recognised as appropriate by the actors within a field if novel field logics become stabilised, e.g., in the form of new shared technological standards (van Wijk et al., 2013) or legal frameworks (Reusswig et al., 2018).

[6]Organisations here refers to all entities (i.e., economic and none-economic) that have been created by individuals to support the collaborative pursuit of specified goals and that operate within a specific set of rules, norms, and beliefs that significantly influence their practices, and behaviours (Scott, 2008).

[7]The terms field logics and field rules are used synonymously throughout this chapter.

However, competing ideas, conflict and contestation among field actors about, for example, specific visions of the future of an industry and competing technological preferences (Schmid et al., 2017) represent challenges to such stabilisation and may significantly delay the emergence of a reconfigured field (Kungl and Hess, 2021).

Applying the above to the regime concept, I propose that each regime dimension can be conceptualised as its own organisational field. This means treating the technology, science, policy, markets and user practices, as well as socio-cultural dimensions, as distinct but interconnected arenas, each with its own (potentially varying) set of actors, interactions, and prevailing field rules. By disaggregating the regime into multiple organisational fields, it becomes possible to analytically investigate the semi-coherence that characterises regimes, where different regime fields might evolve at different paces or in different directions, creating internal tensions and broader opportunities for change. This conceptualisation, thus, brings the inherent tensions and conflicts within and between regime fields to the foreground by enabling a detailed examination of how specific changes in one field, such as the emergence of an innovation in the technology field, can create tensions by causing a misalignment with prevailing regulatory frameworks in the policy field, market readiness in the economic field, or social acceptance in the socio-cultural field. Moreover, understanding regimes composed of multiple organisational fields allows for an easier analysis of different actors' interactions, positions and strategies within each field. Therefore, this enables a better understanding of the multi-actor interactions within and across fields that collectively influence a system's overall evolution and reconfiguration. Overall, I would argue that this more granular conceptualisation of the internal works of the regime aligns more closely with the notion that regimes are not monolithic (Stirling, 2019) but are composed of various interacting and continuously evolving elements. It thus ultimately captures the multi-dimensional and often contentious processes that underly endogenous regime change in more depth and, with that, enhances both theoretical and practical understanding of how the dynamic evolution of these different regime fields contribute to broader system reconfigurations.

2.2.2 From regime rules to meta-rules

Under certain conditions, regime rules within a single socio-technical system may cross system boundaries and influence the evolution of multiple socio-technical systems in a particular direction. As specific regime rules demonstrate success in their respective socio-technical systems, these rules start to travel beyond their original context and diffuse across multiple systems through the processes of replication and adaptation. As these rules spread, they begin to align with prevailing regime rules in other systems, creating a broader pattern of adoption. This alignment is facilitated, i.a., by actors who advocate for the new regime rules, demonstrate their advantages and integrate them into existing regimes. Over time, these rules become stabilised, meaning they are embedded into the policies, standards, and societal norms of multiple systems, turning them into *meta-rules*– overarching principles that guide the development and coordination of various socio-technical systems. An example of such a meta-rule is the use of fossil fuels. Initially, a regime rule within the energy sector, the use of fossil fuels focused on providing a reliable and abundant energy source. As its energy density and transportability benefits became evident, other systems, such as transportation and manufacturing, adopted the principles of using fossil fuels, transforming it into a meta-rule that guided industrial practices across multiple systems.

However, the concept of meta-rules is not only helpful in understanding the historical developments that have contributed to today's environmental degradation and climate crisis but also has high relevancy in the context of researching net-zero transitions. New meta-rules such as electrify everything (Barnard, 2023) and the circular economy (Kern et al., 2020) are emerging in response to deal with these problems and have the potential to alter the directionality of various socio-technical systems towards low-carbon and resource-efficient practices. Nonetheless, when it comes to the process of how these emerging meta-rules might diffuse–understood here as the process of interpretation, prioritisation and implementation across multiple systems–current theorisations remain somewhat underdeveloped[8]. Thus, limiting the analytical ability of transition researchers to thoroughly investigate how emerging meta-rules are adapted and adopted across various socio-technical systems and the conflicts and tensions that might arise during this process.

2.2.3 An organisational institutionalism perspective on meta-rule diffusion

In response to the above and building on the previous conceptual propositions from 2.2.1, this sub-chapter introduces several additional ideas from organisational institutionalism to develop a more refined theorisation of how meta-rules diffuse. Key concepts relevant to this endeavour are *compatibility* and *interpretive flexibility* of meta-rules, *interstitial issue fields*, *field multiplicity* and *adaptive tensions*. I propose that actors within the organisational fields of a prevailing regime reinterpret the meta-rules through the lens of their field's existing rules. Thus, whether or not an emerging meta-rule diffuses within a regime field and the speed at which it diffuses depends on its degree of compatibility, (Besharov and Smith, 2014), understood here as the extent to which a meta-rule coincides with, supports, or contradicts existing field rules. Highly compatible meta-rules are diffused quickly, while less compatible ones might remain contested or are not diffuse at all, therefore providing a conceptual explanation of why the scope and speed of meta-rule diffusion among multiple systems may vary. Additionally, building on the concept of interpretive flexibility (Greenwood et al., 2011) used in this context to describe the extent to which a meta-rule is very specific or allows for more open and flexible interpretations further allows to

[8]For more elaborated criticisms please refer to Paper II.

conceptualise the possibility of varying interpretations and system-specific adaptions of a metal-rule to occur across multiple systems.

As these meta-rules start to cross system boundaries and increasing interactions to align meta-rules across multiple systems can be observed, this gives rise to the formation of interstitial issue fields (Rao et al., 2000; Zietsma et al., 2017) between systems. Essentially, these interstitial issue fields are arenas in which actors from multiple systems and with different interpretations and prioritisations of an emerging meta-rule set interact to coordinate and negotiate their actions to solve a common societal problem (Furnari, 2016; Rao et al., 2000), such as the decarbonisation of a whole sector. Given the presence of diverse and potentially conflicting interpretations of meta-rules within and across different systems, these interstitial issue fields are characterised by field multiplicity. This concept is built on previous contributions on institutional pluralism (Greenwood et al., 2010; Zietsma et al., 2017). It is used in the context of this work to describe a state where multiple interpretations and applications of meta-rules coexist and potentially conflict within an interstitial issue field. This prompts actors to negotiate over viable meta-rule interpretations, leading to adaptive tensions between systems as actors strive for coordination and alignment. Similarly to the concept of regime tension[9] introduced earlier, such adaptive tensions offer opportunities to foster innovation (Dalpiaz et al., 2016; Fehrer and Wieland, 2021) . Still, they may also slow down the diffusion of meta-rules as they can cause fragmentation and complexity (Greenwood et al., 2011) that can hinder the stabilisation of an overarching meta-rule set that can guide the evolution of multiple systems. In conclusion, I would argue that this more nuanced theorisation of meta-rule diffusion is analytically helpful because it allows for an empirical investigation of the potentially varying speeds and scopes of meta-rule diffusion and allows us to move beyond a narrow focus of alignment to investigate tensions that might impact the overall process of meta-rule stabilisation.

2.3 Incumbent actor reorientations

A second crucial component to enable system reconfigurations are incumbent actor reorientations, understood throughout this thesis as a process during which established actors within existing systems shift their strategies, resources, and political support from stabilising carbon-intensive socio-technical configurations towards low-carbon innovation (Geels, 2021; Geels and Turnheim, 2022; Kump, 2023). A variety of different definitions of what constitutes an incumbent has been proposed in recent years, focusing on aspects such as company size, economic and political power, established operational practices, abilities

[9]Regime tensions arise within a single socio-technical system when there is a mismatch and a lack of coherent alignment between rules across its different regime dimensions (Geels, 2004; Ghosh and Schot, 2019). Adaptive tensions, on the other hand, arise between multiple socio-technical systems when actors from different regime fields interact and negotiate over the interpretation and implementation of meta-rules, highlighting conflicts and compromises that arise from differing field rules and priorities across these systems.

to mobilise resources, and a vested interest in preserving the status quo (Galeano Galvan et al., 2020; Johnstone et al., 2017; Magnusson and Werner, 2023; Steen and Weaver, 2017) however the term is still prone to definitional ambiguity (Kungl, 2024). In line with previous calls for a more heterogeneous view of incumbents (Turnheim and Sovacool, 2020), this thesis follows Smith et al. (2005) and defines incumbents as all actors who are members of an existing socio-technical system. This membership is delineated by the degree to which an actor participates in activities that reproduce a system's various prevailing socio-technical elements (Smith et al. 2005). This definition allows me to move beyond a narrow analytical scope on large established companies (Steen and Weaver, 2017) by also considering actors such as universities, end users, and governing entities as incumbents who, through their actions, contribute to the stability of prevailing regimes and, thus, can influence the speed and scope of system reconfigurations. It also implies that socio-technical stability is not the result of individual actors' incumbency–established dominant position and maintained economic, political and social power–but the product of relational processes among many actors and prevailing socio-technical elements (Darnhofer et al., 2019; Stirling, 2019). Therefore, actor reorientation is also best understood not in isolation but as a process embedded within a network of interactions and dependencies in regime fields, where the collective actions of diverse actors, including both core and peripheral actors, contribute to system reconfigurations. Thus, it emphasises that system reconfigurations do not just require the reorientation of a handful of dominant cooperate firms but rather the collective reorientation efforts of a wide array of different actors.

Early contributions to the transition literature have frequently reported that incumbent actors may resist change, mobilise their power to defend prevailing socio-technical configurations or slow down transition dynamics (Bergek et al., 2013; Dijk et al., 2016; Geels, 2014; Penna and Geels, 2015; Sovacool et al., 2017) However, faced with increasing societal and political pressure to address their negative contributions to climate change, a purely resistive stance is becoming less viable (Markard, 2018; Roberts et al., 2018; Turnheim and Sovacool, 2020) and many recent contributions have highlighted that incumbent actors also possess the ability to experiment with low-carbon alternatives, innovate their business models to gain a competitive advantage, interact with niche innovations and actors or lobby in favour of environmental regulations or (Apajalahti et al., 2018; Berggren et al., 2015; Ciulli and Kolk, 2019; Nurdiawati and Urban, 2022; Steen and Weaver, 2017). Incumbent actor behaviour is thus best understood as a scale (Magnusson and Werner, 2023) rather than a binary distinction, where they can exhibit a range of responses to transition dynamics from resistance to proactive innovating towards net zero.

Yet, while it becomes clear based on the preceding that incumbent actors have the ability to reorientate towards low-carbon alternatives, *how* this reorientation of incumbents occurs is, according to Kump, (2023, p. 1), "among the crucial under-researched topics in transition studies". In addition to analysing such reorientation empirically, the work presented in this thesis also builds on path constitution theory (Stache and Sydow, 2023; Sydow et al., 2009, 2012a, 2020) to put forward a theorisation of the underlying processes of how incumbent actors might overcome path dependencies to escape prevailing carbon lock-ins and reorientate their activities to contribute to achieving net-zero gaols.

2.3.1 A path constitution perspective on incumbency reorientations

Path constitution theory, originating from the broader theory of path dependence, focuses primarily on unpacking the mechanisms through which organisations, institutions, technologies and whole industries sectors become locked into specific paths[10], making these paths increasingly difficult to alter over time (Schreyögg and Sydow, 2010; Sydow et al., 2020). It further highlights that lock-in occurs as a result of self-reinforcing mechanisms, where initial decisions or events lead to positive feedback loops, such as increasing returns, coordination benefits, and learning effects, that gradually narrow the scope of future options and increase the inertia against change (Apajalahti and Kungl, 2022; Dobusch and Schüßler, 2013; Sydow et al., 2009). As these processes unfold, industries become increasingly committed to a particular trajectory, i.e., path-dependent, even when it may no longer be the most efficient or cost-beneficial option (Breslin, 2024). Nevertheless, even during a lock-in phase, there are opportunities for actors to make on-path changes by altering the underlying processes that reinforce the status quo: prevailing paths can be both expanded through incremental innovation and strategically extended in response to new market opportunities (Schreyögg et al., 2011; Sydow et al., 2012b). Path constitution theory, however, also acknowledges that actors can engage in path-breaking activities, especially when triggers, such as technological shifts, regulatory changes, or societal pressures, destabilise prevailing paths (Garud et al., 2010; Garud and Karnoe, 2001). These triggers, weaken the existing self-reinforcing mechanisms and allow actors to mindfully deviate from established paths and dissembed themselves from the structures that constrain their actions (Simmie, 2014; Stache and Sydow, 2023).

To enable a better understanding of how path dependencies are maintained and how new paths can be created through the reorientation of incumbent actors, I propose an alternative way to conceptualise the structure of socio-technical systems. Instead of a heterarchical or networked structure as illustrated in Figure 2, a structure initially put forward in Geels (2005) and reproduced in hundreds of publications; I suggest that in the

[10]In this thesis, the terms path and socio-technical trajectory are used synonymously to refer to the processes through which socio-technical elements evolve over time in a certain direction and become entrenched in certain configuration.

context of studying endogenous change, it might be much more helpful to think of the various socio-technical elements, that make up socio-technical systems as *nested and hierarchical*[11] (Baum and Singh, 1994). Under this view, a socio-technical system has three interrelated levels: (1) the organisational level, which contains the individual firms or organisations that operate within a specific system (including company policies, internal and routines practices, management strategies, etc.) (2) A technological level that includes the technologies and complementary infrastructure, and successive incremental innovations that reinforce the adoption and evolution of specific technology in a system. Lastly, (3) the industry level captures a system's broader regulatory frameworks, market structures, and collective norms. Figure 8 illustrates this proposed alternative structure and how the various elements of a socio-technical system may be interconnected.

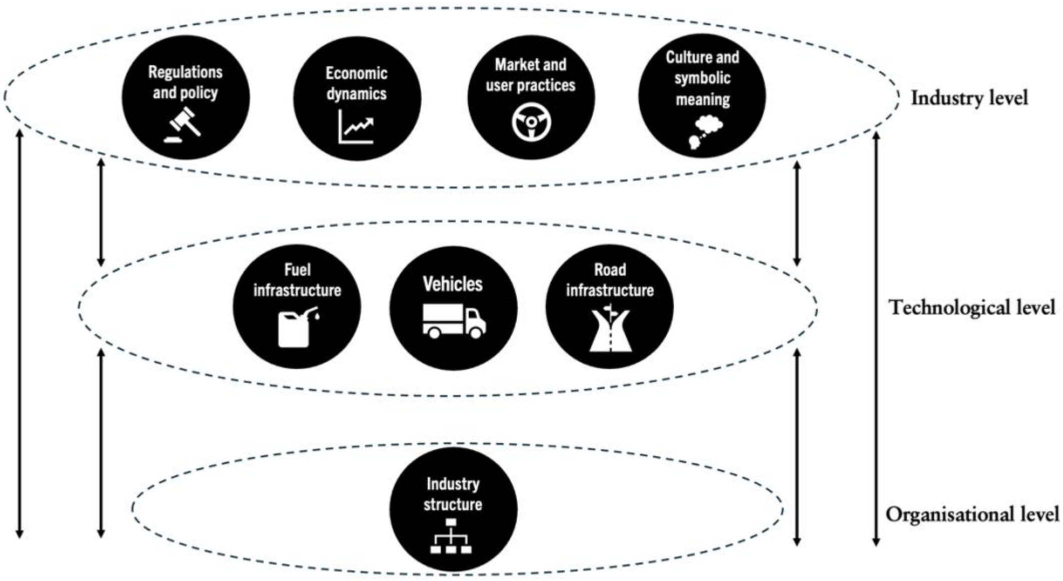

Figure 8 Nested hierarchical structure of different socio-technical elements that comprise the heavy-duty road freight transport system.

This structure provides a more explicit account of how organisations, technologies, and industry dynamics are interconnected and how they influence one another. At the organisational level, the actions taken by firms and other actors, such as adopting or developing new technologies, are influenced by the existing technological standards, prevailing infrastructure and industry norms. However, these organisational actions also have the potential to affect both the technological and industry levels. For example, when a firm develops a new technology, it must operate within the constraints of current regulations and market conditions., however at the same time, successful commercialisation of new technology can lead to changes in these constraints by setting new standards or influencing policy changes, thereby altering the way a system is

[11]While the idea of a nested hierarchy has not been explicitly applied to the structure of socio-technical systems Geels (2005) acknowledges hierarchical nature of regime structures to differentiate between dominant and subaltern regimes.

configured. At the technology level, technological advancements can create new opportunities for firms, but they also introduce new constraints. For example, adopting a new technology might require complementary changes in infrastructure, which can then impact the entire operational rules of a system. Finally, at the industry level, changes, such as new regulations or shifts in consumer demand, can significantly influence the technological developments and organisational strategies within a system. These industry-level changes can cascade down, impacting how technologies evolve, and organisations operate, thereby shaping the overall trajectory of a socio-technical system. The assumptions of actor agency implicit in this alternative view on the structure of socio-technical systems reflect path constitution theory's emphasis on the recursive relationship between structure and agency, borrowed from structuration theory's duality of structure (Giddens, 1984). This duality implies that existing socio-technical configurations shape actors' decision making, yet these actors also have the capacity to reshape these configurations through their actions. Thus, agency and structure are mutually constitutive, with actions at the organisational level potentially triggering incremental or radical reconfigurations across technological and industry levels and vice versa. Conceptualising socio-technical systems as nested and hierarchical therefore allows me, therefore, to better account for how different socio-technical elements of a system interact and how actors within these configurations exercise their agency.

2.3.2 Incumbent actors as users of innovation

As outlined above, an amplitude of previous research has explored the role of incumbent actors in transition dynamics, and this body of work has significantly diversified the view of incumbents in recent years (Kungl, 2024; Werner, 2023); nevertheless, the majority of empirical studies have engaged with this topic from a supply-side technological development perspective (Andersen and Geels, 2023; Geels and Turnheim, 2022) often focusing on the strategies and behaviours of lead firms (Steen and Weaver, 2017). This neglects one crucial role incumbent actors, specifically operational firms, play across different systems and diverse industry sectors: the role of *users and adopters of innovation* (Hargreaves et al., 2013; Meelen and Schwanen, 2023). Once low-carbon alternatives have been commercialised through extensive R&D, experimenting, and pilot projects in the emergence phase, their success, i.e., whether or not their diffusion accelerates, heavily depends on said low-carbon alternatives gaining significant market share (Markard and Rosenbloom, 2022). However, in hard-to-abate industry sectors such as heavy-duty road freight transport, the market is not made up of more classic end-consumers or households but approximately 1.3 million companies across the European Union (Statista, 2023). These companies are deeply entrenched in the existing socio-technical configurations and contribute through their operational routines and investment cycles to the prevailing carbon lock-in and overall stability of the system, portraying them as a potential barrier for system reconfigurations. I would, thus, argue that the relevance of understanding incumbent firms' decision-making processes for adopting low-carbon technologies extends beyond the immediate context of individual companies as it provides insights into the broader mechanisms of system reconfigurations in established industries. Nonetheless, despite previous acknowledgements of the potential benefits of understanding the adoption behaviour of operational firms (Scherrer, 2024), , the role of incumbent actors as consumers and users of low-carbon alternatives remains an underexplored research area in the transition literature (for an exception, see Meelen and Schwanen, 2023).

2.3.3 An organisational behavior perspective on innovation adoption decision making

Beyond the transition literature, organisational innovation adoption theories have frequently focused on exploring how rational determinants such as economic and operational factors, organisational characteristics, or opportunities for increased competitiveness influence firms' decisions to adopt low-carbon innovation (Anderhofstadt and Spinler, 2019; Bae et al., 2022; Cantillo et al., 2022; Konstantinou and Gkritza, 2023). In contrast, the work presented in this thesis builds on recent contributions from behavioural and psychological organisational research that acknowledges the influence of individual actor-internal factors–cognitive, affective and conative elements of individual decision-makers in firms, including attitudes, perceptions and emotions–on organisational behaviours and innovation adoption decisions (Mohammed et al., 2020; Perez et al., 2017; Roberts et al., 2021; Wolff and Madlener, 2019). The origins of this research can be traced back to the early studies in organisational behaviour, which recognised that beyond rational calculations, the psychological states and subjective experiences of decision-makers significantly shape their strategic choices and actions (Cyert and March 2006; Simon, 1947). This perspective has become crucial in understanding the complexities of technology adoption, particularly as it highlights how actor-internal factors influence the human decision-making process and, thus, can either facilitate or hinder the uptake of new technologies within firms(Ajzen, 1991; Rogers, 2003).

The novelty of my approach that is presented in depth in the work that follows (see Chapter 8) lies in explicitly examining how a prevailing policy mix influences said actor-internal factors and, in turn, how the interplay between these elements shapes the low-carbon innovation decision-making process of individuals within firms. This perspective is important because it addresses a gap between the neo-liberal principles that often guide net-zero policy mix design (Markard et al., 2020)—emphasising market-based solutions, technology neutrality and rational choice models (Novy and Hammer, 2007; Tödtling and Trippl, 2021)—and the reality of how individual decision-makers within firms actually interpret and respond to these policies. Neo-liberal policies typically assume that firms and their managers will make decisions based solely on economic incentives and market signals (Harvey, 2005), thus sidelining cognitive, emotional, and cultural factors that also play a significant role. By focusing on the interaction between policy mixes and these internal actor-internal factors, my approach reveals how policy effectiveness can be compromised when these human elements are neglected. It, therefore, enables new insights into how the design of net-zero policy mixes can be more effectively tailored to overcome potential psychological and emotional barriers that hinder innovation adoption within firms, thus slowing down transition dynamics.

3. Methodological approach

The term "methodological approach" is a shorthand for a congruent epistemological position with associated choices for research design and tools for data collection and analysis. This extends well beyond methodology in the narrow sense of a set of research tools. This definition also takes into account that knowledge production need not be restricted to academics and that analysis can serve diverse knowledge interests. (Köhler et al., 2019, p.18)

This chapter discusses this thesis's underlying research paradigms and logical reasoning and outlines the different data collection and data analysis methods employed throughout my different Papers. It also provides some broader reflections on the methodological challenges I faced during this PhD journey.

3.1 Research paradigm(s) and logical reasoning

My own (implicit) beliefs and assumptions about the nature of transitions and knowledge more broadly have undoubtedly guided the method selection of my research. Nevertheless, I have had difficulties categorising myself within one "ideal type" social science research paradigm (Weber, 1978), primarily because sustainability transitions research inherently draws from multiple disciplines (Köhler et al., 2019), making it difficult to fit my research into a single paradigm (Geels, 2010; Zolfagharian et al., 2019). First and foremost, I would like to position myself in this thesis as a young researcher who embarked on this PhD journey wanting to know more about the challenges currently preventing the acceleration of the ongoing decarbonisation efforts in the heavy-duty freight transport sector. Epistemologically, this has led me to develop a strong emphasis on the practical meaning of knowledge that can inform future practice and policy-making, which is frequently attributed to pragmatism (Creswell, 2012; Zolfagharian et al., 2019). Additionally, pragmatist ideas, such as researchers should steer clear of metaphysical debates about the nature of truth or reality but rather focus instead on the generation of practical understandings of concrete, real-world issues and actionable knowledge (Kelly and Cordeiro, 2020), resonate well with me and are reflected in the contributions of my research.

Nevertheless, a careful reader might also detect an apparent influence of critical realism within this body of work, exemplified by my frequent interest in understanding the underlying mechanisms that drive a particular phenomenon and a focus on the interplay between structure and agency in explaining stability and change (Sorrell, 2018). Thus, this thesis can be viewed as an attempt to bridge these two paradigms as it recognises the need for actionable knowledge that can help accelerate contemporary transition processes informed through a research focus on the prevailing structures, causal mechanisms, and varying forms of agency underlying transition processes. What unites both paradigms is their openness to different methods; pragmatism and critical realism both advocate for methodological pluralism, recognising that complex research problems often require a combination of quantitative and qualitative approaches to fully understand the underlying phenomena (Morgan, 2014; Mukumbang, 2023). This openness is reflected in the diverse choice of methods employed in this thesis, which followed both multi-method and mixed-method approaches (as outlined in more depth in the following text).

Moreover, my method of reasoning significantly influenced how I designed my research instruments and interpreted the obtained data. Throughout all Papers in this thesis, an abductive reasoning process (Kovács and Spens, 2005; Sætre and Van de Ven, 2021) was employed, resulting in a theory-driven approach to research instrument development and data interpretation. As outlined in Figure x, my research process and the development of each paper started from empirical information or observations of a phenomenon that either deviated from existing theories and conceptualisations or was inadequately addressed in the current transition research literature (1). I then proceeded to match this deviating empirical data against existing theories, predominantly from organisational studies, in an iterative process (2) with the aim of creating a new framework that could increase my understanding of the phenomena at hand (Paper I-IV) or developing concrete hypothesises (Paper V) (3).

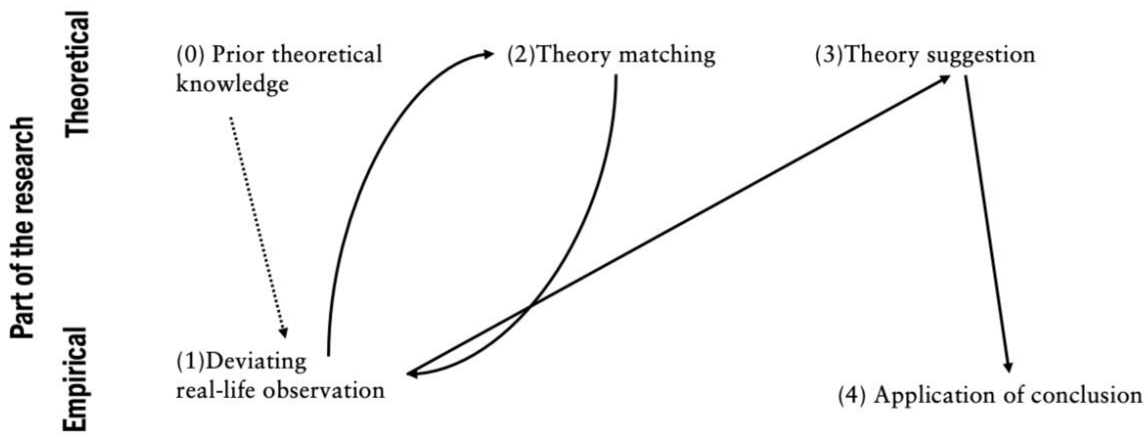

Figure 9 Abductive research process based on Kovács and Spens, 2005.

This abductive reasoning process allowed me to draw more robust, theoretically informed and empirically grounded conclusions. Nevertheless, this attempt to bridge empirics and theory also brought challenges for the research instrument development, data collection and data analysis, which are discussed in more depth below.

3.2 Methodological challenges of studying a predetermined transition case

From the start of my PhD journey, as specified in the initial doctoral position advertisement, the decarbonisation of road freight transport in Sweden with the help of electric road systems (ERS) was established as the primary empirical focus of my research. Entering a PhD project with such a predetermined contemporary transition case influences the research approach towards case-based research and has clear implications for the research design. Thus, rather than retroactively justifying the selection of this specific case, this section explicitly outlines the constraints and challenges of studying a predetermined transition case and describes the strategies employed throughout my PhD process to overcome them. One significant challenge is that such a narrow focus could limit broader insights. By concentrating exclusively on one technological decarbonisation pathway for road freight transport in Sweden, the research may overlook broader systemic factors and transitions occurring in other sectors. This narrow scope can constrain the ability to generalise findings and restrict the exploration of decarbonisation strategies that may have broader applicability. Another constraint is the potential bias towards case-specific findings. The necessity to focus on a specific contemporary transition case may lead to highly contextual and less generalisable results. This bias can reduce the broader applicability and impact of the research, as the unique characteristics of the road freight sector may not fully capture the complexities and variations present in other sectors or geographical regions. Furthermore, the dynamic policy and market environments pose a considerable challenge: The road freight transport sector is subject to rapid technological advancements, newly emerging policies, and changing market conditions. These changes require continuously adapting the research focus and methods to ensure the study remains relevant and timely. This necessity for frequent adjustments adds complexity to the research process and demands a flexible research design capable of accommodating ongoing developments while maintaining rigorous analytical standards.

To overcome the above-described constraints and challenges, I have developed several strategies and approaches to enable a more reflexive research process:

(1) Acknowledging the multi-system and spatial dynamics of transitions. As outlined earlier in the Introduction and Background chapter, net-zero targets, such as the widespread electrification of central societal sectors, have given an impetus for multi-system dynamics—interactions and complimentary couplings between multiple systems to address the required decarbonisation challenge (Andersen and Geels, 2023; Rosenbloom, 2020). To confront these complexities, my thesis adopts a broadened research scope that transcends the conventional focus on the innovation diffusion dynamics within a single system and includes other relevant systems such as energy, waste management, information and communication technology. Additionally, previous work has highlighted how the dynamics of industry transitions are deeply embedded in local, national and regional contexts,

necessitating a multi-scalar approach to accurately reflect and understand ongoing change processes (or lack thereof) (Binz et al., 2020; Truffer et al., 2015). In response this thesis includes research at the national level of Sweden but also examines broader EU-level dynamics to develop a more comprehensive understanding of the transition acceleration challenges within this sector.

(2) Exploring multiple decarbonisation pathways. Following calls to broaden the research focus of transitions away from the dynamics of the diffusion of a single low-carbon technology towards a diverse range of possible pathways (Stirling, 2008; Stirling et al., 2023), I have made a deliberate effort to consider as many (competing) technological alternatives and resulting pathways for the decarbonisation of the road freight sector as possible in this thesis, including battery-electric vehicles, fuel-cell electric vehicle, plug-in hybrid electric vehicles, hydrogen combustion engine vehicles, gas combustion engine vehicles and their varying infrastructural configurations. This has enabled me to develop a more relational perspective on socio-technical change processes and generate new insights into how these different technological alternatives and the actors that advocate for them dynamically interact, compete and co-exist to shape the directionality of the ongoing net-zero transition.

(3) Integrating historical perspective to better understand contemporary dynamics. The inherent trade-offs of choosing between a retrospective or contemporary analytical focus can be considered one of the key methodological dilemmas for transition researchers (Köhler et al., 2019). On the one hand, reconstructing transition dynamics with the help of historical case studies has enabled the generation of much of the field's foundational knowledge (e.g., Geels, 2007, 2005) on the other hand, the increasing urgency of climate change has made transitions in the making (Farla et al., 2012) and their effective governance (Loorbach, 2022) an important topic. Paper III makes a deliberate attempt to break free from this either-or dilemma and employs a process-tracing method (Langley et al., 2013) to perform a longitudinal study of the European HDV sector over the last 30 years. This approach enabled me to generate insights into how past dynamics shape the sector's current transition towards net-zero goals and also offers concrete policy recommendations to accelerate transitions in hard-to-abate sectors.

(4) Utilising multi and mixed-method approaches. Lastly, instead of solely relying on one qualitative data collection method, such as interviews, which are frequently associated with case-based transition research (Hansmeier et al., 2021), I employ a multi-method approach throughout Papers I-III. Therefore, next to using interviews with key actors as a main source of empirical data, additional modes of qualitative

data collection and resulting data sources included industry events and, field visit observations, and secondary data. These three different types of qualitative data were combined to answer the same research question (Hesse-Biber et al., 2015) and support triangulation to enhance the internal validity of the studies (Meijer et al., 2002). In addition, Papers I-III[12] also utilise mixed-method data analysis approaches, thus deliberately combining qualitative and quantitative forms of data analysis (Creswell, 2013). Paper I performs a qualitative content analysis in combination with an automated quantitative text analysis; Paper II first carries out a qualitative content analysis that informs a Social Network Analysis, and the process tracing method used in Paper III includes both qualitative and quantitative data for the construction of its historical narrative. To some, this combination of different methods might seem like my initial perception of the *smörgåsbord* when I first moved to Sweden—a broad buffet of various foods that did not necessarily seem to fit together. However, I would argue that these different ways of researching transitions have enabled me to generate a more pluralistic understanding of transition dynamics in the empirical context and have led me to produce better knowledge on a diverse range of transition acceleration challenges. Chapter 10 picks up on this point again in more depth and discusses the methodological contributions of the thesis.

Table x gives an overview of each paper's research question, analytical methods, and data sources. Paper IV is a conceptual paper, and thus, no specific data analysis method was employed. However, the secondary data collected throughout this research process still served as the foundation for many of the arguments put forward in the paper. A more detailed description of the empirical material and the methods follows.

[12]While Paper V in its current manuscript form only presents the survey as its sole source of data, its ideation and the development of its research instrument nevertheless relied on insights from interviews with Swedish hauliers.

Table 3 Research question(s), data sources and analysis methods of each paper.

	Paper I	Paper II	Paper III	Paper IV	Paper V
Research Question	(1) How are the meta-rules of CE diffused across varying systems? (2) What are the implications of divergent meta-rule interpretations for the speed and scope of the second DT towards the CE?	How do incumbency reorientations and the resulting relational changes actively contribute to (or hinder) system reconfigurations?	(1) How has the timing and sequencing of varying path constitution processes influenced the European HDV sector's evolution over the past three decades? (2) How do carbon-intensive and low-carbon paths coevolve to affect the overall trajectory of this industry transition?		How does a technology-neutral policy mix interact with actor-internal factors to shape their decisions to adopt ZEVs?
Data analysis method	Mixed-method content analysis	Social Network Analysis	Process tracing		Mediation, & moderation analysis
Data source	Semi-structured expert interviews (n=32)	Semi- structured expert interviews (n=36), industry event observations (n=21) & policy documents, newspaper articles (n=165)	Semi-structured expert interviews (n=45) Statistics from national and international transportation databases	Secondary data	Survey data (n=156)
Data analysis software	MAXQD	MAXQD & Kumu	MAXQD		PROCESS macro for IBM SPSS

3.3 Empirical material

The following sub-section describes the data collection methods and sources utilised throughout this thesis's research. While the interview and survey data were collected specifically for each paper[13], the observations and secondary data were used throughout all papers. Figure x outlines the timeline of the data collection in more detail.

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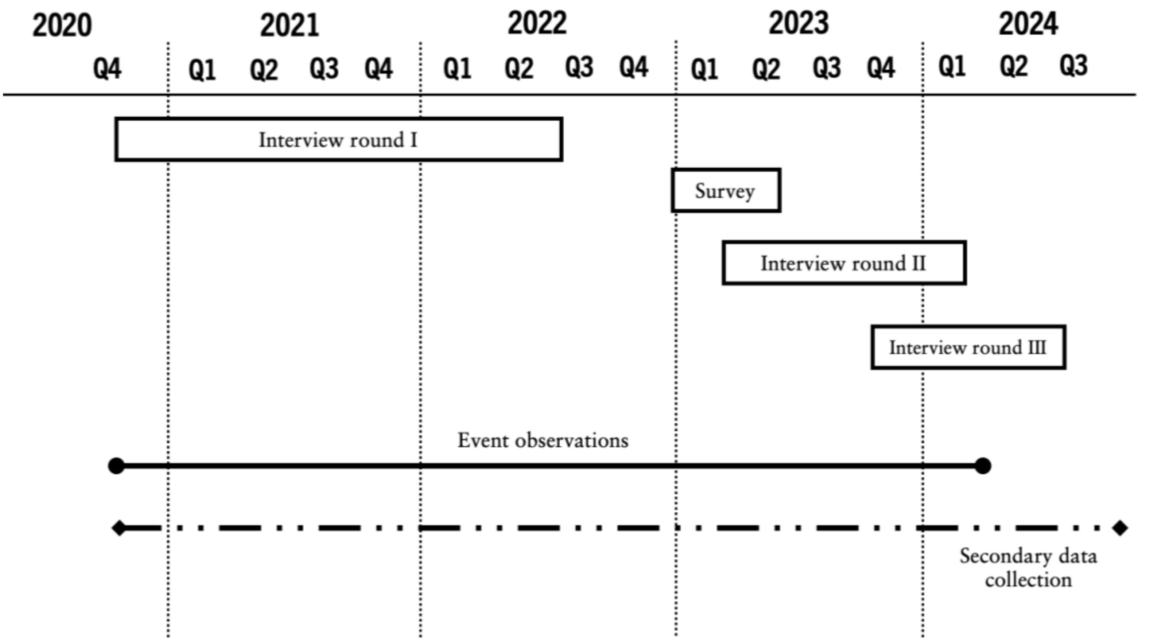


Figure 10 Timeline of the data collection.

3.3.1 Semi-structured expert interviews

For Papers I-II, expert interviews served as primary empirical data. In the context of this thesis, a person was considered an expert if they possessed the institutionalised authority to construct reality (Hitzler et al., 1994), in the sense that all interviewed individuals held a formally recognised position that enabled them to influence and shape industry standards, regulatory frameworks, and technological advancements that are accepted and implemented by other stakeholders in the road freight transport sector. Their knowledge was consequently of interest due to its potential "to become hegemonial and, thus, to be influential in structuring the conditions of action for other actors [....] in a relevant way" (Bogner and Menz, 2002, p. 46 translated by Meuser and Nagel, 2009). The interviews were conducted between September 2020 and March 2024 and interviewed experts ranged from representatives of European heavy-duty truck manufacturers, electric utility and grid companies, charging infrastructure providers, battery manufacturers, recycling and waste management firms to regional and national policymakers, transport lobbies, NGOs, and academic researchers involved in the road freight transport sector.[14] The interview process followed a purposeful snowball sampling approach, meaning initial interviewees were

[13]Some interview data (n= 16) informed multiple papers.
[14]Each paper includes a detailed list of interviewees.

asked to recommend other individuals with relevant expertise and knowledge on the topic in question, thereby expanding the pool of participants who fit the research criteria through referrals (Parker et al., 2019). Additionally, experts were recruited at industry events (detailed further in Section 3.2.2).

Three separate semi-structured interview guides were drafted for the data collection, which included questions related to the main research question(s) and the conceptual building blocks of the frameworks put forward in the different papers. Given each Paper's ambition to make a conceptual contribution, drafting interview guides that effectively translated complex theoretical concepts, such as meta-rules, antagonistic interactions or rule-regimes, into practical, accessible questions without losing the depth and nuance of the original concepts proved initially very challenging to me. However, this process improved over time: Iterative refinements based on continuous feedback from interviews helped me to simplify and clarify questions throughout the data collection process without compromising the theoretical ambition of the research. Direct engagement with industry representatives and policymakers at industry events also provided valuable insights into how theoretical concepts could be framed in practical terms to better resonate with interviewees' experiences and language. Aligning theoretical exploration with practical applicability by integrating practical examples and scenarios related to the interviewees' position was especially helpful in grounding abstract concepts in real-world contexts and often prompted more meaningful responses.

The data collection for this thesis began at the onset of the second wave of the COVID-19 pandemic in the fall of 2020. Therefore, the initial set of interviews was conducted online via the video meeting platform Microsoft Teams. This continued to be the preferred mode of interviewing because I observed that even though high-ranking industry representatives, especially if I had no prior contact with them, frequently declined in-person interviews; however, the pandemic-induced changes in meeting habits made them willing to schedule time for digital interviews. Conducting interviews in this mode also enabled me to reach a wider range of participants across Europe, which would not have been possible within the budget of my PhD if travel for in-person interviews had been required. While online interviews have limitations, such as potential technical issues and reduced personal interaction (Fielding et al., 2017), the benefits of access thus outweighed these drawbacks. This interview mode allowed for a more diverse and comprehensive data collection, enhancing my research's overall quality and scope. The interviews lasted between 37-106 minutes, with the majority carried on for just over one hour. They were either recorded and later transcribed verbatim or transcribed live using the transcription function in Microsoft Teams meetings, except 12 participants who preferred not to be recorded.

3.3.2 Observations and secondary data

Relying on interviews only carries the inherent risk of becoming overly dependent on the respondents' interpretations of what constitutes a desired answer, the narrative they wish to present and how they want to frame their actions (Qu and Dumay, 2011). Given the previously documented efforts of incumbent actors to resist, slow down, or prevent transition processes altogether (Geels, 2014; Penna and Geels, 2015; Sovacool et al., 2017), I would argue this risk becomes especially prominent when utilising interview data from actors who may have an economic interest in maintaining the status quo, as is the case in this thesis. To minimise this risk, Paper I-III employs data triangulation to enhance the research's overall reliability (Flick, 2018). To support this triangulation, I followed a multi-method approach (Roller and Lavrakas, 2015), which means that multiple data sources and modes of data collection were combined to help answer each paper's research question(s). More specifically, the triangulation of interview data was carried out with the help of two additional sources of data:

(1) Industry event and field visit observations. Over the course of my four-year PhD process, I had the opportunity to attend over 40 different online and in-person transport industry events at which I continuously collected observation data via taking field notes. The industry events varied from one-hour webinars or half-day workshops to multi-day fairs and conferences. Attending these events provided invaluable insights into the latest industry trends, stakeholder perspectives, emerging decarbonisation challenges and interactions among different actor groups. Additionally, I conducted just over a dozen field visits to, for example, several European heavy-duty truck manufacturers, Swedish battery manufacturers, Swedish battery recyclers, charging infrastructure developers, regional and national transport administrations lobbying groups and a transport policy NGO. These field visits were crucial for gaining an in-depth understanding of key industry players' operational practices and challenges and helped me verify information gathered through interviews.

(2) Secondary data. Inspired by the concept of a qualitative datum, "a bracketed string of words capturing the basic elements of information about a discrete incident or occurrence (the unit of analysis) that happened on a specific date, entered as a unique record (or case) in a qualitative data file, and subsequently coded and classified as an indicator of a theoretical event." (Van de Ven, 2007, p.18), I have systematically collected and organised secondary qualitative data throughout my research process. Sources included publicly available reports, press statements, annual company reports, industry analyses, media clippings, academic literature, publications from lobby groups, government policy documents, white papers from industry associations, technical standards, patents, and regulatory filings, and

statistics from national and international transportation databases all related to the decarbonisation of road freight transport in Europe. At the time of writing, this database includes more than 2000 qualitative datums.

3.3.3 Survey data

For Paper V, data was collected via a national survey. This survey, designed as a self-administered online questionnaire via SurveyMonkey, targeted transport operation managers working at transport and haulage companies across Sweden. The questionnaire was developed collaboratively with my co-authors. It included established scales from the literature to measure key concepts such as anticipated regret and perceived technological change, which were tailored to the context of road freight transport. Additionally, novel items were developed to capture managers' perceptions of the prevailing policy mix with regard to its technology neutrality and their attitudes towards ZEV technologies, drawing from previous academic sources.[15] In line with my preference for abductive reasoning, the idea for this survey emerged from my real-world observations during interviews, where hauliers frequently expressed concerns and uncertainty about which ZEV technology to adopt in the near future due to the government's prevailing technology-neutral policy mix. To me, this adoption uncertainty triggered by the current policy-mix characteristics represented an emergent governance challenge that was not adequately addressed by existing work, thus prompting the need for further investigation through this targeted survey. Before full deployment, I conducted a pre-study using a small sample of ten transport operation managers from my professional network. This pre-test ensured that the questions were clear, and the survey length was appropriate. The survey was distributed through email databases of two major Swedish road freight transport industry associations, and 155 completed responses were received.

3.4 Methods: quantitative & qualitative approaches

This sub-section describes the analytical methods employed throughout this thesis's different Papers. I also provide brief justifications for their choice and discussions of their limitations; however, further details are available in the method sections of the respective papers in which they are used.

3.4.1 Content analysis

Papers I and II analysed the collected data with the help of content analyses, a method for interpreting textual data through systematic coding and identifying themes or patterns (Harwood and Garry, 2003). For both Papers, I performed a directed content analysis, an approach to content analysis that uses existing theory to guide the initial data coding. Therefore, operational definitions were developed for the conceptual frameworks' key concepts (e.g., the different regime dimensions or CE meta-rule compatibility), which

[15]For a complete list of all measurement items please see Appendix B of Paper V.

could serve as the initial coding categories (Assarroudi et al., 2018). A key challenge in developing these operational definitions was ensuring they accurately represented the theoretical concepts while being specific enough to be applied consistently to empirical data (Hsieh and Shannon, 2005). Admittedly, this involved a lot of trial and error initially, and iterative improvements were made to the coding frameworks throughout. To ensure the accuracy and robustness of these coding frameworks, both papers were additionally presented at several conferences and paper development workshops, and the coding framework of Paper II was further improved during the peer review process of its publication. It is further important to briefly reflect on the fact that such a theory-based approach introduces a clear bias by potentially limiting the analysis to pre-established categories, which may overlook emerging patterns and novel insights from the data (Hsieh and Shannon, 2005). To avoid the pitfalls of the "law of the hammer" (Poole et al., 2000), I continuously revisited the data to remain open to new themes and patterns that did not fit the initial coding framework and also excluded theoretical concepts that simply proved to be operationalizable.

Moreover, in Paper I, the content analysis was applied using a mixed-method approach (Castro et al., 2023). Thus, in addition to qualitatively coding for instances of, e.g., contestation over R-framework interpretations, system-specific adaptations, or symbolic diffusions, I also employed a quantitative approach to determine the (word) frequency of mentions of the different R rules across two time periods through an automated text analysis in MAXQDA. This combined approach enhanced the overall results of the paper by providing a comprehensive study that captures both the depth of qualitative insights and the breadth of quantitative trends via descriptive statistics on the developments of CE in the Swedish HDV sector.

3.4.2 Social Network Analysis

Additionally, Paper II employs a social network analysis (SNA) approach informed by secondary data, observations, and expert interviews. SNA, as such, is a research method used to study the relationships between actors within a social network. It is a quantitative approach that maps and analyses social relationships, interactions, and patterns among individuals or groups (Scott, 2017). At its basics, it can be considered an application of graph theory in which members of a network, individuals or organisations, are represented by points, so-called nodes, and their connections are expressed through lines, referred to as edges, forming systems of points and lines that can be visualised in network maps (Scott and J.Carrington, 2014). SNA has seen an increasing application in transition research in recent years due to its analytical ability to move beyond the analysis of the characteristics of individual actors towards the study of their relational dynamics (for examples, see Giurca and Metz, 2018; Scherrer et al., 2020; Song et al., 2023). For Paper II, the SNA method involved a directed content analysis (as described above) of interviews, observation notes, and secondary sources with the help of MAXQDA to identify actors and their activities and sort those based on the five previously established regime dimensions: technology, science, policy, market and user preference, and socio-cultural meaning. Actor interactions were derived from the identified activities within the data and were categorised based on the nature of interactions: symbiosis, competition, and antagonism. A two-mode data matrix was created in MAXQDA, and this exported data matrix was visualised using the network visualisation software Kumu. To identify important actors in the network, as well as patterns and clusters of relationships between actors, Paper II further utilises a variety of different analytical techniques applied to the network visualisation, such as centrality measures and clustering algorithms. An in-depth description of the chosen measures and how they were operationalised can be found in the method section of Paper II.

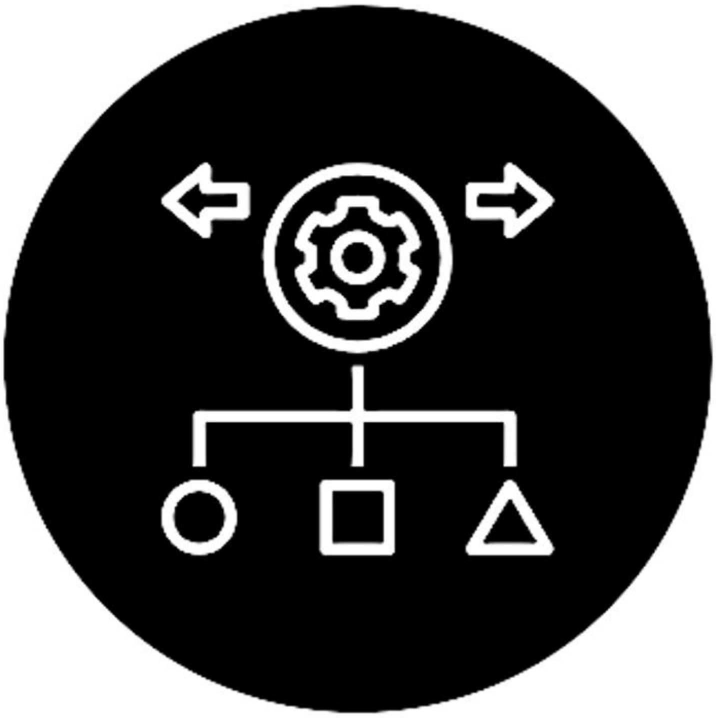
3.4.3 Process tracing

Paper III utilises a process tracing approach to explore and theorise the timing, sequencing and interactions of the adoption of low-carbon innovation and the decline of carbon-intensive technologies in hard-to-abate industry sectors. As such, process tracing enables researchers to uncover the processes, mechanisms and sequences of events that drive patterns of change and lead to specific outcomes (Langley et al., 2013). More specifically, the theory-building variant of process tracing, which "seeks to build a generalisable theoretical explanation from empirical evidence" (Beach and Pedersen, 2019, p.3), was employed and nested in a mixed-methods design, incorporating both qualitative (expert interviews) and quantitative data (sector-specific statistics) to ensure a comprehensive analysis. Instead of developing and testing hypotheses, process tracing was used in Paper III to construct a detailed narrative of the historical development of the sector and gain a better theoretical understanding of the relationship between decline and innovation. As previously acknowledged by Langley, 1999 however, "moving from a shapeless data spaghetti toward some kind of theoretical understanding that does not betray the richness, dynamism, and complexity of the data" (p. 694) can be considered one of the significant challenges of process tracing. To deal with this challenge, existing theoretical concepts and insights from path constitution theory (Sydow et al., 2021, 2012) guided the analysis of the empirical material. They thus functioned as an analytical plotline to reduce researcher subjectivity (Poole et al., 2000).

3.4.4 Mediation and moderation analysis

Lastly, to examine how the interplay of a technology-neutral policy mix and actors' internal factors affect the innovation adoption intentions of transport operators, a mediation and moderation analysis, informed through survey data described in 3.2.3, was performed in Paper V. The PROCESS macro, an add-on for IBM SPSS (Version 24) developed by Andrew F. Hayes was used for this analysis because it allows for the estimation of direct and indirect effects in statistical models through bootstrapping methods which provide a more reliable estimates especially in smaller sample sizes (Hayes, 2013; Preacher and Hayes, 2008), such as the one of our study (n= 155). Bootstrapping is a resampling method that generates multiple samples from the existing data, thereby reducing the reliance on the assumptions of normal distribution and enhancing the robustness of the estimates (Mooney and Duval, 1993). In our study, the PROCESS macro (specifically, Model 7) was employed to conduct a mediation analysis to test whether anticipated regret mediated the relationship between perceived technology neutrality and adoption intention delay and to perform a moderation analysis to examine whether the perceived rate of technology moderated this mediation effect. By generating 5,000 bootstrap samples, we obtained bias-corrected confidence intervals for the indirect effects, ensuring the reliability of our findings. A specific challenge of this method is the potential for overestimating effects due to multicollinearity among variables, which in turn may affect the precision of the mediation and moderation estimates (Hayes, 2020). To mitigate this risk, we conducted a principal component analysis to reduce the dimensionality of the data and address multicollinearity by transforming correlated variables into a smaller number of uncorrelated components (Lafi and Kaneene, 1992). This step ensured that the variables used in the PROCESS analysis were orthogonal, thus improving the precision of our estimates.

4. Whole-system transitions



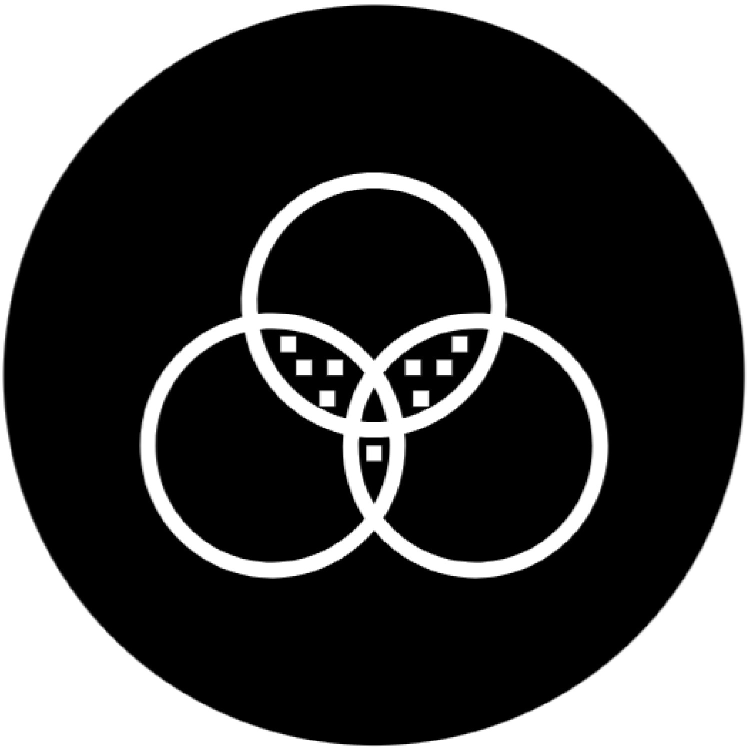
Under review as: Ertelt, S.-M. (forthcoming). Reinterpreting circularity? Understanding the contested directionalities of the Swedish heavy-duty vehicle sector towards the Circular Economy. In: *Greener and smarter? Industry transformation, sustainability, and innovation*, INTRANSIT book project to be published early 2025.

Abstract: This chapter examines the contestations, conflicts, and divergent interpretations of the emerging Circular Economy (CE) meta-rules -reduce, reuse, recycle and recover- within the value chain of the Swedish heavy-duty vehicle sector. Building on institutional theory, specifically organisational fields, institutional logics and field multiplicity, an analytical framework is proposed to enable an in-depth analysis of the sector-transcending (re)interpretation processes of meta-rules across entire value chains. In doing so, the chapter contributes with an expanded conceptual understanding of how the prevailing logics within and across systems shape negotiation as well as implementation processes of CE meta-rules. Additionally, the analysis of the emerging circular value chain of the Swedish heavy-duty vehicle sector allows to theorise the broader implications of interpretative flexibility and clashing prioritisations of meta-rules for the speed and scope of multi-sector industrial transformations towards more circular practices.

Keywords: Circular economy, Value chain transformation, Multi-system interactions, Meta-rules, Institutional logics, Field multiplicity

The following content has been removed as it is currently under review.

5. Multi-system dynamics



Published as: Ertelt, S.M. and Kask, J., 2024. Home field advantage: examining incumbency reorientation dynamics in low-carbon transitions. *Environmental Innovation and Societal Transitions*, 50, p.100802. https://doi.org/10.1016/j.eist.2023.100802

Abstract: Recent work has offered a more nuanced view of incumbent actors' roles in transitions, yet a comprehensive understanding of how reorientation activities and subsequent interaction patterns among different incumbent actor types shape the direction of system reconfigurations remains underexplored. This paper proposes a framework for empirically assessing actors' relational dynamics in response to low-carbon transitions and conceptualises actor interaction types and the nature of their interaction. Through a case study of the low-carbon transition of road freight transport in Sweden, we examine how reorientation dynamics, e.g., coalitions, competition, and contestations, can facilitate and hinder system reconfigurations by creating regime tensions. Our study highlights that incumbency reorientations are multi-dimensional, with actor involvement and strategies varying, leading to divergent actor positions and role constellations as actors attempt to reconfigure the focal regime. Extending beyond the Swedish case, five avenues for future research are outlined.

Keywords: Low-carbon transition, Incumbency, System reconfigurations, Regime change, Multi-system interactions

5.1 Introduction

Phasing out fossil fuels across all industry sectors globally will be necessary to reach net-zero targets and limit warming to 1.5°C. With the growing urgency of such low-carbon transitions — aimed at reconfiguring current socio-technical systems (hereafter: systems) that fulfil societal functions, like mobility or energy, to mitigate climate change (Geels et al., 2017; Geels and Turnheim, 2022) — the role of incumbent actors in these transitions has become an important topic (Mori, 2021; Steen and Weaver, 2017; Turnheim and Sovacool, 2020). Compared to historical transitions, research on ongoing transitions often challenges the stereotype of incumbents — established actors in state, market, or civil society — as transition opponents and resistant to change. In response, recent transition literature has proposed a more pluralistic view on incumbencies in transitions (Apajalahti et al., 2018; Berggren et al., 2015; Markard and Rosenbloom, 2022; Turnheim and Sovacool, 2020) and developed system reconfiguration approaches (Geels, 2018a; Geels and Turnheim, 2022; McMeekin et al., 2019). These contributions provide an analytical perspective on how existing structures and rules that orient established actors and coordinate activities of vital societal functions can be altered endogenously. System reconfigurations thus occur through incumbent actor reorientation activities — a shift in focus, support, or resources from stabilising existing systems to low-carbon innovations (Geels and Turnheim, 2022) — which changes the elements and architecture of an existing system (Geels et al., 2017; Geels, 2018).

However, even though established actors' reorientations are crucial for the diffusion of low-carbon innovation (Geels, 2021; Kump, 2023), incumbency reorientations — the changes in interaction patterns among incumbents as they reorientate their activities in transitions toward net-zero societies — are still not well-understood in transition studies (Farla et al., 2012; Mori, 2021; Steen and Weaver, 2017). Research on how different interests and strategies of established actors and the resulting interaction among them may contribute to regime stability or change is especially scarce (Mori, 2021; Stirling, 2019; van Mossel et al., 2018). Even though transition scholars already use organisational field approaches (Fligstein and McAdam, 2012; Hoffman, 1999; Scott, 1995) to conceptualise a socio-technical regime (hereafter: regime) as the system's path-dependent but dynamic "grammar" that orients actors' interactions (Fuenfschilling and Truffer, 2014; Geels, 2020; Schot and Geels, 2007), this dynamism remains largely black-boxed (Steen and Weaver, 2017). Too often, this results in a congruent and confined portrayal of regimes with established actors aligned over one pathway (Stirling, 2019; Turnheim and Sovacool, 2020). We argue that this frequent disregard for the heterogeneous nature of incumbency exposes a gap in the literature on how diverse actor interaction patterns amongst actors, such as coalitions, competition, or conflictual relations and the potentially resulting tensions, may contribute to (or hinder) system reconfigurations.

Against this backdrop, this paper aims to add to the conceptual understanding of incumbency pluralism and the possibilities of regime tensions in low-carbon transitions. It examines reorientations of established actors, the resulting changes in interactions amongst these actors, and their aggregated impact on system-level reconfigurations. In doing so, this study addresses the following research question: How do incumbency reorientations and the resulting relational changes actively contribute to (or hinder) system reconfigurations? To answer this question, we use organisational fields as a theoretical and methodological construct (Wooten and Hoffman, 2017). Rather than focusing solely on actors per se, our analysis emphasizes actor interconnectedness and interdependencies (Darnhofer et al., 2019; Stirling, 2019) and the varying nature of the resulting interactions (Konrad et al., 2008; Raven and Verbong, 2007) may impact reconfiguration processes.

Empirically, we draw from a case study of the Swedish road freight sector, analysing a governmental initiative referred to as the Electrification Pledges — formal commitments made by 252 public and private actors specifying concrete activities to accelerate electrification (Regeringskansliet, 2021). This concerted effort aligns with Sweden's goal of net-zero freight transport by 2045 (Regeringskansliet, 2020), making the pledges a significant step toward that goal. These pledges are characterised by a variety of reorientation activities aimed at promoting electrification and decarbonisation, including planning and locating charging infrastructure, connecting charging services to grid-related services to mitigate costly grid peaks, ensuring robust electricity grid capacity, and updating procurement processes to facilitate electric goods transport services. Automotive manufacturers, utility and grid operators, charging and hydrogen infrastructure providers, fuel suppliers, freight companies, transport service purchasers, regional authorities, municipalities, and state agencies are involved. These pledges show high collaborative engagement among these stakeholders to lead, participate in, or coordinate electrification projects. Sweden can be considered a frontrunner in the electrification of freight transport due to its vision of a fossil-free economy, strong heavy vehicle manufacturing industry, and high numbers of newly registered battery-electric trucks (Volvo, 2022a). Thus, with the dominant presence of automotive incumbents and their documented engagement in transition processes (Berggren et al., 2015; Werner et al., 2022), this case is particularly apt for studying incumbency reorientations. Previous research has shown that electrification might require interactions and reconfigurations extending beyond the transport system (Andersen and Markard, 2020; Geels, 2018b; Rosenbloom, 2019). In response to such calls for system boundary-spanning changes to realise transitions and a focus on multi-system interaction (Andersen and Gulbrandsen, 2020; Kanger et al., 2021; Rosenbloom, 2020), our analysis covers incumbency reorientations within and across three systems: freight transport, energy, and communication.

This study contributes to theory and research practice. First, we propose a conceptual framework for assessing incumbency reorientations in response to low-carbon transitions, including six actor interaction types and three different interaction natures. This allows us to uncover how heterogeneous incumbency reorientations dynamics across different regime dimensions result in changes to the focal system trajectory. Second, we present a multi-system analysis of activities and interactions in the selected case to outline five future research avenues to better understand the role and influence of incumbency reorientation dynamics in low-carbon transitions. Third, the lessons from the case have implications for practice on its own merits.

The following section presents the theoretical background and the conceptual framework for analysing incumbency reorientations in system reconfigurations. Section 3 details the research methods, case, and data collection. Section 4 presents the case findings, followed by an analytical discussion based on these in Section 5. Section 6 concludes the paper by outlining implications for future research, limitations of the study and policy recommendations.

5.2 Theoretical background

This study analyses actor reorientations in an ongoing low-carbon transition using a system reconfiguration approach drawn from socio-technical transition research (Geels, 2018b; Geels and Turnheim, 2022; McMeekin et al., 2019). This perspective highlights the role of internal regime processes inside existing systems and the potential for endogenous change driven by reorientation activities in the form of gradual shifts of incumbent actors' strategies, resources, and/or political support toward niche innovation (Geels et al., 2017; Geels and Turnheim, 2022). It also acknowledges that deep decarbonisation of existing systems generally entails interactions across multiple regimes and systems (Geels, 2018b; Markard and Rosenbloom, 2022; Zhang and Fujimori, 2020), emphasizing the need to understand broader multi-system dynamics (Andersen et al., 2020; Rosenbloom, 2020). The remainder of this section covers these aspects and develops a conceptual framework to guide our analysis and interpretation of results.

5.2.1 Endogenous change

Transition research initially focused on how exogenous sources of change, like radical innovations, affect a system. However, recent studies have shifted focus toward endogenous change, which comes from actors within a regime (Friedrich et al., 2023; Runhaar et al., 2020). Using institutional theory, numerous scholars have improved our understanding of the regime[16] and the potential for endogenous regime change (Brodnik and Brown,

[16]Applying the regime concept in the transition literature has been diverse and incoherent (Markard and Truffer, 2008). To detangle the regime, incumbency, and system concepts, this work adopts the interpretation

2017; Fuenfschilling and Binz, 2018; Ghosh, 2019; Smink et al., 2015). This literature has yielded an important insight: regimes are semi-coherent sets of rules (normative, cognitive, and regulative) rather than monolithic and homogeneous incumbent structures (Runhaar et al., 2020). In this context, semi-coherence refers to a regime containing a wide range of rules that evolve along five *dimensions*: technology, science, policy, market and user preference, and socio-cultural meaning (Geels, 2004). The complexity and diversity of the regime concept and its various interacting components (e.g., technical artefacts, scientific knowledge, and regulations), thus, are reflected in the multiplicity of these regime dimensions (Geels, 2002; 2004). Each of these regime dimensions is governed by its own set of rules; nevertheless, they are linked, and their alignment is coordinated through the regime that serves as the shared "deep structure" that directs the behaviour of actors in a system (Fuenfschilling and Truffer, 2014; Geels, 2004, 2011; Schot and Kanger, 2018). However, different actor groups' varying interests, values, and objectives along the five regime dimensions are never fully aligned, resulting in the semi-coherent characterisation of the regime and the possibility of regime *tensions*, defined here as mismatches between rule sets (Geels, 2004).

analytical understanding of how such tensions may arise during *reconfiguration processes* benefits from zooming in on the dynamics of the five regime dimensions by conceptualising them as *organisational fields* (Fligstein and McAdam, 2012; Hoffman, 1999; Scott, 1995). Organisational field refers to a set of actors (e.g., organisations, government, special interest groups, and the public) whose interrelated activities form a web of interactions (Scott, 1991; McAdam and Scott, 2005; Scott, 1991). Examples include competition for resources, influence, market share, collaborations on joint projects, and negotiation and conflict over resources and field rules (Fligstein, 1997; Fligstein and McAdam, 2012). Previous transition research (Fuenfschilling and Truffer, 2014; Geels, 2020) has frequently used organisation fields, and building on this work, we argue that the five dimensions of a regime are best understood as organizational fields, each characterised by its specific rules and interacting actors. These *regime fields* are technology, market and user practices, policy, socio-culture, and science (cf. Geels, 2004). Within each regime field, specific actors–such as companies, government agencies, cultural organisations, and academic institutions–engage according to evolved field rules. These

of a regime as a "set of rules" and actor interactions (Geels, 2004; Geels and Turnheim, 2022; Schot and Kanger, 2018), making a conceptual differentiation between (1) the whole system configured of a material, relational, and institutional dimension, (2) the five interdependent regime fields that together represent the regime of such a system, and (3) the incumbent actors that through field-level activities stabilise or restructure regime fields to shape the trajectories of a system.

rules may include technical standards, legal regulations, social norms, and scientific methods. The dynamics within these regime fields are crucial for endogenous change as actors interact, whether in agreement or conflict. Through these interactions, they either stabilise or change the existing regime or pose tensions to it, which, in the aggregate, may reconfigure a system. In other words, we view the five regime fields as relational spaces where sets of actors interact to (re-)produce rules and develop a common meaning system (Scott, 2001) to either stabilise or change the evolutionary trajectories of an existing system (see Fig. 1). These common meaning systems are continuously contested (Fligstein and McAdam, 2012; Hoffman, 1999) and result from the regime fields members' actions and tactics (Oliver, 1991).

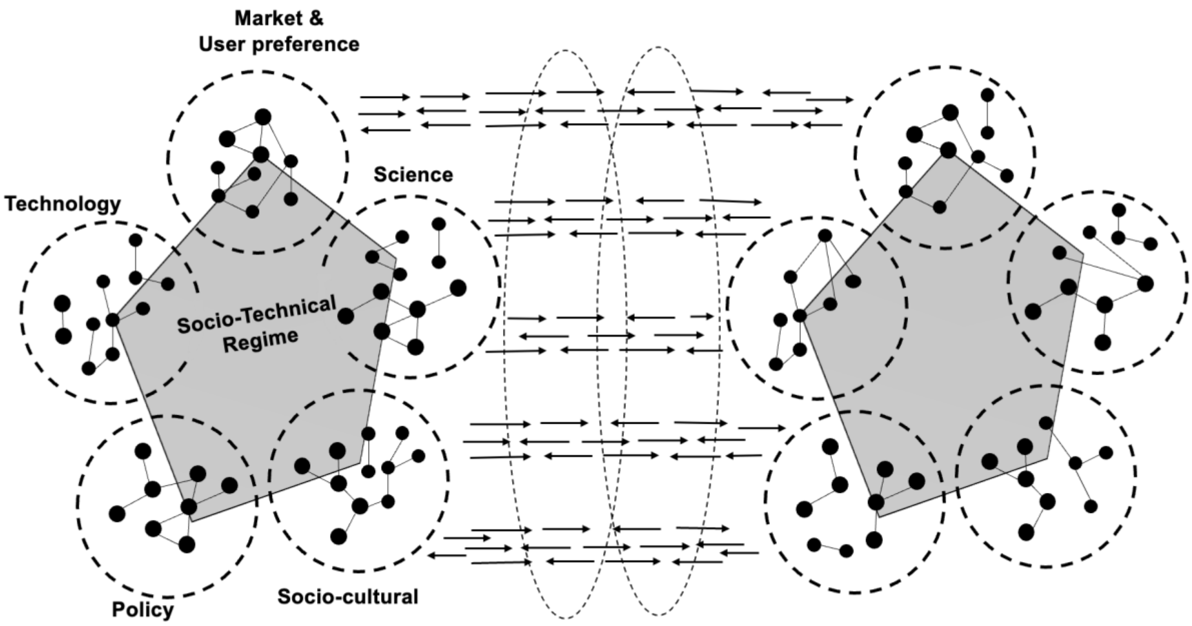


Figure x. Dynamically evolving regime fields (black dots represent actors, lines represent interactions) that form a regime. Arrows pointing in different directions represent field-level contestation about a common meaning system, while changes in actors and interactions lead to changes in the regime fields (substantially adapted from Geels 2004; 2011).

In line with established theorisations of regime stability (Geels, 2004; Geels, 2011), even stable regime fields are dynamic in the sense that gradual restructuring can be observed as a result of its actors continuously working on reproducing the status quo (Fligstein and McAdam, 2012; Lounsbury and Glynn, 2001). This process, however, is not driven solely by established actors but rather by the interplay among a broad and diverse spectrum of actors, as peripheral and niche actors may also significantly contribute to the reproduction of existing rules (Geels, 2011; Smith et al., 2010). As a result, only incremental adjustments are made, and the regime is "dynamically stable" (Geels, 2004; Geels and Turnheim, 2022). Factors that lead to such field-level stability may include fixed regulative structures (Fligstein, 2001), institutionalised norms, technological stability (Scott, 2008), as well as interdependence and cohesion among field actors (Davis and Marquis, 2005). Under this perspective, endogenous regime change, as Fig. 1 illustrates, results from significant restructuring processes in the regime fields. These radical changes are produced by field-level activities like the exit or entry of a powerful actor (Barnett and Carroll, 1993; Hoffman, 1999; Scott et al., 2000), as well as the creation of new field rules through reorientation activities that alter existing — or create novel — interaction patterns (Brint and Karabel, 1991) both between incumbents and across incumbents and niche actors.

Novel field rules that have been stabilised, such as shared technological standards (van Wijk et al., 2013) or legal frameworks (Reusswig et al., 2018), play an important role in legitimising these restructured regime fields (Kungl and Hess, 2021). However, tensions such as competing ideas among field actors about how to decarbonise a specific sector (Köhrsen, 2018), different interpretations of the future (Neukirch, 2016), or incompatible technological visions (Schmid et al., 2017) may impede such stabilisation. Consequently, from the standpoint of system reconfiguration, such tension may hinder endogenous change processes, necessitating analytical attention.

5.2.2 A relational perspective on incumbency reorientations

Incumbent actors can exhibit a range of reactions and play different roles in transitions (Kungl, 2015; Mori, 2021; Steen and Weaver, 2017). While some incumbents may resist reorienting to maintain the status quo (Johnstone et al., 2017), others can drive and facilitate endogenous change through diverse activities such as proposing new regulations, developing niche alternatives, political lobbying or diverging from a dominant technological trajectory (Apajalahti et al., 2018; Berggren et al., 2015; Heinze and Weber, 2016; Strambach and Pflitsch, 2020). Recent work has emphasised the latter's importance as an essential aspect for accelerating low-carbon transitions (Geels and Turnheim, 2022; Kump, 2023). Regarding their agency, incumbents are entrenched in the structures of existing systems, but they also have accumulated intangible resources and a strong network position that allows them to influence political processes (Galvan et al., 2020). Their ability to act or effect change is thus "embedded" in the sense that it is constrained and shaped by the rules of a regime (Grin et al., 2010). Hence, on the one hand, the field rules that actors follow inform their activities to a high degree (Hoffman, 2013) . However, conversely, incumbents also engage in activities to restructure the rules (Apajalahti et al., 2018). Such activities are embedded in complex networks of interactions (Hoffman, 2013), and actors anticipate each other's behaviour as they engage in interrelated activities to influence change and stability within a field (McAdam and Scott, 2005; Scott, 1995).

These interdependent dynamics, which reproduce rules but also produce new rules in some circumstances due to actor reorientation, may be challenging to capture solely by focusing on (incumbent) actors in isolation (Darnhofer et al., 2019; Turnheim and Sovacool, 2020). Instead, a relational perspective (Darnhofer et al., 2019; Stirling, 2019) emphasizes the interconnectedness and interdependencies of actors and the intricate web of interactions within the different regime fields. Thus, to better understand the dynamic stability of a regime, our analytical perspective examines how regimes are reproduced through relational processes among many actors in various fields (Stirling, 2019). Building upon Hoffmann's (1999) definition of fields as relational spaces that "bring together various field constituents with disparate purposes" (p. 4), we analyse how actors relate to one another within the regime fields. This aids in bridging the gap between actor interactions, aggregated field restructuring, and the possible tensions emerging from this process.

5.2.3 Multi-system interactions

Recent research has emphasised that drastic decarbonisation of entire industries broadens the scope of transition dynamics from single systems to interactions and reconfiguration processes between multiple systems (Andersen and Geels, 2023; Andersen and Gulbrandsen, 2020; Geels, 2018a; Rosenbloom, 2019, 2020). Drawing again on the organisational field literature, it is clear that as actors from an adjacent system enter a focal system, like energy companies entering the transport system, their interpretation of the focal systems' dynamics is shaped significantly by rules from their original fields (Kungl and Hess, 2021; Wassermann et al., 2015), which prompts questions about how actors from different systems interact and the nature of these interactions.

Previous work has conceptualised interactions of actors within a given system (Dijk, 2014; Geels, 2007; Lin and Sovacool, 2020; Smith, 2007) and *across* systems (Rosenbloom, 2019; Sutherland et al., 2015; Ulmanen et al., 2009). Both within and across systems, interactions can occur between actors of regimes and niches (Geels 2006), between actors of two regimes (Konrad et al., 2008; Raven and Verbong, 2007) or two niches (Bakker et al., 2012). In previous transition studies, conceptualisations of different interaction natures can also be found. *Symbiosis* is when two interacting parties' benefit from cooperation and may become mutually dependent (Konrad et al., 2008; Raven and Verbong, 2007; Rosenbloom, 2019). *Competition* refers to interacting actors actively competing for markets and resources because they serve the same or similar societal function (Raven and Verbong, 2007; Sandén and Hillman, 2011). *Antagonism* refers to asymmetric interactions, such as predator-prey interactions or power imbalances, in which one actor benefits more and the other may be adversely affected (Dijk, 2014; Sandén and Hillman, 2011).

5.2.4 Conceptual framework

Drawing upon these three conceptual building blocks elaborated above, this section synthesizes these elements to develop a conceptual framework. It makes it possible to analyse endogenous regime change processes across five regime fields to study incumbency reorientation for a system reconfiguration. Each regime dimension is understood as a distinct organisational field in this framework. Moreover, it emphasizes the importance of a relational perspective on incumbency to uncover potential regime tensions, zooming in on actor interactions and their varying natures in these fields. Acknowledging the multi-system interactions at play in reconfiguration processes, we propose two over-arching categories for a more precise categorisation of actor interactions within and across systems: *Intra-system interactions* are those in which actors within the same system interact, resulting in changes to the fields of a focal regime. *Inter-system interactions* are those in which actors from different systems interact with each other, precipitating changes that span across multiple systems and restructuring the fields of a focal regime. This distinction is necessary when adopting a multi-system transition perspective to pinpoint those interactions that bring actors from multiple systems into contact. Hence, it enables understanding how the reorientation dynamics of various actors and social groups between existing systems can lead to novel couplings. Recognizing the heterogeneity of interactions, we argue further that the nature of the interaction must also be considered in the framework, and we build on the previously conceptualised interaction natures, including competition, symbiosis, and antagonism. This allows for a more nuanced understanding of the multi-actor dynamics of transitions, where interactions of different systems are not limited to one kind of interaction (Rosenbloom, 2020) but are shaped by many micro-level interactions of varying natures.

Fig. 2 shows our conceptual framework for study analysis and interpretations. This framework allows a system to have multiple regimes, each comprising five regime fields and multiple niches at its periphery. As actors in these fields reorient, aggregated restructuring occurs through 6 types of interactions: *Intra-system interactions*, taking place within the same system, between (1) two regime actors of the same or different regimes, (2) a regime actor and a niche actor, or (3) two niche actors of the same or different niches. *Inter-system interactions* take place across two different systems, between (4) actors from regimes, (5) regime and niche actors, or (6) niche actors in different systems. The nature of these interactions may be competitive, symbiotic, or antagonistic. We apply this framework to analyse relational patterns of actors from multiple systems to increase our understanding of how restructuring processes and the tensions that may arise in this process at an aggregated level contribute to or hinder low-carbon system reconfigurations.

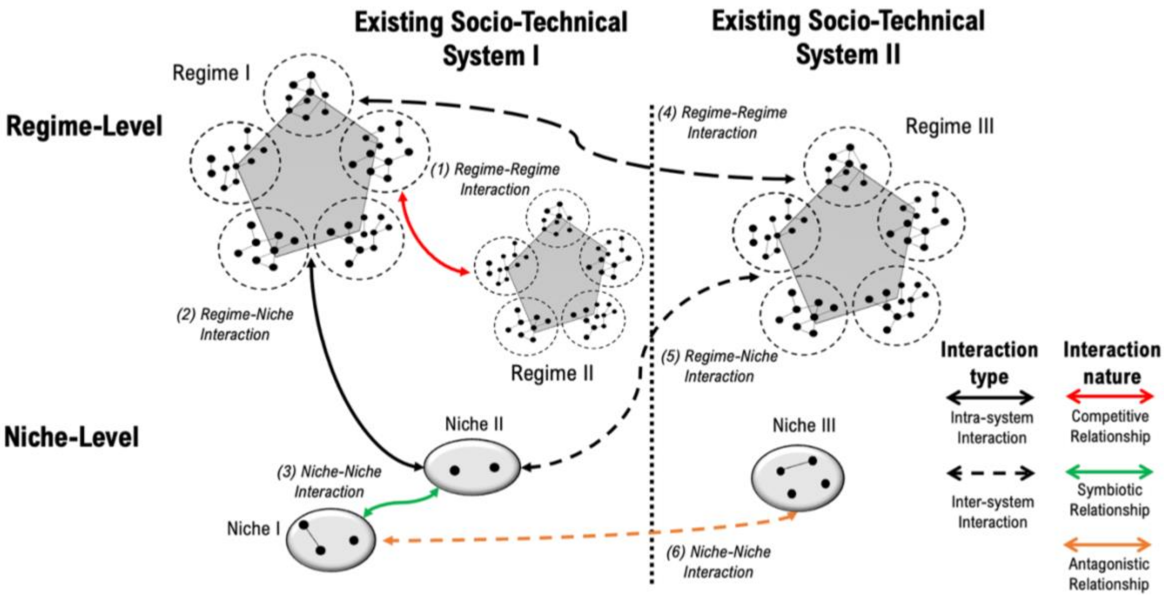


Figure 2. Multi-system reorientation framework (substantially adapted from Rosenbloom, 2020).

5.3 Methods

5.3.1 Case selection

The framework is used to analyse actor-level interactions in the Swedish road freight transport sector to assess interaction patterns within the regime fields of the low-carbon transition toward electrification. Sweden frequently ranks among the top three countries in the world for logistics (World Bank, 2018), and the road freight transport industry has generated over EUR 9 billion per year on average in the last decade (Statista, 2022). For the largest Nordic economy to remain competitively integrated with the world market, efficient road transport of goods is vital. Heavy commercial vehicle manufacturers represent two of the largest companies by annual revenue. These companies are some of Sweden's largest employers and exporters, making them a pillar of the country's economy (Pohl, 2017). Nevertheless, road freight transport today accounts for approximately 90% of Sweden's transport-related CO2 emissions, with heavy trucks contributing the most. Given the expected rise in transport demand, decarbonising the sector by 2030 will be crucial to meeting national climate goals (Fossilfritt Sverige, 2017). In the last seven years, increased awareness of the sector's contribution to climate change and its negative impact on global warming through air pollution and resource depletion have put pressure on governments and freight transport value chain actors. In response, Swedish heavy truck manufacturers are investing multiple hundred million euros in R&D for zero-emission vehicles (ZEVs) and production facilities (Volvo Trucks, 2022b; Scania, 2021), entering strategic joint ventures to finance adequate charging infrastructure (Volvo Trucks, 2022c), and scaling back combustion engine investments (Traton, 2022).

To accelerate the decarbonisation of this sector, the Swedish Government established the Commission for Electrification in 2020 (Regeringskansliet, 2020). This commission's initial plans outlined large-scale electrification of road freight transport to meet the national climate target of cutting the transport sector's CO2 emissions by 70% by 2030 (Regeringskansliet, 2020). Since most Swedish domestic goods are transported regionally (Transport Analys, 2022), the commission has focused on coordinating regional activities to accelerate the transition to fossil-free regional road freight transport. In 2021, this led to 17 Electrification Pledges across 16 Swedish regions (Regeringskansliet, 2021). In the broader European context, the Swedish Electrification Pledges stand out as a unique initiative due to their collaborative approach, engaging a diverse set of stakeholders from the public and private sectors toward a common goal of electrification. Unlike some initiatives with abstract goals, the Electrification Pledges mostly outline actionable activities, providing a clear roadmap for accelerating road freight electrification. Moreover, they involve a sector coupling strategy that aims to electrify the freight transport industry while also increasing the efficiency of the energy systems by, for example, harmonising transport and energy systems through smart charging.

Three interrelated factors motivate the case selection: first, previous studies (Scherrer et al., 2020; Werner et al., 2021) have shown that the electrification of road freight transport involves many different incumbent actors, so studying this transition provides an illustrative case of how established actors reorient their operations in interaction with other actors. Second, Sweden is investigating battery-electric (BEV) and fuel-cell-electric (FCEV) commercial vehicles simultaneously. Accordingly, parallel investments in electric road systems demonstration pilots, stationary mega-watt charging systems, and hydrogen solutions have been made (Regeringskansliet, 2020). Therefore, this case will aid the understanding of the role of regime tensions in system reconfigurations by shedding light on struggles and disputes between actors promoting different technological solutions for electrification. Third, as previously acknowledged (see, e.g., Andersen and Markard, 2020; Geels, 2018b; Rosenbloom, 2019), the reconfiguration of the fossil fuel- and combustion engine-dependent transport sector toward electrification cannot be achieved solely through interactions and reconfigurations within the transport system. Instead, it can be considered a multi-system transition as linkages with other systems, such as the energy system, are needed. Thus, this case is especially prominent for applying our framework because it allows for analysing actors' reorientation activities and the resulting interaction patterns across multiple regimes and systems.

5.3.2 Data collection and analysis

We employ social network analysis (SNA) to map and analyse actor interactions that result from reorientation activities and contribute to field restructuring processes in the focal regime of analysis, road freight transport (see Table 2). Recently, SNA has gained popularity among scholars studying actors and their interactions in transition (Giurca and Metz, 2018; Scherrer et al., 2020; Song et al., 2023). SNA, an application of graph theory, uses nodes to represent network members like organisations and edges to represent their connections, forming a network that can be visualised in maps (Scott and Carrington, 2011). SNA is an appropriate and warranted method for this study because it aids us in mapping actor networks and interactions, thereby revealing the sets of actors that comprise our regime fields and revealing, in the aggregate, structures and change dynamics. SNA, thus, provides insights into actors' network positions, the interactions, and their effect on the network's overall structure (Prell et al., 2009; Scott, 2000). It also enables the production of graphic representations that allow a holistic visualisation of actor interactions at a network level. (Christopoulos, 2006; Prell, 2012). These qualities make the method especially suited for multi-system transition studies, as it allows researchers to capture ongoing developments in detail even when zooming out to study connected transition dynamics across multiple systems.

Our SNA utilised primary and secondary data: We conducted 32 semi-structured expert interviews[17] with stakeholders from the transport, energy, and communication sectors, selected through a snowball sampling technique (Biernacki and Waldorf, 1981). Experts were initially recruited via email or industry events, and they referred us to additional experts. During the interviews, experts supplemented our data with additional resources such as membership lists, unpublished project reports, relevant publications, and presentation slides, which were incorporated into our analysis. We also attended 21 industry events — both online and offline — where actors, policymakers, and researchers discussed the sector's electrification initiatives. Considering the risk of bias in responses during interviews and events (Fisher, 1993), we used secondary sources to triangulate and contextualise our primary data, enhancing the study's reliability (Flick, 2018). To this end, we sourced publicly available reports, individual electrification pledges, press statements (of the Commission for Electrification on road freight transport), annual company reports, industry analyses, media clippings, academic literature, and international research collaboration publications through web-based research. Table 1 provides a comprehensive overview of all data sources used to construct the SNA datasets.

Table x Data sources that informed the SNA.

Type of data	**Number**
Interviews	32
Industry event observations	21
Policy documents	28

[17]A list of the interviewed experts, including which system they were categorised as, actor type, and position of those interviewed, can be found in Appendix C.

Company reports & press releases	41
Media Clippings	72
Scientific publications & research project reports	24

Next, we conducted a directed content analysis on interview transcripts, observation notes, and secondary sources to identify actors and their activities (Potter & Levine-Donnerstein, 1999; Hsieh and Shannon, 2005).[18] Our initial coding categories, formed from the five regime dimensions (technology, science, policy, market and user preference, and culture) and associated rules for each dimension (Geels, 2002: 2004), served as a coding framework for the identified pledge activities. In the first step, all identified activities were categorised based on which regime dimension the activity related to and in the second step, the activities were coded based on which rule of a given dimension they are associated with (cf. Gosh, 2019 for a similar approach).[19] The identified actors performing these activities were grouped into different systems and regimes based on what societal need each actor fulfilled (Papachristos et al., 2013). To represent the plurality of incumbency in the analysis, not only large companies with significant market shares were classified as incumbent actors, but also a variety of other established actor types, such as intuitional, governmental, or societal (cf. Stirling, 2019; Turnheim and Sovacool, 2020) that actively contribute to the stabilisation of existing systems[5]. The remaining actors were grouped into six niche categories, which emerged through coding the interview transcripts, observations and documents based on their primary business models and activities.[20] Table 2 lists the actors for each regime and niche included in the analysis. The connections in the SNA (i.e., actor interactions) were derived from the previously categorised activities of actors within specific regime fields (dimensions). Based on categories of interaction nature from our conceptual framework (symbiosis, competition, and antagonism), these interactions were categorised as symbiotic when activities necessitated collaboration, resulting in mutual benefit. When actors performed activities in parallel, vying for similar resources or market share, these were classified under "competition." Additionally, when actors engaged in

[18]All data sources were manually coded using the qualitative data analysis software MAXQDA.

[19]Appendix A outlines the coding framework for the categorisation of activities including a description of each regime dimensions and associated rules.

[20]As illustrated in previous transition studies on the electrification of the transport system (Werner et al., 2021; Scherrer et al. 2020; Späth et al., 2016; Berggren et al. 2015) also this analysis showed incumbent actors that are active at a niche level. For example, two identified vehicle manufacturers were actively involved in niche development by supplying electric vehicles to commercial demonstration projects around Sweden. We consider this as an example of a reorientation activity. Yet, because the main product offering and the way that these organisations make their largest profit today is through the sale of ICEVs, contributing firmly to the stability of the existing socio-technical system, we classified them as incumbent actors in this study.

cooperative activities, but the benefits or contributions were skewed, leading to power imbalances, these interactions were termed antagonistic.[21]

Table x. Existing socio-technical systems, regimes, niches, and their actor groups are included in the SNA.

System	Freight Transport S1	Electricity S2	Communication S3
Regimes	***Road freight transport*** Vehicle Manufacturers; Carriers; Shippers; Gas Station Franchises; Transport Associations; Road Administration Bodies; Transport Terminals	***Power generation*** Energy Generators; Power Distributors ***Grid infrastructure*** Energy Transmission Operators; Energy Safety Agencies ***Electricity consumption*** Electricity Network Operators; Electricity Suppliers; Energy Market Regulators	***Telecommunication*** Telecommunication Service Providers; Network Providers
Niches	***Electric freight mobility N1*** Autonomous Electric Transport Solution Developers; EV Manufactures; Vehicle Converters ***EV battery technology N2*** Vehicle Battery Technology; Battery Storage; Battery Recycling Solutions Developers ***EV charging N3*** Dynamic & Static Charging Infrastructure Providers ***Hydrogen-powered vehicles N4*** Hydrogen Fuel-Cell Vehicle Manufactures	***Hydrogen Energy N5*** Green Hydrogen Producers; Storage & Refuelling Infrastructure Providers ***Smart-grids N6*** Smart-grid Charging Solution Developers	

Throughout the analysis, we refined those categories and combined the science and culture regime fields due to the following three reasons (1) significant overlaps between the regime fields, (2) maintaining separate regime fields for both science and culture added unnecessary complexity to the analysis without providing additional insight and (3) improved visual data representation in the SNA. This approach produced four node and undirected edge datasets labelled *hereafter Technology & Infrastructure, User Practices & Markets, Policy & Regulations, and Socio-culture & Science*, listing all identified actors for each regime field, containing actors, actor interactions, their nature, and type. We visualised these datasets in *Kumu*, an open-source software that allowed us to analyse and compare the dynamics of individual nodes in regime field networks using advanced metrics

[21]A decision tree for actor classifications can be found in Appendix B.

algorithms. Table 3 offers a synopsis of the SNA metrics used in this study and their interpretations.

Table x. SNA metrics employed and their interpretations in this study.

Network level metrics	**Interpretation**	**Node level metrics**	**Interpretation**
Network Density (DEN= 2En(n−1))DEN= 2En(n−1))	Level of the interconnectedness of actors in a regime field.	Betweenness centrality ($g(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}$)	Identify the actors that fall on the shortest pathway between other pairs of actors thus, have a positional advantage. Following Hanneman and Riddle (2005), actors situated "between" others, hence serving as essential intermediaries for facilitating exchanges, are likely to leverage this brokerage role to wield influence within a regime field.
Average degree (AD=$2En$)AD=$2En$)	The average number of reorientation interactions present in a regime field.		
Average path length (l=1N(N−1)$\sum_{i \neq j} dij$)l=1N(N−1)$\sum i \neq jdij$)	Level of separation between actors in a regime field.		

5.4 Results

5.4.1 Actors in Sweden's reconfiguration of road freight transport

The analysis of Electrification Pledges and additional material on Sweden's low-carbon system reconfiguration identified 324 relevant actors. As shown in Figure 3, many incumbents from three existing systems (Freight Transport, Electricity, and Communication) are driving this transition. Freight Transport (S1) incumbents consistently made up more than half of the total actors in every regime field. Transport carriers, shippers, and regional authorities were this regime field`s most identified actor types. Many actors are embedded in all four regime fields. However, actor involvement varied, with most actors being engaged in activities supporting a low-carbon transition within the *Socio-Cultural & Science* and *Policy & Regulations* regime field.

Three interrelated factors influence actor participation in the regime field differently: (1) low availability of heavy commercial BEVs and FCEVs, (2) lack of public charging infrastructure, and (3) operational costs and functional suitability uncertainties. These barriers to actor reorientations have led to lower involvement of transport carriers in the *Technology & Infrastructure* and the *User Practices* & *Markets* regimes. Electricity system (S2) actors, including electricity suppliers, energy generators, and power distributors, constitute the second largest group of stakeholders. Like road freight incumbents, their participation varies across the different regime fields. The lower contribution of energy incumbents to reconfiguration processes within the *Technology & Infrastructure* and *User Practices* & *Markets* regime fields compared to the other two regime fields can, on the one hand, be attributed to this actor group's expressed difficulties in finding strategic partners. On the other hand, while E-mobility represented a new business opportunity for most of these incumbents, their core business, such as generating and selling energy, remained unchanged. A few Communication (S3) incumbents are also actively involved in reconfiguration processes across all regime fields. Like the S2 actors, they see e-mobility as a new business opportunity. Their digital technologies contribute to a more efficient BEV and charging station operation and management by ensuring seamless connectivity and data transmission.

Moreover, it shows a consistent involvement across all four regime fields of new entrants housed in six different niches. These niches represent low-carbon alternatives to the prevailing internal combustion engine vehicles (ICEVs) and fuelling infrastructure. The two largest identified niches, N3 and N5, include novel actors pioneering technological innovations related to dynamic or stationary charging of BEVs, as well as hydrogen production and refuelling infrastructure. In comparison, both N1 and N4, in which new entrants develop BEVs and FCEVs, are relatively small in actor size, which can be explained by the fact that established vehicle manufacturers in Sweden represent first-mover incumbents in the sense that they not only hold strong positions in the existing market and have already started to substantially reorientate their activities and business strategies toward the manufacturing of zero-emission vehicles (ZEVs). Two additional niches, small in actor size, were identified: N2 includes actors developing battery technology for electric vehicles, and N6 houses a start-up offering smart charging solutions to reduce expensive grid peaks. Both can be considered critical complementary technologies for a low-carbon transition.

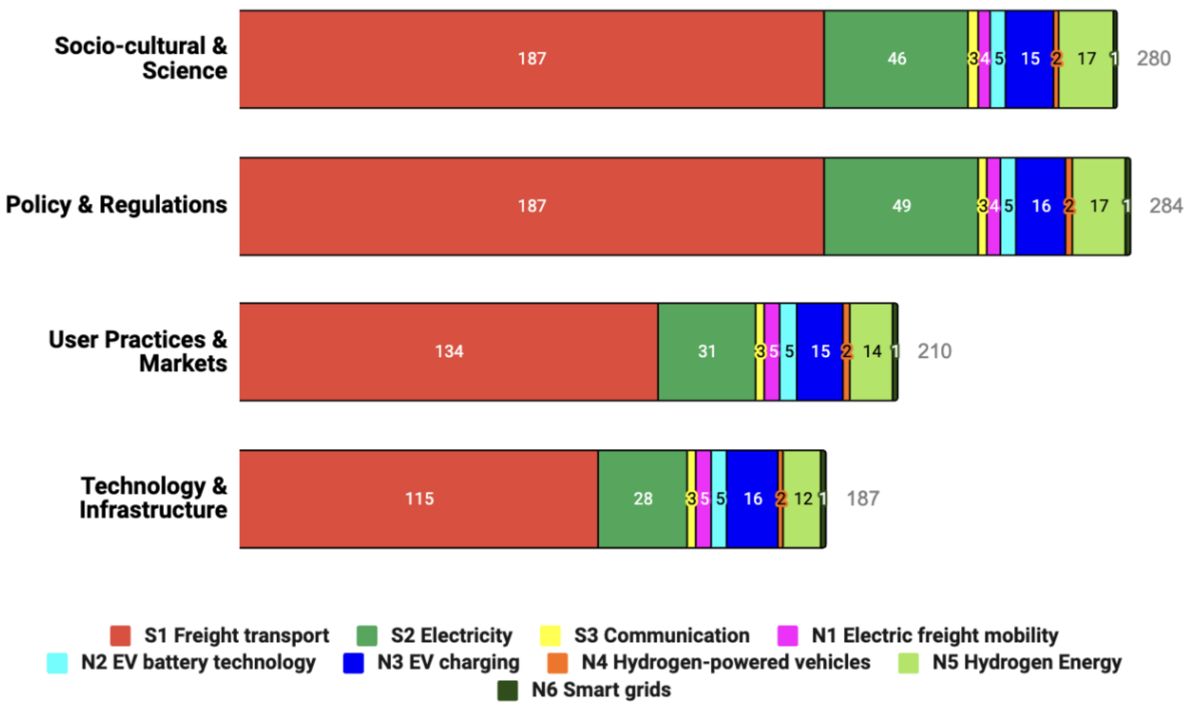


Fig. x Amount and types of actors contributing to the reconfiguration processes of the four regime fields.

The stakeholders in all the electrification pledges examined are committed to a wide range of reorientation activities currently underway in the Swedish road freight sector. The actors' activities were divided into two categories across the four regime fields. The first represented already ongoing activities, such as investments into charging infrastructure and measurable actions with concrete targets, such as shippers committing to convert a portion of their ICEV fleets to ZEVs. They outline substantive reorientation that is already taking place and include quantifiable goals for ongoing and planned activities, thus allowing for a measurable assessment of actor reorientations over the next few years. Figure 4 depicts examples of such concrete reorientation activities organised by regime fields.

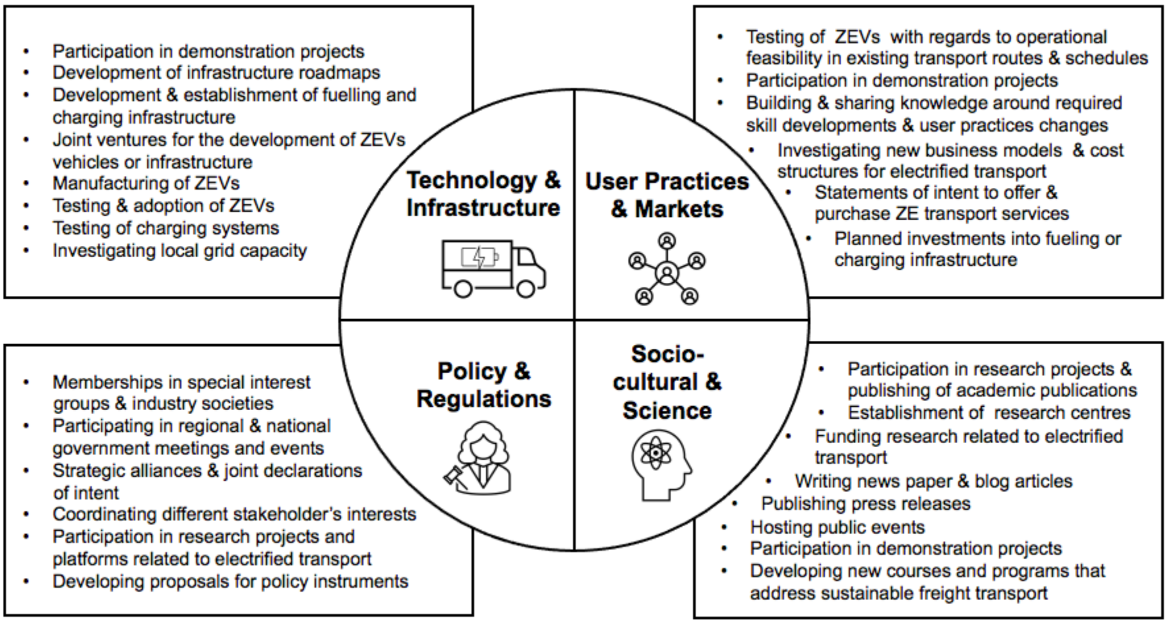


Fig. 4. Examples of different reorientation activities in support of a low-carbon transition within the four regime fields.

Pledges covering joint measures by S1, S2 and S3 actors indicate that the decarbonisation through electrification may cause sector coupling, bringing formally independent systems together. In relation to this, the need for a sufficient amount of charging infrastructure was identified, and S2 actors (e.g., electricity providers) are working jointly with S1 to develop it. To optimise and control charging processes and collect user payments, S3 actors (e.g., telecommunication service providers) collaborate with niche actors and incumbents from S1, providing them with required internet connections and Inter-of-Things platforms. Additionally, several regions entail actor pledges outlining current investments in infrastructure for green hydrogen production and FCEV refuelling. This shows that actors still debate about whether battery- or hydrogen-powered vehicles can achieve fossil-free road freight transport. Only one region focused solely on hydrogen for road freight transport, and few transport operators have ordered or already adopted FCEVs. Instead, most actor activities focus on adopting and accelerating BEVs and their complementary technologies (i.e., charging systems, vehicle batteries, and payment services). Lastly, a substantial amount of the identified reorientation activities included participation in research projects, investigations into required electricity grid capacity, developing roadmaps outlining optimal charging locations, and feasibility studies of ZEVs for various transport assignments (i.e., urban deliveries, long-distance or waste collection). This indicates knowledge gaps about, for example, the functional suitability of ZEVs, required fuelling infrastructure, and ways to handle potentially increased grid loads that must be addressed to accelerate the low-carbon transition.

To contextualise these results regarding their counterpart, it is crucial to highlight that the incumbents included in this analysis do not currently dedicate themselves solely to substantial actor reorientations. For example, heavy commercial vehicle manufacturers, despite expanding their market share in ZEVs continuously (Volvo Trucks, 2023), still predominantly produce and sell ICE-powered vehicles (Volvo Trucks, 2023; Scania, 2023). Similarly, many shipping companies have begun offering electric goods transport services, yet it still represents only a modest, albeit growing, share of their total offerings (Postnord, 2023).

The analysis also identified intentional reorientation activities without clear goals, timelines, or other details that indicate a readiness to change and a desire to help the low-carbon transition. In line with the Swedish word for pledge (*löfte* {neut.} promise), actors promised to reorient to low-carbon technologies and invest in electric transport. These forward-looking reorientation statements frequently ended with "if the feasibility allows for it" and used words like "intent" or "anticipate." To avoid conflating the reorientation dynamics, our SNA excluded these intended activities. It is unclear if and to what extent actor change and reorientation will follow these promises.

5.4.2 Interactions that give rise to field restructuring

The ongoing reorientation activities of incumbents in support of a low-carbon transition and the entry of novel niche actors have allowed actors from multiple systems to interact and engage in field restructuring processes. Figure 5 presents four network graphs of actor types interacting within the four regime fields of the focal regime. Table 5 compares the four networks in terms of the total number of actors and interactions and network metrics.

Table x Network metrics scores within the four regime fields.

	Technology & Infrastructure	**User Practices & Markets**	**Policy & Regulations**	**Socio-cultural & Science**
Total number of actors (Nodes)	187	210	284	280
Total number of interactions (Edges)	713	2697	1085	1239
Intra-system (Symbiotic/Antagonistic/Competitive)	478 (307/62/109)	2431 (300/46/2085)	746 (611/102/33)	902 (841/28/33)
Inter-system (Symbiotic/Antagonistic/Competitive)	235 (120/46/69)	266 (135/48/82)	339 (212/64/63)	337 (251/23/63)
Density	4%	12%	3%	3%
Average degree	7.62	25.68	7.63	8.81
Average path length	2.74	2.42	2.9	2.79

5.4.2.1 Technology & Infrastructure regime field network

As seen in Table 4, the *Technology & Infrastructure* regime field network had the fewest interactions of the four. While it had the second highest network density (4%) among all regime fields, this network showed a minor average degree but not a smaller average path length. This shows that actors, on average, had fewer field restructuring interactions but no greater separation between actors. In this network, the highest percentage of inter-system interactions (33%) were found: predominantly symbiotic interactions between established actors of S1 and S2, highlighting the importance of strategic partnerships between incumbents of the two existing systems for reconfiguring the dominant design of ICEVs and fossil fuel infrastructure toward low-carbon alternatives. Table 5 shows examples of inter-system interactions in this regime field network.

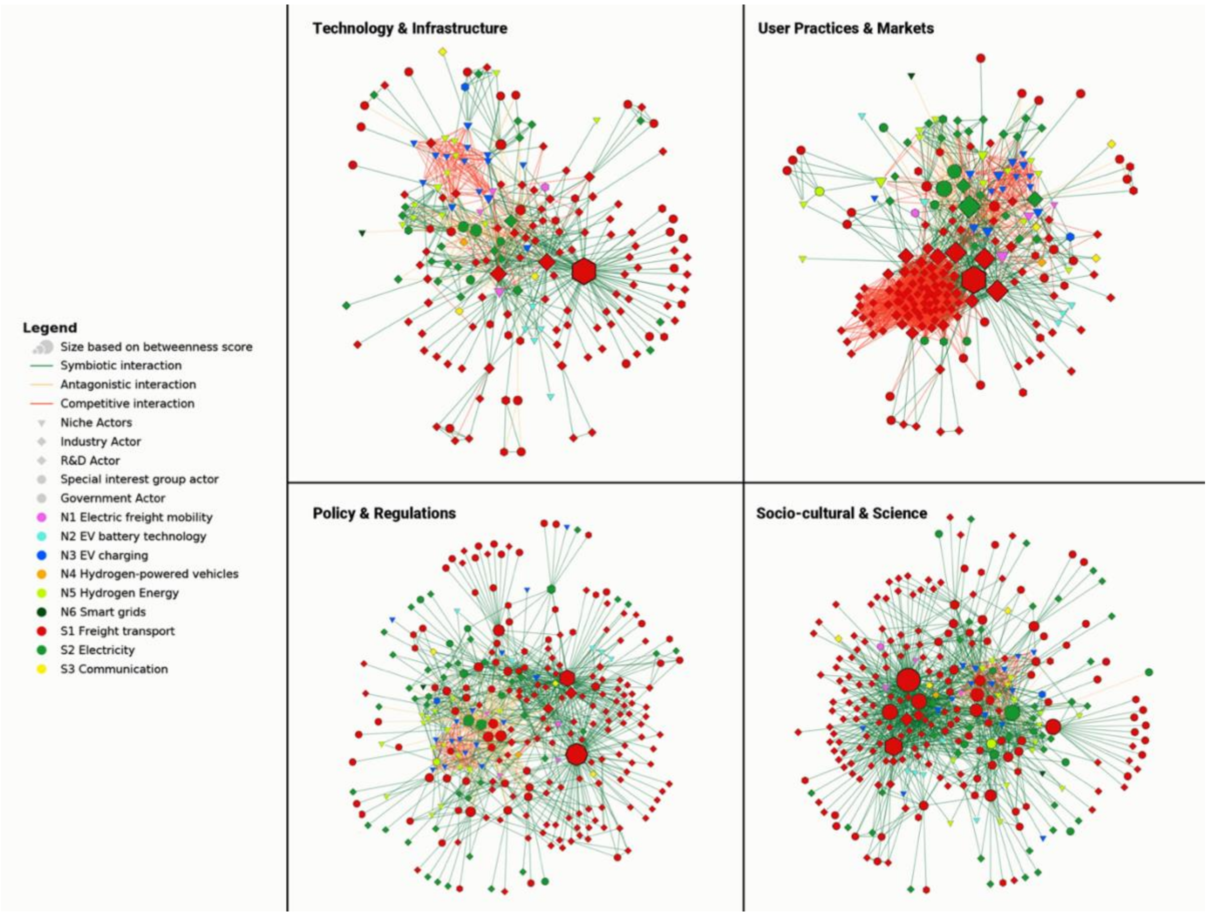


Fig. x Interactions within the four regime field networks, illustrated as binary, undirected network graphs; edge colour represents the interaction nature, and node size indicates the betweenness score.

There are many symbiotic inter-system interactions between incumbents in the same system and between established actors and niche actors that operate at the edges of S1 and S2 and between niche actors. The highest number of competitive interactions was observed between niche actors of N3 and N5, illustrated through the tight web of red interactions at the top right of the *Technology & Infrastructure* graph (see Figure 5). Actors in these two niches develop dynamic and static charging and hydrogen refuelling infrastructure. Thus, they are in direct competition for governmental subsidies and industry partnerships. The dense interactions and competition between N3 and N5 highlight a critical stage of technology development where electric and hydrogen solutions compete to set future industry standards. As shown in Table 4, antagonistic interactions are the most common in this regime field network. Examples (see Table 5) include actors' asymmetric dependence on government fund agencies and regulatory bodies.

Table 5. Illustrative examples of different types of interactions present in the *Technology & Infrastructure* regime field network derived through our analytical framework.

	Intra-system			**Inter-system**		
	Regime-Regime	Regime-Niche	Niche-Niche	Regime-Regime	Regime-Niche	Niche-Niche
Symbiotic	Interactions between energy generators & electrical infrastructure companies to develop charging systems for BEVs.	Interactions between shippers & vehicle converters to refit ICEVs with batteries.	Interactions between vehicle battery technology developers & battery recycling companies to advance battery recycling schemes.	Interactions between vehicle manufacturers & power companies to develop charging systems for BEVs.	Interactions between shippers & hydrogen refuelling infrastructure providers to build refuelling stations.	Interactions between FCEV manufactures & hydrogen refuelling infrastructure providers to offer integrated vehicle + refuelling solutions.
Antagonistic	Interactions between vehicle manufacturers & transport administration to find technological standards.	Interactions between transport administration & dynamic charging companies to decide on dominant technology.	----	Interactions between transport administration & energy transmission operators for charging station permits.	Interactions between energy safety agencies & green hydrogen producers to develop product safety standards.	----
Competitive	Interactions between vehicle manufacturers to develop superior BEV technology.	Interactions between vehicle manufacturers & BEV manufacturers to develop superior BEV technology.	Interactions between stationary & dynamic charging providers to develop superior charging solutions.	Interactions between energy generators & vehicle manufacturers to develop superior charging solutions.	Interactions between vehicle manufacturers & FCEV manufacturers to develop superior FCEV technology.	Interactions between stationary charging providers & hydrogen refuelling infrastructure providers to develop superior technological solutions.

The *Technology & Infrastructure* regime field network's most central actor was a national research platform (seen at the lower left side in the graph of Figure 5). No other actor in any of the four regime field networks scored such a high betweenness number (see Table 6), indicating the national research platform's influence in connecting different types of actors and orchestrating reorientation activities within this regime field. Looking at the following nine actors based on betweenness centrality, we can see that incumbents from the Freight Transport (S1) and Electricity (S2) systems act as key bridges within this regime field and influence restructuring processes.

Table 6. Top 10 actors ranked by betweenness scores within each regime field.

Betweenness centrality rank	**Technology & Infrastructure**	**User Practices & Markets**	**Policy & Regulations**	**Socio-cultural & Science**
#1	Research Platform (0.334)	Research Platform (0.101)	Special Interest Group (0.257)	Media Outlet (0.188)
#2	Vehicle Manufacturer (0.167)	Electricity generator, supplier & power distribution network operator (0.078)	Research Platform (0.17)	Research Platform (0.142)
#3	Vehicle Manufacturer (0.156)	Vehicle Manufacturer (0.074)	Vehicle Manufacturer (0.093)	Media Outlet (0.097)
#4	Electricity generator, supplier & power distribution network operator (0.091)	Shipper (0.072)	Freight Transport Consortium (0.083)	Media Outlet (0.092)
#5	Autonomous Electrified Transport Service Provider (0.072)	Vehicle Manufacturer (0.070)	National Energy Agency (0.076)	National Energy Agency (0.092)
#6	National Energy Agency (0.061)	Carrier (0.048)	National Transport Administration (0.074)	Freight Transport Consortium (0.091)
#7	Stationary Charging Solution Developer (0.061)	National Energy Agency (0.039)	Vehicle Manufacturer (0.065)	Vehicle Manufacturer (0.076)
#8	Shipper (0.042)	Electricity generator, supplier & power distribution network operator (0.038)	National Transport Research Institute (0.063)	National Transport Administration (0.074)
#9	Energy Safety Agency (0.042)	Carrier (0.038)	Energy Safety Agency (0.061)	National Commission for electrification (0.066)

#10	Electricity generator, supplier & power distribution network operator (0.042)	Electricity generator, supplier & power distribution network operator (0.035)	Regional Authority (0.051)	Vehicle Manufacturer (0.052)

5.4.2.2 User practices & Markets regime field network

The *User practices & Markets* regime field network has the most restructuring interactions and the shortest average paths. With fewer actors than *Policy & Regulations* and *Socio-cultural & Science*, this regime field network has the highest average degree and network density (12%). Inter-system interactions within S1 of competitive nature contribute significantly to these scores, as shown by the red interaction webs in Figure 5. These actor clusters represent interaction patterns between transport carriers and shippers, fiercely competing to adopt ZEVs cost-effectively to offer sustainable, low-emission transport. Moreover, Table 7 shows how symbiotic intra-system interactions help legitimise the new technology. The prevailing symbiotic interactions within the intra-system category reveal a high-level cooperation amongst actors to address shared regulatory challenges related to electrification.

Table 7. Illustrative examples of different types of interactions present in the *User practices & Market* regime field network derived through our analytical framework.

	Intra-system			**Inter-system**		
	Regime-Regime	Regime-Niche	Niche-Niche	Regime-Regime	Regime-Niche	Niche-Niche
Symbiotic	Interactions between vehicle manufacturers to co-create proposals for changes to weight requirements regulations for BEVs.	Interactions between research institutes & BEV manufacturers to develop favourable policy instruments, e.g., direct user insensitive.	Interactions between green hydrogen producers & refuelling infrastructure providers to influence favourable policy developments for hydrogen solutions.	Interactions between vehicle manufacturers & power companies to co-create proposals for regulatory changes.	Interactions between transport administration & smart-grid charging solution providers to co-create proposals for BEV smart-charging regulations.	Interactions between FCEV manufacturers & green hydrogen producers to influence favourable policy developments for hydrogen solutions.

Antagonistic	Interactions between special interest groups & transport administration to influence favourable policy developments for transport operators.	Interactions between transport administration & autonomous electric transport solution developers over required road regulations.	---	Interactions between energy market regulators & special interest groups to influence favourable policy instruments for reliable electricity pricing for transport operators.	Interactions between energy market regulators & stationary charging providers over needed electricity regulatory frameworks for the deployment of high-power charging Infrastructure.	---
Competitive	---	---	Interactions between stationary & dynamic charging providers to influence policy in favour of their technological solution.	---	---	Interactions between FCEV manufacturers & BEV manufacturers to influence policy in favour of their technological solution.

Inter-system interactions within this regime field network are predominantly symbiotic, but like the *Technology & Infrastructure* regime field network, new entrants from N3 and N5 stand in direct competition. Both market formation and understanding of user practices such as travel behaviours and vehicle charging times are essential for developing charging standards, infrastructure deployment best practices, optimal charging locations, and payment solutions. Industry actors and regulatory bodies from S1 and S2 also have antagonistic interactions in this network (see Table 7). This antagonism represents a barrier to the swift implementation of BEVs, as it points to currently unresolved issues in regulatory frameworks related to vehicle standards, charging infrastructure and energy requirements.

The node with the highest betweenness centrality (see Table 6), representing the actors with the most influence over ongoing regime field restructuring processes, is once again a national research platform that connects industry actors and public agencies from S1 and S2 in pilot projects directly aimed at co-creating favourable market conditions for BEVs.

5.4.2.3 Policy & Regulations regime field network

Policy & Regulations has the second-lowest number of interactions and network density (3%). (Table 4). This regime field had the lowest average degree and longest average path length. The top and bottom actors from S1 cluster around special interest groups in Figure 5. These groups allow actors to express their concerns, voice opinions, and build common future visions, attempting to influence public policy. Consequently, Table 6 lists a special interest group of freight transport as the actor with the highest betweenness scores in the *Policy & Regulations* regime field network. Over a third of all interactions were inter-system interactions, and most were symbiotic (see Table 4). Table 8`s left side shows examples of inter-system interactions within this regime field. Within and across systems, competitive interactions between new entrants to niches with non-complementary technological solutions were mainly observed. Inter- and intra-system antagonistic interactions mostly occurred between influential actors (higher betweenness scores) of S1 and S2 and governmental authorities like the transport administration and the energy market inspectorate. This influence of governmental authorities in this regime field network is also reflected by their four appearances in the top ten actors with the highest betweenness scores (see Table 6).

Table x. Illustrative examples of different types of interactions present in the *Policy & Regulations* regime field network derived through our analytical framework.

	Intra-system			**Inter-system**		
	Regime-Regime	Regime-Niche	Niche-Niche	Regime-Regime	Regime-Niche	Niche-Niche
Symbiotic	Interactions between carriers & vehicle manufacturers to understand the total operating costs of BEVs.	Interactions between shippers & autonomous electric transport solution developers to understand the skills development required for the terminal personnel.	Interactions between green hydrogen producers & refuelling infrastructure providers to develop integrated business economics models.	Interactions between vehicle manufacturers & power companies to understand the profitability of charging systems for BEVs.	Interactions between energy generators & EV battery developers to showcase the functionality of their battery solutions for trucks.	Interactions between FCEV manufactures & hydrogen refuelling infrastructure developers to generate financing models.
Antagonistic	Interactions between gas stations & transport administration to develop a road network for charging stations.	Interactions between transport administration & FCEV manufactures to legitimise the application of their technology for trucks.	Interactions between vehicle converters & vehicle battery technology providers to scale up modular battery pack developments.	Interactions between transport administration & electrical infrastructure providers to legitimise their technological solutions through funding.	Interactions between energy market regulators & dynamic charging infrastructure developers to legitimise their technological solution through funding.	Interactions between FCEV manufacturers & green hydrogen producers to secure an upscaling of hydrogen fuel production.
Competitive	Interactions between energy generators to locate optimal charging locations.	Interactions between vehicle manufacturers & BEV manufacturers to understand travel	Interactions between stationary & dynamic charging providers to	Interactions between energy generators & vehicle manufacturers over the	Interactions between gas stations and refuelling infrastructure providers over	Interactions between battery & hydrogen storage providers over

		behaviours & vehicle charging times.	understand infrastructure deployment best practices.	development of charging standards.	favourable locations for optimal infrastructure locations.	the lowest cost of energy storage.

5.4.2.4 Socio-cultural & Science regime field network

The Socio-cultural & Science regime field network had the most actors and was the second-largest network for detected interactions. Actors in this network also showed the second-highest average degree. Despite a low network density (3%), actors were not less (or more) closely connected than within the other regime fields (Table 5). Intra-system interactions of a symbiotic nature were the most common and mostly revolved around established actors from S1 reconfiguring together the storylines and dominant cultural discourse around road freight transport. Table 9 lists examples.

Table x. Illustrative examples of different types of interactions present in the *Socio-cultural & Science* regime field network derived through our analytical framework.

	Intra-system			**Inter-system**		
	Regime-Regime	Regime-Niche	Niche-Niche	Regime-Regime	Regime-Niche	Niche-Niche
Symbiotic	Interactions between transport operators & media outlets to produce articles on their sustainability efforts.	Interactions between universities & autonomous electric transport solution developers to collaborate on research projects.	Interactions between vehicle battery technology producers & battery recycling solutions providers to co-fund research projects.	Interactions between (transport) media outlets & power companies to produce articles on their charging system offerings for transport operators.	Interactions between power companies & stationary charging solution providers to produce press releases on their heavy vehicle charging solutions.	Interactions between FCEV manufacturers & green hydrogen producers to influence the dominant cultural discourse around the application of hydrogen for heavy vehicles.
Antagonistic	Interactions between universities & transport administration to obtain funding for research projects.	Interactions between the energy agency & green hydrogen producers to obtain funding for system demonstrators.	---	Interactions between the transport agency & power companies to obtain funding for pilot projects.	Interactions between energy agency & battery storage developers for research around battery energy storage systems for transport terminals.	---
Competitive	Interactions between vehicle manufacturers to alter the	Interactions between vehicle manufacturers & stationary	Interactions between stationary & dynamic	---	Interactions between gas stations and refuelling	Interactions between FCEV manufacturers & BEV

	dominant cultural discourse around commercial applications for BEVs in their favour.	charging providers to shape norms and beliefs around who can provide charging systems to transport operators.	charging providers to shape norms and beliefs around which technological solution is the best.		infrastructure providers to influence the cultural discourse around the future of truck fuelling infrastructure.	manufacturers to shape norms and beliefs around which technological solution is the best.

Transport media outlets' influence over the reconfiguration process is reflected in how this actor type scored the highest, third highest, and fourth highest betweenness values of all network actors in this regime field (see Table 7). Actors in N1 compete with one another to shape norms and beliefs about the best technological solution, and they also compete across the niches with N5 actors. Overall, this regime field network had the fewest inter-system interactions of the analysed networks, which were mainly symbiotic (Table 4). Figure 5 shows how research platforms, the electrification commission, and universities clustered S1, S2, and S3 actors together, facilitating inter-system interactions. These actors simultaneously contribute to restructuring socio-cultural and science regime fields through publications, events, and new research that creates scientific programs that ultimately change the discourse around freight transport.

5.5 Discussion

5.5.1 Toward a dynamically evolving view of regime field restructuring

Examining the relational dynamics across different regime fields, our findings uncovered a range of disagreements and conflicts among actors concerning potential system reconfiguration pathways. These conflicts primarily arose from divergent views on technological adoption, infrastructure development, and regulatory requirements and have created tensions rather than alignment. In Sweden, ambitious decarbonisation goals for the road freight sector provide an impetus to shift regime fields from dynamic stability to more radical field restructuring processes. These result from the entrance of new actors, including energy service providers, charging infrastructure developers, zero-emission truck start-ups and novel interaction patterns of varying natures among field members. Our analysis, hence, revealed a more dynamic view of regime change processes, in line with a non-static theorisation of organisational fields (Wooten and Hoffman, 2017). Figure 5 depicts dynamic sites of conflict, competition, and collaboration where actors come together to develop new field rules and a common meaning system, encompassing shared beliefs, norms, and expectations about how electrification should proceed, what the benefits are, how challenges should be addressed, and what roles various stakeholders play in this low-carbon transition. Thus, our study's results show that regime fields are dynamically evolving in the context of a low-carbon transition as actors try to make sense of required field restructuring processes and re-establish a common meaning system. Endogenous change mechanisms include strategic activities of field members, novel multi-actor interaction patterns, and the formation of new coalitions between formerly independent systems.

Nevertheless, our results disclose that the stabilisation of field rules is currently challenged by various regime tensions, as represented through competitive and antagonistic interactions within the different regime fields. These include disputes and competitions over which ZEV drivetrain will be the leading technology for sector decarbonisation, rivalry over technological standards for electricity payment and charging solutions, asymmetrical dependencies on energy transmission operators for providing adequate grid capacity, and reliance on policymakers for drafting a consistent regulatory framework for electrification. Moreover, our analysis found differences in incumbent actors' involvement in restructuring processes across regime fields. The type and number of actors and their strategic positionings across the different regime fields may naturally vary because different sets of rules (e.g., dominant technological designs, regulations, or user practices) are produced by different actors (e.g., engineers and lawmakers). Nevertheless, we identified barriers to entry and a lack of involvement of relevant incumbent actors from the road freight regime in the *Technology & Infrastructure* and *User practices & Markets* regime fields.

For both regime fields, transport operators, who represented the actor group with the most significant discrepancy in regime field involvement, face high initial capital costs when considering the adoption of electric trucks. The limited availability of charging infrastructure and concerns about grid connections further represented barriers to the reorientation of transport operators. Additionally, participation in funded research projects is often not feasible for smaller hauliers due to limited resources and expertise, hindering their ability to partake in the ongoing low-carbon transition actively.

5.5.2 Plurality of incumbency and their influence over system reconfigurations

As our results show, once one moves past a constraint analytical scope on established actors, like large companies, toward a more relational perspective that examines interactions and dependencies between different actors in the various regime fields as they reorientate toward low-carbon innovations, it becomes possible to investigate a multiplicity of different forms of incumbency (Stirling, 2019; Turnheim and Sovacool, 2020). In the case of the Swedish road freight sector, additionally to established companies, such as vehicle manufacturers, universities, special interest groups and end users – through their (inter) actions – reproduce the stability of prevailing regime fields and influence the directionality of system reconfigurations. For example, the nation's internationally recognised engineering institutions, as of today, still run specialized programs producing a steady stream of engineers with expertise in ICEVs. While strengthening Sweden's prowess in traditional automotive engineering, this educational orientation inadvertently stabilises the existing regimes. The deep entrenchment of such educational and professional pathways exemplifies the intricate layers of incumbency within the studied context. Our results, thus, illustrate the interconnected nature of incumbency in the sense that it is so deeply embedded in the social and material realms that guide an industry sector. It will, therefore, not be enough for individual incumbent actors to be "overthrown" by new entries to decarbonise the sector drastically. Instead, reconfiguring existing systems requires radical restructuring and the creation of new field rules. This would enable a shift in the common meaning system of incumbency, triggering rhizomatic change from within.

In this study, incumbent actors held strong positions across all regime field networks, with heavy vehicle manufacturers having the highest betweenness scores, making them the most influential actors with a home field advantage. Acknowledging this central role of established actors raises questions about their power and influence (cf. Turnheim & Sovacool, 2020) over the pace and direction of low-carbon system reconfigurations: These vehicle manufacturers understood that change would occur with or without them. Interviewees described a reorientation toward electrification as a way to actively shape the future of a fossil-free freight transport sector and maintain industry competitiveness. This may lead to new forms of undesirable lock-in by influencing the directionality of reconfiguration, e.g., by shaping the market for commercial ZEVs through their product offerings. Presently, manufacturers develop BEVs with increasingly large batteries to match the driving range of ICEVs, allowing transport operators to switch with fewer changes to transport management practices. BEVs with large batteries have higher vehicle life-cycle emissions compared to those with smaller batteries (Morfeldt et al., 2022), so if manufacturers continue this trend without considerations for second-life solutions for these big batteries, they may promote a drive-train substitution and inhibit more radical system reconfigurations needed for effective and fast decarbonisation of the sector. Actor reorientation activities, thus, should not be viewed as inherently positive, but their motives and activities must be critically evaluated case by case.

5.5.3 Inhibitors and enablers of a low-carbon system reconfiguration

Through the application of our framework, many competitive interactions between transport operators in the nascent market of sustainable low-emission transport were revealed in the *User practices & Markets* regime field network, which currently hinders an accelerated reconfiguration. Both carriers and shippers perceive a switch to ZEVs as a way to increase customer value and gain a competitive edge in today's low-margin freight market. The reconfiguration toward fully electrified transport raises questions about logistic flows around charging networks, operational costs, fleet characteristics, and the overall work environment. Individual organisations must address these knowledge gaps while running their day-to-day business. Several research initiatives are underway in Sweden to help transport operators electrify their operations, but collaboration and data sharing are rare. Transport operators recognise the role that shared data can play in accelerating system reconfigurations (e.g., sharing data on vehicle routes would enable a better understanding of both charging network locations and power requirements) but fear losing their competitive edge. This reluctance to share data, driven by competitive concerns, stagnates the development of a common meaning system and thus acts as an inhibitor of broader reconfigurations essential for a low-carbon transition in the road transport system.

In addition, the electrification of road freight transport in Sweden requires integration with the energy system, and the findings across all regime field networks showed a broad involvement of actors from there. Hence, this study corroborates prior findings (Andersen & Markard, 2020; Rosenbloom, 2019; Geels, 2018b) that decarbonisation of entire industry sectors cannot be achieved merely by reconfiguring one system. Instead, it involves establishing new field rules that emerge from symbiotic interactions between actors across multiple systems. For example, energy companies have formed strategic collaborations with incumbents and niche actors in freight transport based on common interests. Such novel ties between actors from formally separate systems shape the directionality of reconfiguration processes, yet establishing them is challenging for many organisations. Our analysis also highlights the role and influence of research projects and initiatives in addressing this challenge by bringing stakeholders of multiple systems together. These projects and initiatives serve as multi-system intermediaries, enabling actors of different systems to connect, coordinate their interests, and develop a common meaning system within regime fields.

5.6 Conclusion

In this study, we have explored the complex dynamics of incumbency reorientations in ongoing low-carbon transition. While recent reconfiguration approaches (Geels, 2020; Geels & Turnheim, 2022) have developed an analytical perspective that emphasises the importance of incumbent reorientations, our paper has complemented such approaches by enhancing our conceptual understanding of *how* such incumbency reorientation dynamics - the changes in interaction patterns among incumbents as they reorientate - unfold. By focusing on actor reorientation activities and the nature of actors' interactions within the different dimensions of a regime, our work thus highlights that i) incumbency reorientations do not happen in isolation but through novel interaction and interaction patterns within and across multiple systems and that ii) actor involvement and interactions may vary across regime fields, so incumbency reorientation dynamics are multi-dimensional. These interaction patterns vary strategically for each regime field, resulting in divergent actor positions and role constellations across the different regime fields as actors restructure fields, produce new field rules, and, at an aggregated level, shape system reconfiguration processes. By applying our conceptual framework, we were, therefore, able to better understand the multi-actor dynamics of unfolding low-carbon transitions by showing how changes to field-level interactions shape system reconfigurations.

In addition, while previous work acknowledged internal regime tension (Geels, 2004), our study underscores the potential of these tensions to hinder system reconfigurations by using organisational fields as a methodological construct to explore the dynamics of incumbency reorientations. Therefore, future research should explore how to overcome such tensions to allow for the stabilisation of field rules within different regime fields. This presents an important area of future work that can enhance the understanding of how to accelerate system reconfigurations. This paper introduced a novel analytical lens focusing on emerging reconfiguration processes that lead to multi-system interactions by differentiating actor interactions within and across existing systems. While this study is a first attempt to gain a better understanding of the role of reorientation dynamics of incumbent actors from multiple systems, the cascading effects of transitions across multiple systems and bi-directionality of interactions — how one system's reconfiguration can affect another — also need more research.

We further revealed three aspects that have the potential to inhibit ongoing reconfigurations: First, a lack of involvement of actors may slow the development of new common rationalities in any regime fields and hinder the reconfiguration of the dominant system trajectories. This raises questions about the inclusion and exclusion of stakeholders in reorientation activities and suggests a third future research direction on how missing actor participation affects the pace and scope of system reconfigurations. Second, given the strong influence of incumbent in our studied context, a decline in their reorientation commitments may also slow down the low-carbon transition and instead stabilise existing systems. This highlights the potential pitfalls of a dominant involvement of incumbency in system reconfigurations. Therefore, understanding how to manage these challenges effectively constitutes a fourth warranted direction for future research where more attention is needed. Third, although market competition can force organisations to innovate and become more efficient and cost-effective, in the studied case, these competing issues between transport operators are slowing the BEV adoption, inhibiting a low-carbon transition. In Sweden's road freight sector, platforms for anonymous data sharing may be a solution. However, our findings highlight that revisiting axiomatic market principles as a fifth route for future research could be worthwhile to understand their effects on low-carbon innovation adoption and diffusion.

The presented research has limitations that could inform further research. First, our study should be viewed as an initial attempt to capture the heterogeneous dynamics of incumbency reorientations in low-carbon transitions by empirically focusing on an industry transition in a technologically advanced country. Future studies could apply our framework to analyse actors, activities, and field-level interactions in other industries to explore their system reconfiguration and build a comparative research portfolio. Moreover, this study examined how incumbency reorientation dynamics contribute to system reconfigurations by analysing incumbents' responses to a low-carbon transition. However, investigating actor activities that contribute to the stability of existing regime fields is beyond the scope of this paper. Previous studies have highlighted that incumbents may continue to carry out stabilising activities (Steen and Weaver, 2017). Still, we call for future research to address how incumbent actor strategies can simultaneously overcome the dualism of stabilising and reconfiguring. Without an integrated analysis of reorientation and stabilisation actor activities, it is difficult to assess whether regime field restructurings can lead to radical system reconfiguration. Therefore, it is warranted for research to explore this by focusing on developing frameworks and methodologies that allow a comparative analysis of change and stability. Furthermore, despite the efforts to include only tangible, ongoing reorientation activities in our analysis, minor discrepancies may persist between interviews, pledges, and actual practices. At present, the reorientation dynamics in the Swedish road freight sector are beginning to emerge, and our analysis can thus only provide insights into a temporal window of system reconfiguration. Given the unfolding nature of these dynamics, outcomes are still unclear. Therefore, further long-term studies are needed as more data becomes available.

Lastly, this work has important policy implications. Our analysis of the pledges highlights that many actors currently merely *intend to* reorientate to low-carbon practices. Thus, policymakers must create measures and instruments that encourage actors to fulfil their pledges, allowing intended change to occur. Our findings can also help policymakers understand the influence and interdependence between actors from multiple systems in a transition. In the studied case, the lack of a coherent regulatory framework across industries hindered actor reorientations. Therefore, a successful system reconfiguration will require a shift from today's single-system-focused policy instruments to a multi-system transition governance approach that can solve regulatory issues that emerge through interactions and couplings between formerly separate systems.

6. Decline and resistance

Presented at the International Sustainability Transition Conference 2024 as: Ertelt, S.-M., Breslin D., and Kask J., (2024). From carbon lock-in to climate neutrality? Exploring the decline-innovation nexus in the net-zero transition of the EU heavy-duty vehicle sector. (In preparation for submission).

Abstract: Achieving global net-zero ambitions will require profound changes in hard-to-abate sectors, which are currently responsible for up to 30% of global CO_2 emissions. These sectors are characterised by high levels of path dependency due to entrenched, carbon-intensive technologies and their transition thus will not only require the development and rapid deployment of low-carbon innovations but also the phase-out of prevailing carbon-intensive technologies. Utilising path constitution theory this paper explores the timing and sequencing of this path creation (innovation) and destruction (decline) through a longitudinal case study of the European heavy-duty vehicle sector. Our findings reveal that once a threshold of path destabilisation is reached, innovation and decline become mutually reinforcing. Based on these findings, we theorise this process as one of punctuated equilibrium, characterised by a nested hierarchy of coevolving path dynamics at organisational, technological and industry level that is facilitated by seven specific conditions. Consequently, this study contributes to the theoretical understanding of the decline-innovation nexus and provides policy recommendations to accelerate net-zero transitions in hard-to-abate sectors.

Keywords: Hard-to-abate industry, Path constitution, Technological decline, Low-carbon innovation, Punctuated Equilibrium

The following content has been removed as it is unpublished original material.

7. Consumer practises and demand patterns

Published as: Ertelt, S.-M., 2024. Beyond predict and provide: Embracing sufficiency synergies in road freight electrification across the European Union. *Energy Research & Social Science,* 111, p.103498. https://doi.org/10.1016/j.erss.2024.103498

Abstract: The challenge of aligning with the net-zero ambitions of the European Union necessitates a critical examination of the road freight transport sector, a pivotal contributor to global commerce and greenhouse gas emissions. Despite the sector's potential for electrification to mitigate emissions, the prevailing 'predict and provide' planning approach may inadvertently reduce this low-carbon transition to mere technological substitution, neglecting deeper intrinsic transport issues. This perspective critiques the 'predict and provide' approach and advocates for the adoption of 'sufficiency-oriented planning'. It presents a comprehensive, interconnected approach, challenging not only the technology in use but also the foundational principles of transport demand. Furthermore, it explores the broader implications of this multi-system transition for the energy sector. The perspective consequently underscores the necessity of a paradigm shift in planning for road freight transport electrification for the sector to genuinely contribute to sustainability objectives and not risk diminishing the transformative potential of this transition.

Keywords: Road freight transport, Electrification, Sufficiency, Multi-system transition, Transport planning

7.1 Introduction

The challenge to combat climate change is becoming increasingly urgent as the European Union (EU) member states continue their collective journey towards the Paris Agreement's targets and the broader goal of net-zero emission societies. The road freight transport sector is essential in this decarbonisation journey (Meyer, 2020). Economically, it is indispensable, acting as the backbone of commerce by facilitating the movement of goods across the EU and beyond. Yet, its environmental footprint is disconcertingly substantial: Heavy-duty vehicles represent less than 5% of vehicles on European roads but are responsible for around 25% of road transport carbon dioxide (CO2) emissions and approximately 2-4% of the EU's total emissions (Shoman et al., 2023)(EEA, 2022). Despite the overall decline in CO2 emissions across various sectors in the EU, truck emissions have steadily increased over the last three decades (1990-2020), except for a brief downturn in 2020 due to the COVID-19 pandemic (EEA, 2022). The sector's considerable greenhouse gas emissions underscore its dual role as both an economic catalyst and a significant environmental challenge (McKinnon, 2018). Achieving a balance between continued movement of goods and substantive emissions reductions is therefore crucial if the aims of the Paris Agreement and net-zero ambitions are to be realized.

Electrification has rapidly emerged as a potential solution to this challenge (Liimatainen et al., 2019), (Nykvist and Olsson, 2021). While there is no clear technological pathway for the electrification of road freight transport as of now (Plötz, 2022), potential solutions, for example, include direct use of electric energy in battery-powered trucks and hydrogen fuel-cell trucks powered by green hydrogen from renewable electricity (Plötz et al., 2023). The EU supports the electrification of the sector through the ‘Fit for 55’ package, which aims to reduce greenhouse gas emissions by at least 55% by 2030 (European Comission, 2023a). This includes the Alternative Fuels Infrastructure Regulation (AFIR), which introduces targets for deploying truck charging and hydrogen refuelling infrastructure. Additional policy initiatives include the review of emission standards for heavy-duty vehicles (European Comission, 2023b), incentivizing trackmakers to manufacture electrified trucks and the revision of the Weights and Dimensions Directive, potentially allowing for changes in vehicle design that can accommodate the additional weight of electric batteries (“The weights and dimensions law can accelerate zero-emission truck sales,” 2023). By transitioning from predominantly diesel-fuelled trucks to electric counterparts, the hope is to significantly curtail direct emissions. Moreover, as electrical grids continue to green—due to increasing shares of renewable energy—the potential emissions savings from electrified road freight transport increase further (Binsted, 2022). While the market adoption rates of commercially available electrified trucks in the EU at less than 1% of total vehicle sales are still low (Mulholland and Rodríguez, n.d.), based on the sales announcements of trackmakers in compliance with existing CO2 standards, there could be more than 600.000 of such vehicles on European roads by 2030 (T&E, 2022).

The point of departure for this perspective is the critique that the prevailing 'predict and provide' (P&P) approach, (Filippi, 2022), (Alessandrini et al., 2023), (Curtis, 2020) commonly adopted in planning for this transition, may inadvertently oversimplify the complexities inherent in this process to a simple fuel-source switch and drive-train substitution thus, risking diminishing the transformative potential of this transition. The essence of the P&P approach entails forecasting future transport volumes and subsequently ensuring that the necessary infrastructure— in the case of road freight transport electrification charging stations, grid enhancements, and road capacities—is in place to meet this anticipated demand (Curtis, 2020). While ostensibly pragmatic, this strategy can potentially render the electrification transition merely a technological substitution, i.e., replacing diesel drivetrains with electric ones. A simple drivetrain substitution of the entire road freight transport fleet, while beneficial from an emissions perspective, however, does not address other intrinsic issues such as road congestion, wear and tear on infrastructure (Stenico de Campos et al., 2019), or the broader environmental implications of manufacturing, recycling, and disposing of vehicle batteries (Yang et al., 2022), (Chordia et al., 2021).

Going beyond a drivetrain substitution, the electrification process hence signifies a multi-system transition that demands attention to the broader interactions between transport and energy systems (Nykamp et al., 2023), (Andersen and Geels, 2023). An electrified truck becomes a component within the wider energy network, connecting to grid infrastructures, energy production dynamics, and storage mechanisms (Robinius et al., 2017). Therefore, when planning for this transition, it must be acknowledged that electrification disrupts traditional sectoral boundaries, integrating different parts of the transport and energy systems into a complex network of interactions, heralding a new era of multi-system governance challenges (Kanger et al., 2021), (Andersen and Geels, 2023). Charging an electric truck ties the elements of transportation management—routes, cargo loads, schedules—to the broader concerns of the energy system, such as peak demand periods, renewable energy assimilation, and grid reliability. Thus, this perspective paper argues that the P&P approach, in its current form, may inadequately address the interconnected challenges and opportunities arising from this intertwined relationship. Furthermore, by adhering strictly to anticipated transport needs, this strategy might inadvertently entrench existing inefficiencies, fail to capitalize on the potential of a more comprehensive multi-system governance approach, and perhaps most importantly, miss opportunities to holistically reimagine road freight transport in the context of broader sustainability goals (Curtis, 2020), (Meyer et al., 2022).

Consequently, this perspective aims to critically examine the prevalent P&P approach applied to the electrification of road freight transport and outline the contours of a novel planning approach to foster *sufficiency synergies*. Sufficiency in the context of transport planning advocates for meeting essential transport needs effectively within ecological limits rather than expanding infrastructure to accommodate increasing demand (Zell-Ziegler, n.d.), (Arnz and Krumm, 2023). The sufficiency-oriented planning approach for road freight transport electrification developed in this paper puts forward a comprehensive, interconnected vision by weaving together crucial elements of the transport and energy sectors. The objective, thus, is to highlight pathways for the sector that not only plan to substitute diesel with electricity but also ensure the transition contributes meaningfully to global decarbonisation goals. Such a paradigm shift—away from the narrowly focused, reactive P&P strategy towards a more holistic, anticipatory, and sufficiency-grounded planning approach—holds the potential to ensure the net-zero success of road freight transport electrification. Without this strategic recalibration, the environmental objectives underpinning electrification risk being undermined by the unintended consequences of an inadequately planned transition.

The rest of the perspective is structured as follows: Section 2 highlights the potential limitations of the current P&P approach, particularly in the face of the complex multi-system transition that intertwines the energy and transport sectors. Departing from this critique, Section 3 explores sufficiency considerations already emerging within transport planning. Informed by these considerations, Section 4 discusses an integrated multi-system planning approach, promoting sufficiency synergies. Section 5 concludes the perspective paper and draws implications for multi-system governance strategies.

7.2 Predict and provide planning in the context of road freight electrification

Historically, transport planning, especially in the context of road freight, has been deeply entrenched in a demand-oriented paradigm. Its dominant strategy, the P&P approach, has been a cornerstone of transport planning for several decades. Originating in the mid-20th century, this method is anchored in forecasting future transport needs and constructing the necessary infrastructure to meet these anticipated demands (Owens, 1995). The planning approach emerged in response to the rapid urbanization and motorization witnessed in many parts of the world (Lay, 2005). The ever-increasing number of vehicles on the roads and the consequent demand for road space necessitated a proactive planning strategy to alleviate potential bottlenecks and congestion (Filippi, 2022).

When planning for road freight transport, the P&P paradigm has found extensive application (Great Britain Department of Transport and Great Britain Department of the Environment, 1978). As an illustration, one can consider the development of major highways and freight corridors: Transport planners, using projected growth rates of industries, population centers, and trade flows, have often laid out extensive road networks to facilitate the seamless movement of goods. These forecasts have led to significant investments in infrastructure projects like dedicated freight corridors, bypasses around major urban centers to reduce congestion, and the construction of logistics hubs at strategic locations (Lay, 2005). Furthermore, as globalization intensified, so did the volume of goods transported across continents. In anticipation of this surge, many countries established major freight terminals and optimized road networks to facilitate smoother transcontinental trade (McKinnon, 2021). In this sense, the P&P approach sought to ensure that road infrastructure would not become a limiting factor in the growth of global trade.

7.2.1 Electrification prediction limitations and provision uncertainties

To meet the CO2 reduction targets and net-zero ambitions of the EU, the electrification of road freight transport has emerged as a viable solution[22], and three different vehicle technologies can be identified as potential options: (1) Battery electric trucks power an electric motor with stored electrical energy in batteries, which rely on the availability of a comprehensive network of charging stations (Shoman et al., 2023). (2) Hydrogen fuel cell trucks produce electricity onboard from hydrogen, requiring the development of green hydrogen production and refuelling infrastructure (Plötz, 2022). (3) Lastly, electric road system trucks draw power from overhead lines (catenary) or charge dynamically from embedded road systems (in-road), necessitating the installation of extensive road infrastructure. However, the technology may reduce reliance on heavy onboard batteries and could alleviate grid stress during operation (Soares and Wang, 2022).

In this perspective, the specific focus lies in critiquing the P&P approach in the context of adopting battery electric trucks, which is motivated by their market availability and maturity. Battery electric trucks are currently more prevalent in the EU due to their relative technological advancement and the existing charging infrastructure (International Energy Agency, 2023). As the road freight transport sector gears up to adopt this new vehicle technology, the P&P paradigm takes on new dimensions. Instead of merely anticipating the construction of roads and related infrastructure, there is an imperative to forecast electric charging infrastructure requirements for battery electric trucks, the distribution of power across regions, and the capacity of the electrical grid to handle surges in demand. Many EU nations have crafted national electrification roadmaps based on future vehicle projections, leading to large-scale infrastructure rollout plans for charging stations, e.g.,

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[22]While biofuels and synthetic fuels also present alternative solutions for CO2 reduction of road freight transport, their inclusion in the EU's CO2 standards for such vehicles is a subject of ongoing negotiations as of January 2024 (European Parliament, 2023). The current EU regulations focus on setting emission reduction targets and promoting zero- and low-emission vehicles, without definitive provisions for trucks running exclusively on these alternative fuels. The deliberation on integrating these fuel technologies into the regulatory framework reflects the complexity of balancing immediate environmental benefits with long-term sustainability goals and technological feasibility.

(The federal govermen of Germany, 2023), (BMK, 2023) or (Regeringen, 2022). Additionally, national governments across EU nations have initiated vehicle incentive programs to stimulate electric truck demand (EV Markets Reports, 2022), (International Energy Agency, 2023), matching anticipated supply. Meanwhile, manufacturers, aligning with these projections, focus on developing electric truck models designed to replace diesel counterparts directly (Transport & Environment., 2023). Anticipating the surge in electricity consumption from these electric fleets (Danese et al., 2021), a drive towards significant grid enhancements in specific regions can also be observed (ICCT, 2022).

One recent concrete manifestation of the P&P approach is the European Commission's proposal to change AFIR (European Council, 2023). Under this reformulated infrastructure regulation, a blueprint is laid out for developing charging points based on anticipated demands. The core Trans-European Transport Network is targeted to have 1,400 kW of charging power every 60 km by 2025, scaling to 3,500 kW by 2030. Similarly, secondary highways of this transport network have goals set at 1,400 kW every 100 km by 2030, expanding to 3,500 kW by 2035. This endeavour, while signalling a strong commitment towards enabling the electrification of road freight in the EU, hinges on forecasting mechanisms and, thus, operates within the confines of the P&P logic: foreseeing a future demand and creating infrastructure in response without necessarily reimagining the foundational principles of the road freight transport system itself. A glaring issue is the challenge of ensuring that the infrastructure meets real-world demand, a task made even more difficult given the considerable uncertainties surrounding the required scope and distribution of charging infrastructures.

While the AFIR proposal aims to facilitate the transition to zero-emissions truck and bus operations, it also reflects uncertainties over how much charging infrastructure is genuinely required. A recent analysis of the European Federation for Transport and Environment suggests that the infrastructure targets set under AFIR could potentially surpass the actual demand from the heavy-duty vehicle fleet by 2030, risking a notable portion of the charging infrastructure becoming a dormant asset (Transport & Enviroment, 2023). Adding to the ambiguity, truck manufacturers represented through the European Automobile Manufacturers' Association put forward a different picture, with some recommending charging provisions suitable for an electric truck fleet nearly 4.2 times the projected size for 2030 (ACEA, 2023). This variety of models and suggestions highlights a significant challenge: Without a clear consensus or standardized framework, how can infrastructure be effectively and efficiently planned? The discrepancies in these models are not trivial. If public infrastructure is built based on overly optimistic projections, it could result in vast underutilization. This would be financially inefficient and hinder the business case for further investments in such crucial infrastructure. However, not only financial and utilization efficiency must be considered, but also the environmental costs. Manufacturing and installation processes involve the use of materials and land, leading to embodied emissions (Mulrow and Grubert, 2023) and potential habitat disruption (Orsi, 2021) which significantly contribute to the overall ecological footprint of electrification.

Moreover, integrating charging infrastructure for road freight transport electrification within the energy system amplifies existing uncertainties and introduces several layers of complexity. Beyond just predicting the amount and placement of charging stations, the P&P paradigm grapples with broader, interconnected energy concerns that are uncertain. From an energy consumption perspective, it is unclear how much charging power will be necessary to accommodate an ever-evolving fleet of electric trucks (ICCT, 2022). Projections vary widely, with some models suggesting the need for immense power provision (ACEA, 2022) while others advocate for a more conservative approach (ICCT, 2022), (Transport & Enviroment, 2023). This discrepancy creates palpable challenges for energy providers, who must anticipate and make provisions for demand spikes, potentially straining grid capacities (Nadolny et al., 2022). Furthermore, grid requirements and capacity are themselves intricate variables to predict. As regions and cities witness varying rates of electric vehicle adoption, the demands on local grids can fluctuate dramatically. A sudden surge in electric road freight in a particular region could result in unanticipated pressures on the local grid (Burges and Kippelt, 2023), potentially requiring significant, costly upgrades or risking grid instability (Shoman et al., 2023). Then, uncertainties regarding the availability of renewable energy are added to the equation (Ash, 2020). The environmental value proposition of electrifying road freight is closely linked with sourcing the power from renewable resources. However, the availability of renewables—be it solar, wind, or hydro—varies significantly across EU member states (Lindstad et al., 2023), (EEA, 2023). Some areas might boast ample renewable energy supply, while others could be deficient. Predicting these variances accurately is challenging, especially when considering the temporal variability of renewable sources, and the margin for error becomes unsettlingly large. The consequences of miscalculation are not merely economic or logistical—they could diminish the broader emission reduction goals underpinning electrification.

7.2.2 The reactive nature of Predict & Provide and its broader implications for electrification

As discussed in the previous section, electrifying road freight transport can be seen as a pivotal strategy to substantially reduce greenhouse gas emissions in the transport sector. However, the predominantly reactive nature of the P&P approach may paradoxically jeopardize its primary environmental objective. A core issue lies in the model's seemingly uncritical acceptance of escalating road freight volumes. For instance, predictions by (Tölke and McKinnon, 2021) point towards a yearly 1% increase in road freight volumes in the EU, culminating in a 36% rise by 2050. By just reacting to these growth patterns without questioning their broader ramifications, the approach overlooks significant environmental challenges intrinsic to electrifying such an ever-growing commercial vehicle fleet and fails to account for the consequential ripple effects across other societal systems. The increase in road freight volumes not only places pressure on infrastructure development but also increases energy demand (Earl et al., n.d.). If met with non-renewable sources, this surge in the sector's energy demand may impede the critical transition towards a 100% renewable energy system and, consequently, delay essential climate change mitigation efforts.

For instance, in Germany, the projected energy demand for battery electric trucks by 2030 stands at a significant 13 TWh, or about 1% of the nation's total electricity output (Bernard et al., 2022). Ideally, this electricity should stem from renewable sources to maintain the environmental integrity of the electrification initiative. However, the current reactionary stance of P&P entails no planning mechanisms to ensure that such energy needs are met sustainably but rather inherently operates on the presumption of seamless energy availability. However, if regions like Germany find themselves unable to harness renewable energy in line with the rising demand, a potential fallback on non-renewable, carbon-intensive sources may become uninventable. Adding to that mere prediction of transport growth, without simultaneous consideration of the electrical grid's capacities and limitations (Burges and Kippelt, 2023), could leave regions unprepared for the consequential spikes in electricity demand and significantly impact the rollout of charging stations (Shoman et al., 2023). While the majority of electric trucks, particularly long-haul trucking, is anticipated to rely on off-shift charging, predominantly overnight, there is a potential risk that fast and ultra-fast charging sessions during mid-shift periods, which are necessary to extend the range of these vehicles, could coincide with peak demand times and potentially lead to electricity demand spikes that may challenge the grid's stability. Even with on-site charging facilities, simultaneously charging multiple battery electric trucks overnight could impose significant demand on the local grid infrastructure (Borlaug et al., 2021). Without strategic interventions, such as grid reinforcements, there may be a heightened risk of blackouts or service interruptions. However, several EU member states have already expressed concerns over the timely implementation of grid enforcement given long permit processes. These challenges might escalate and delay decarbonisation processes without proactive and coordinated grid planning between the transport and electricity sectors.

Additionally, the anticipated boom in electric truck adoption due to the predicted transport volume growth has broader supply chain implications, particularly concerning battery production (International Energy Agency, 2023). A surge in electric trucks necessitates a corresponding battery increase, escalating the demand for critical minerals such as lithium and cobalt. This heightened extraction demand brings significant environmental and ethical challenges to the fore (Sovacool, 2021), (Owen et al., 2023), (Marín and Goya, 2021). Exploitative mining practices, environmental degradation, and geopolitical tensions surrounding mineral-rich regions are issues that cannot be overlooked. Focusing predominantly on meeting transport growth predictions increases the risk of exacerbating pressures on mineral extraction. The interconnected challenges stemming from heightened mineral extraction must be acknowledged and proactively addressed to ensure that broader sustainability goals of electrification are not compromised.

In summary, the limitations inherent in the P&P planning approach underscore the necessity for a more refined road freight transport electrification planning approach to truly deliver on its promise of reducing emissions. The present approach clearly lacks an integrated understanding of the complexities between this transition's ecological, societal, and technological dimensions. Given the above-outlined challenges, a pressing need emerges for a multi-system governance framework that seamlessly aligns road freight transport electrification within the broader energy matrix. Recognizing and capitalizing on the synergies between the transport and energy sectors is paramount. However, such an integrated strategy should be grounded in a sufficiency paradigm (Princen, 2005), (Spangenberg and Lorek, 2019), (Jungell-Michelsson and Heikkurinen, 2022) to ensure that transport planning caters to projected demand growth and critically assesses and optimises it. Adopting a sufficiency-driven planning approach to road freight electrification makes it possible to mitigate the risk of reproducing existing inefficiencies by merely swapping one fuel source for another without addressing the underlying demand and consumption patterns.

7.3 Towards a new paradigm of sufficiency-oriented planning

Following the comprehensive critique of the P&P planning approach to road freight transport electrification, it thus becomes imperative to introduce the starting point of an alternative: *sufficiency-oriented planning*. In its 2022 Sixth Assessment Report, the IPCC's Working Group III emphasized the importance of demand-side mitigation measures, spotlighting the need to revisit energy and material consumption patterns (Shukla et al., 2022). This nod from influential bodies underlines the growing emphasis on sufficiency in today's sustainability discussions. Drawing from an array of literature, sufficiency is a multifaceted concept addressing questions of optimal consumption (Raworth, 2017), (Shove, 2018) and 'enoughness' (Jungell-Michelsson and Heikkurinen, 2022). Originating from the energy literature, Herring introduced the idea of energy sufficiency into policy debates on energy consumption, emphasizing a paradigm shift from the striving towards improved energy efficiency to "living well on less"(Herring, 2006). The concept has transcended to passenger transport in recent years, with sufficiency challenging the correlation between increased mobility and quality of life (Steg and Gifford, 2005), (Waygood et al., 2019). Although a uniform definition of transport sufficiency remains elusive, a broad overlap exists with the Avoid-Shift-Improve strategies of sustainable mobility (Zell-Ziegler et al., 2021), (Arnz and Krumm, 2023). In this context, the goal of sufficiency is to modify or reduce the need for movement (Avoid) and then transition to more sustainable modes or methods (Shift) as well as lower the environmental impact of transport through higher energy efficiency (Improve) (Tiwari et al., 2011), (Lah, 2017). Policy targets for transport sufficiency include encouraging modal shifts, reducing the km travelled by motorized means of transport, and adopting zero-emission vehicles (Zell-Ziegler et al., 2021), (Zell-Ziegler, n.d.).

The application of the sufficiency concept, therefore, is not novel in transportation studies and related policy per se, nevertheless, historically, it has been an underexplored concept in road freight transport. However, its application to this domain, particularly in the context of electrification, offers a promising paradigm. Building upon previous work within the research on transport sufficiency (Waygood et al., 2019), (Zell-Ziegler, n.d.), the following definition can be drawn: *Sufficiency-oriented planning for road freight transport electrification is a strategy that aligns electrification efforts with ecological constraints and societal needs, ensuring that energy demand and GHG emissions are minimized while maintaining essential transport functions within evolving cultural and spatial contexts*. In essence, sufficiency-oriented planning shifts the focus from merely meeting predicted demand to questioning the nature and validity of that demand. Instead of asking, "How can we accommodate growth?" it urges us to reflect, "What level of freight transport is sustainable and genuinely needed?".

As a starting point, it thus mandates a deeper reflection on demand. Contrary to the blanket acceptance of forecasted transport needs, sufficiency invokes critical analysis of the very essence and character of these demands (Arnz and Krumm, 2023), and it encourages reflection on the actual necessity of transporting certain goods, the feasibility of localizing production, and the potential for optimizing delivery frequencies. At the heart of sufficiency lies a commitment to creating a sustainable road freight transport system not by mere expansion but by intelligent and efficient allocation of resources. However, such a reflection on demand must also be extended to include the role of individual consumer choices in shaping freight transport needs, particularly in the context of ever-increasing e-commerce growth (McDonald et al., 2019). By incentivising the purchasing locally sourced products, consumers can significantly contribute to the decentralization of supply chains and, thus, a reduction of road freight demand. A preference for local goods has the potential to reshape transport patterns, reducing the frequency and distance goods are transported as well as lowering transportation-related emissions and thereby contributing to increasing the overall sufficiency of the road freight sector (Striebig et al., 2019).

Optimal infrastructure utilisation is a second pillar of the sufficiency-oriented planning paradigm for road freight electrification. This emphasizes connecting existing infrastructure with new developments while integrating transport and energy infrastructures. Road freight transport electrification is closely tied to its energy supply chains, and merging these infrastructural realms requires a clear vision that combines the logistics of goods movement with the energy systems powering it. A standout feature of this integration is decentralized solutions - utilizing localized renewable energy sources - the sufficiency approach strategically positions energy access points along key transport routes. This strategy boosts the resilience of the electrified freight system and decreases reliance on central energy grids, paving the way for a sustainable, self-reliant transport network. Additionally, rather than perpetually constructing new elements, emphasis is placed on enhancing, repurposing, and maintaining existing infrastructures, ensuring their prolonged efficiency and relevance. Consequently, unnecessary capital investments are minimized, and the risks of overexpansion are mitigated.

The third pillar of this planning paradigm is the employment of a lifecycle perspective. Moving beyond immediate and often superficial concerns like tailpipe emissions, sufficiency-oriented planning adopts a more comprehensive standpoint. It considers the complete environmental footprint of vehicles, considering every phase of a vehicle's existence, from its inception in production lines to its final disposal. This comprehensive evaluation ensures that while the potential benefits of electrification, such as reduced emissions during operation, are acknowledged, potential negative impacts that might manifest at other stages of a vehicle's life cycle are also accounted for. The aim is to foster a transport system where the environmental advantages of electrification are genuine and encompassing, not simply shifted or deferred to another phase of a vehicle’s lifecycle.

Lastly, when planning for the electrification of road freight transport, an introduction of the circular economy principles becomes pivotal. Diverging from the traditional P&P approach, which often results in resource exhaustion and wastage, circularity ensures the systematic and efficient reuse and recycling of resources. This closed-loop model subverts the typical linear pattern of "produce, consume, dispose" by introducing a continuous cycle of resource rejuvenation. By embedding circular economy principles into sufficiency-oriented planning, the demand for freight transport is inherently reduced. As resources are consistently recirculated within the system, the need for raw materials and their consequent transportation diminishes. The cascading effect of this reduction becomes apparent throughout the supply chain, fostering both environmental and economic efficiency. Moreover, Circular Economy mandates the strategic use of renewable energy, further minimizing the carbon footprint of electrified road freight transport.

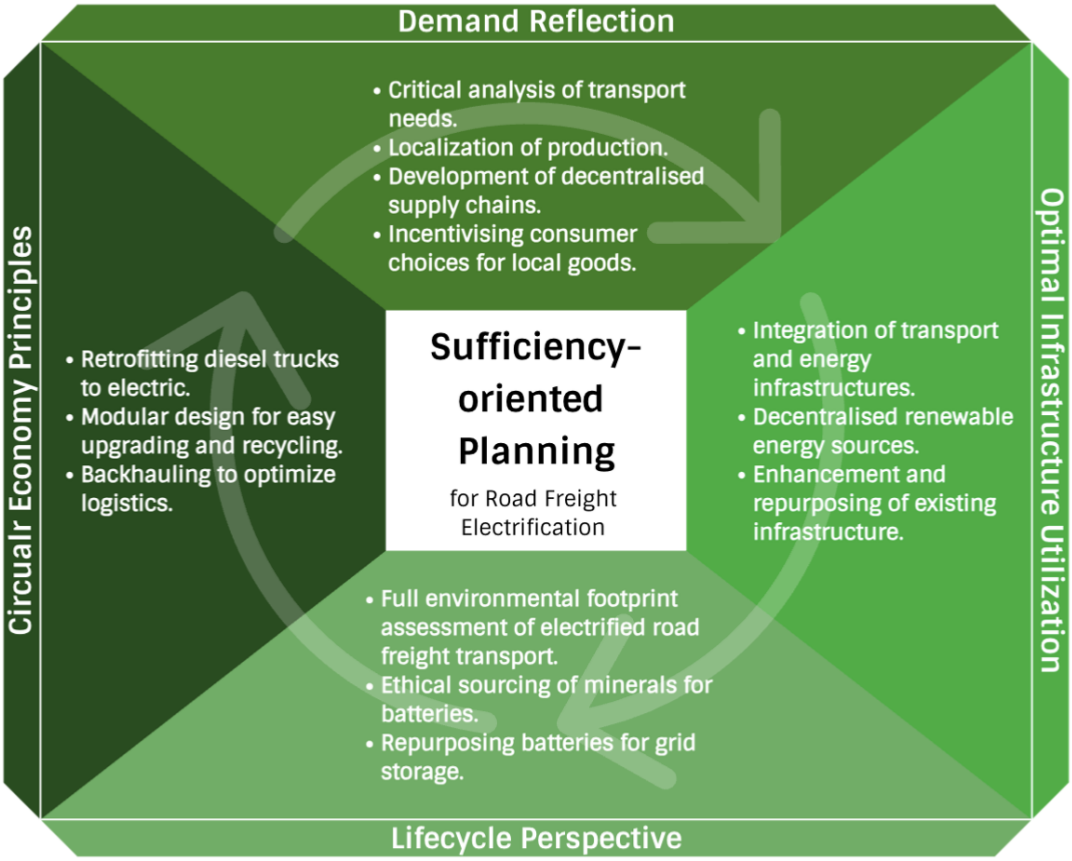

Fig. 1 The four pillars of sufficiency-oriented planning for road freight electrification.

Figure 1 illustrates the four pillars that could underlie a paradigm shift towards sufficiency-orientated planning for road freight electrification and gives concrete implementation examples for each pillar, which are elaborated on in the next section. In sum, sufficiency-oriented planning offers an approach that harmonizes technological advancement with ecological responsibility. It emphasizes the need for genuine, integrated solutions between the transport and energy system—*sufficiency synergies*—and, in doing so, prompts a comprehensive re-evaluation of existing planning practices in the quest for a sustainable future for the sector.

7.4 Implementing sufficiency-oriented planning for electrified road freight transport

While it is beyond the scope of this perspective to outline a comprehensive plan of how to implement such a sufficiency-oriented planning paradigm for road freight transport electrification, this section sketches out some initial ideas to stimulate further exploration and discussions in the field.

In line with the first two pillars outlined above on demand reduction and optimal infrastructure utilization, an essential aspect of implementing sufficiency-oriented planning will lie in the localization of production and distribution. Rather than perpetuating the expansive infrastructures mirroring traditional diesel refuelling points, the electrification transition provides an opportunity to rethink our distribution systems. Localizing distribution centers and establishing adjacent solar or wind farms and adequate battery storage ensure they are powered by renewable energy and can reduce dependency on grid capacity and non-renewable sources while curtailing the need for extensive long-distance transportation. Additionally, by focusing more strongly not only on localization but also on the establishment of shared consolidation centers with charging infrastructure, such facilities would enable electric trucks from various companies to use common charging hubs, conserving space and promoting collaboration (Ye et al., 2022), potentially resulting in more efficient transport routes and consolidated deliveries. Urban nodes, which are projected to have increased charging infrastructure under the AFIR, could be transformed into centers of localized production and distribution, effectively mitigating the risk of infrastructural underutilization. With the decentralization of supply chains and focus on local goods, we can potentially dampen the projected growth in road freight volumes, subsequently lessening the strain on energy resources and infrastructure. Additionally, by leveraging artificial intelligence and machine-learning optimization algorithms, delivery frequencies and routes could be scheduled in accordance with energy availability and grid capacity (Ma et al., 2022), (Chen et al., 2021). Such an alignment would promote operational efficiency and decrease challenges associated with managing peak demand and grid instability. From an environmental perspective, optimizing the use of electric trucks in line with grid capacity can lead to reduced carbon emissions and a decline in the use of non-renewable energy sources during peak times (Ma et al., 2022).

Moreover, the batteries in the employed electric trucks can contribute to optimal infrastructure utilization by playing a dual role in stabilizing the electrical grid through Vehicle-to-Grid technology. Under scenarios of renewable energy intermittency or sudden demand spikes, these truck batteries can feed energy back into the grid, acting as temporary energy storage units (Zhao et al., 2016). This means that trucks, while parked, could effectively increase grid resilience. For vehicle owners, this could translate into an additional revenue stream or cost savings on energy, incentivizing participation in grid services. Yet, this benefit must be balanced against the potential accelerated degradation of the battery due to the increased cycling and depth of discharge, which could impact the vehicle's long-term operational efficiency and resale value. Regarding operational times, this might imply that electric trucks are operating during off-peak energy periods, such as nights or when renewable sources are abundant, while during periods of high energy demand or scarcity, their stationary batteries could be harnessed to stabilise and support the grid. This necessitates a careful scheduling strategy for fleet operators to ensure that vehicles are charged and available for their primary transport duties, avoiding conflict with grid service commitments. This integration not only redefines the conventional operations of road freight transport but also harnesses sufficiency synergies where transport operations can symbiotically enhance the robustness of the energy system (Gonzalez Venegas et al., 2021). In addition, this integration can also bring about a variety of broader benefits for stakeholders: Truck operators could benefit from reduced operational costs, energy companies from a more stable and predictable demand, municipalities from reduced traffic during peak hours, and the general public from the combined environmental and economic advantages of this integrated approach. Although truck batteries alone may not function as the sole stabilisers of the grid, especially as large-scale battery storage solutions become more cost-effective, they can nonetheless make a meaningful contribution, particularly during the current period where many sectors are undergoing electrification at the same time amidst pressing climate change mitigation efforts without the required grid reinforcements in place.

Under the lifecycle perspective pillar, a sufficiency-oriented planning approach in road freight transport electrification requires a comprehensive assessment of battery production for electric trucks, encompassing the entire spectrum from ethical mineral sourcing to end-of-life battery management (Koroma et al., 2022). Initiatives to secure minerals ethically and a thorough evaluation of the environmental footprint across mining, refining, and transport stages become pivotal. Furthermore, to reinforce sufficiency, developing localized value chains for battery minerals may become crucial to minimize extensive international shipping, thereby reducing associated emissions and ensuring a more resilient and transparent supply chain for critical battery components. Moreover, as these batteries near their end-of-life in vehicular applications, their repurposing potential must be harnessed. Preliminary evidence suggests that such batteries, despite diminished capacity, can be redeployed for grid energy storage (Deng et al., 2022), (Vishwakarma et al., 2022) in line with the circular economy principle of reuse. This mitigates waste and leverages the intrinsic energy value from their initial production phase. Such a nuanced, lifecycle-oriented approach to battery production and utilization can substantially inform the planning for a genuinely sustainable electrified road freight transport sector. It is essential to acknowledge that these considerations extend to the electrification of transport beyond the road freight sector. With passenger transport also increasingly being electrified, there is a need to consider the implications of battery production and end-of-life management in a comprehensive transportation policy. Therefore, sufficiency-oriented planning must, to the greatest extent possible, include both sectors to optimize resource allocation, avoid duplicating infrastructural demands, and ensure that the transition to electric mobility contributes to reducing the overall carbon intensity of the transportation system.

Lastly, adopting the circular economy principle in the electrification of road freight transport, as the last pillar of sufficiency-oriented planning, could involve the following measures: To reduce the resources and energy needed to transition towards electrification, the widespread development of retrofitting initiatives which convert existing diesel trucks to electric drivetrain, would allow leveraging of the embodied energy and materials of the current fleet and thus, avoiding the environmental costs of manufacturing new vehicles (Hoeft, 2021). Similarly, if truck manufacturers would stringently adopt the design principle of modularity when developing electric trucks, this would facilitate easy upgrading, replacement, or recycling of parts like battery packs or motors (von Freeden et al., 2022). Thus decreasing waste, extending the vehicles' operational life, and promoting resource efficiency. Complementing such retrofitting and modular design strategies, with logistics optimization through a focus on backhauling—where vehicles carry full loads on return journeys— would allow for increased operational efficiency and maximized vehicle usage (Jayarathna et al., 2023). Therefore, potentially contributing to a reduction in overall transport demand, energy consumption, and emissions.

While not exhaustive, these concrete examples illustrate the practicality and feasibility of sufficiency-oriented planning within road freight electrification. Aligning technological advancements with ecological and societal needs ensures a resilient, sustainable, and efficient freight transport system, attuned to the realities and urgencies of climate change and environmental preservation.

7.5 Conclusion and policy implications

This perspective has been written with the primary intention of challenging the prevailing planning approach to road freight electrification in the EU. In an era where the urgency to address climate change becomes more pronounced daily, the traditional P&P framework, although historically dominant, seems inadequate to address the contemporary complexities and uncertainties of the unfolding transition in the sector. If approached only as a fuel source switch or technological substitution from diesel to electric, road freight transport electrification risks missing broader sustainability potentials. In consequence, this perspective has advocated for a paradigm change towards sufficiency-oriented planning – a more holistic approach, challenging not only the technology in use but also the foundational principles of transport demand and the broader implications of this multi-system transition for the energy sector.

Yet, the objective is not to provide definitive answers. Instead, this work should be seen as an effort to shift the current conversation. The road freight transport electrification discourse must expand beyond discussions and research on the technological feasibility and economic viability of replacing diesel trucks with electric ones. A richer, interdisciplinary dialogue, especially among transport and energy experts, is essential to fully grasp how sufficiency-oriented planning might bridge the gaps and harness synergies between these increasingly intertwined sectors. Additionally, it is important to acknowledge that this perspective has focused on the EU and a region with a well-developed road freight management and planning system and a clear electrification roadmap. Nevertheless, the pillars of sufficiency-oriented planning could potentially be applicable in the future to other growing economies and inform their transport planning practices.

While the sufficiency-oriented planning paradigm for road freight transport electrification presents a promising approach to align technological advancement with ecological responsibility, its successful implementation requires a comprehensive, multi-system governance strategy. Therefore, this perspective ends by outlining a few initial policy implications of the sufficiency-oriented planning approach: First, it will require expertise from diverse fields, including transportation, energy, urban planning, environment, economics, and more. Thus, achieving the implementation of sufficiency-oriented planning will necessitate multi-agency cooperation, potentially leading to the development of interdisciplinary teams or committees at governmental levels. Second, this approach inherently blurs the lines between transport, energy, environmental, and economic policies. This may require a more integrated policy mix formulation and review process to ensure alignment and coherence of different measures across sectors. Lastly, given the emphasis on advancing environmental benefits, monitoring and evaluation tools would need to be more comprehensive, focusing not just on tailpipe emissions but on a wide array of indicators that capture the lifecycle impacts of vehicles and infrastructure.

8. Governance

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Abstract: Despite regulatory efforts and market availability, the adoption of zero-emission vehicles (ZEVs) in the road freight sector is limited. This paper investigates the influence of managers' policy mix perceptions on the uptake of ZEVs in Sweden. Based on a survey of transport operation managers, we analyse the interaction between their perceptions of how technology-neutral the prevailing policy mix is, the anticipated regret of premature technology adoption, the rate of technology change and their mutual influence on the decision to delay ZEV adoption. The study's findings reveal a positive correlation between managers' perceptions of technology neutrality and adoption delay. We further explain the mechanism in this relationship by confirming that anticipated regret mediates the positive correlation between perceived technology neutrality and the ZEV adoption delay decision: The more technology-neutral the policy mix is perceived, the more anticipating regret over adopting ZEVs is expressed by the managers, which, in turn, increases the likelihood to delay ZEV adoption. Moreover, managers' perceptions of the rate of technological change affect their anticipated regret. The work contributes to the transition literature by unveiling how a specific policy mix perception, namely technology neutrality, could delay the adoption of ZEVs and calls for a nuanced re-evaluation of the current policy mix to facilitate a faster transition towards net-zero goals. It also underscores the importance of paying closer attention to how individual actor-internal factors (such as perceptions and emotions) of individual decision-makers in organisations may influence transition processes.

Keywords: Policy mix perceptions, Sustainable freight transport, Zero-emission vehicles, Anticipated regret, Innovation adoption, Emotions

8.1 Introduction

Accelerating the adoption of technological innovations is vital for enabling sector-specific low-carbon transitions and mitigating the growing adverse impacts of climate change (Markard et al., 2020; Matos et al., 2022). Among the sectors, road freight transport stands out, given its urgent need for an accelerated deployment of zero-emission technologies to achieve the Paris Agreement temperature goals and reach climate neutrality by 2050. Currently, road freight transport is responsible for 25% of all land-based transportation greenhouse gas (GHG) emissions in the EU, with heavy-duty vehicles being responsible for 27% of climate emissions from road transport while only representing 2% of the vehicles on the road (T&E, 2022). Consequently, crafting an effective policy mix for a transition towards decarbonised road freight transport has become a central focus for governments and policymakers (Axsen et al., 2020; Bhardwaj et al., 2020). The prevailing policy mix—defined as a policy process, long-term policy strategies and specific instruments with credible and consistent characteristics (Rogge and Reichardt, 2016)—for road freight transport aims to support and promote low-carbon technological innovations to mitigate freight transport emissions. Technology neutrality is frequently considered a guiding design principle in developing and implementing this policy mix (Craglia, 2022; Tongur and Engwall, 2017). Technology-neutral policy mixes do not favour a particular technology or "pick winners" but broadly promote low-carbon technologies to achieve desired emission reduction goals without supporting a specific technological pathway (Jaffe et al., 2005; Azar and Sandén, 2011; Styczynski and Hughes, 2019;).

However, previous research has indicated that technology-neutral policy mixes might not promote the adoption of low-carbon technologies at the speed necessary to meet emission reduction goals (Azar and Sandén, 2011; Carton, 2016; Tongur and Engwall, 2017; Skjærseth et al., 2023). As policymakers refrain from endorsing specific low-carbon innovations, contestations and uncertainties over future technological pathways may grow amongst investors and potential innovation adopters (Meadowcroft, 2009; Haŝcic et al., 2009; Geels, 2012), potentially prolonging transition processes (Geels et al., 2016). Despite these calls for caution, technology neutrality remains largely unchallenged and continues to be a dominant policy mix design principle to support a low-carbon transition towards decarbonised road freight transport. However, a clear understanding of its effects on transport operation managers' innovation adoption decision-making processes is currently missing. Adding to that, current literature across the transition, innovation, and transport fields largely overlooks individual actor-internal factors—here used as an umbrella term for the psychological and cognitive attributes of individuals, including their motivations, knowledge, beliefs, values, and experiences that influence their behaviours and decisions related to sustainability transitions (Bögel and Upham, 2018; Kaufman et al., 2021; Upham et al., 2020)— and their possible effects on willingness to adopt zero-emission vehicles (ZEVs) (for an exception, see Bae et al., 2019). These factors encompass an individual's capacity to process information and make decisions, as well as the psychological predispositions that drive their actions within the context of socio-technical change (Bögel and Upham, 2018). They warrant further investigation because individual actor-internal factors can potentially help to explain why individuals engage differently in transition processes, such as adopting new technologies. Consequently, a study of how the current policy landscape may influence the emotions and cognition of individual decision-makers in organisations, which in turn colours their adoption intentions and, thus, ongoing transition processes more broadly, represents a frequently overlooked but potentially critical area of investigation (Bögel et al., 2020).

In response, this paper aims to explore how different individual internal factors—perceptions, emotions and attitudes—of decision-makers in organisations interact; in other words, how they influence each other and together shape the innovation adoption decision-making process. Perceptions are how individuals make sense of various elements of their environment (Bögel and Upham, 2018), including policies. Regret is an example of an intense and conscious emotion that can arise in response to socio-technical change (Martiskainen and Sovacool, 2021), and individuals' attitudes toward specific items, such as technology, predispose them to behave in a certain way (Bögel et al., 2019). This research focuses on how these different individual actor-internal factors of the decision-makers—such as their perception of a technology-neutral policy mix and resulting anticipation of regret—affect their intention to (or not) adopt ZEVs. To this end, we combine perspectives from transition research with insights from behavioural economics, consumer behaviour studies and psychology. We pose the following research question:

How do perceptions of a technology-neutral policy mix interact with other individual actor-internal factors to mutually influence decision-makers intentions to adopt ZEVs?

To answer this question, our research model builds on the concept of 'interpretative effects' (Edmondson et al., 2019; 2020) to investigate the perceptions of the level of technology neutrality amongst transport operation managers[23] in road haulage companies. The divergent perceptions are examined in the context of their impact on the anticipated regret (Shih and Schau, 2011), a negative emotion related to the fear of adopting a novel technology prematurely. Further building on the new-obsolete paradox (Mick and

[23]Transport operations managers are critical in vehicle fleet operations, overseeing vehicle procurement, daily fleet activities, maintenance and route optimization. These managers are acutely aware of the operational demands, cost implications, infrastructure requirements and potential benefits of transitioning to ZEVs. Moreover, their extensive experience in logistics and transportation equips them with a comprehensive understanding of how such technological shifts can impact broader supply chain operations and business objectives. Due to their integral involvement in decision-making processes surrounding new technology adoptions, their perspectives are invaluable for assessing the impact of a technology-neutral policy mix and understanding the slow adoption of ZEVs in real-world operational contexts.

Fournier, 1998), we hypothesise a moderating effect of the perceived rate of technological change—a construct that measures how rapidly individuals perceive technology will evolve in the near future (Shih and Schau, 2011; Pradeep et al., 2021)—on the relationship between perceived technology neutrality and anticipated regret.

The empirical context for this study is Sweden's road freight transport sector, where the government has set ambitious climate targets of cutting heavy vehicle emissions by 70% by 2030 and reaching net zero by 2045 (Regeringskansliet, 2021). This sector's policy mix is designed to be technology-neutral and does not actively promote individual abatement technologies (Elmer, 2020). Despite progress in low-carbon drivetrain technologies, market availability of commercial ZEVs and regulatory measures such as tighter EU CO2 standards and national public policy initiatives, the adoption of ZEVs in transport and logistics organisations remains limited (Melander et al., 2022; Ragon and Rodríguez, 2022; Werner et al., 2022). According to the Swedish vehicle stock statistics, until the end of 2023, 482 ZEV trucks (>3.5 tons) were registered in Sweden, making up only 0.6% of the total truck vehicle stock (Mobility Sweden, 2024a). To shed light on potential reasons for this gap between ambitious emission reduction targets and slow ZEV adoptions, we surveyed 155 transport operation managers working for road haulage companies. Road haulage companies are organisations that transport goods by road, using a fleet of vehicles such as trucks to provide freight services between varying locations. Transport operation managers in such road haulage companies are responsible for overseeing the daily logistics and management of vehicle fleets. They, thus, play a crucial role in decision-making processes regarding the adoption of ZEVs as they assess operational feasibility, cost implications, and potential benefits related to transitioning to zero-emission transport options.

In doing so, this paper contributes to theory and policy practice: Our findings highlight how the interactions between managers' perceptions of the prevailing policy mix and their emotional response that manifests in anticipated regret in combination influence the current adoption pace of zero-emission trucks in the Swedish road freight sector. Additionally, the results offer insights into several other individual actor-internal factors that complicate their decision-making process, specifically shedding light on the roles of managers' attitudes towards ZEVs and prior experience with them. From a policy practice perspective, these findings underscore the need to revisit and complement technology-neutral approaches in policy design to ensure more rapid and widespread adoption of ZEVs. Beyond the empirical setting, our paper highlights how individual actor-internal factors in the form of policy perceptions, attitudes, emotions, and previous experiences of decision-makers in organisations influence system-level transition processes.

The remainder of the paper is organised as follows: Section 2 presents the theoretical background of this study, while Section 3 puts forward our hypotheses and presents the research model. Next, Section 4 describes the research methods, including case context, measures and data collection, while Section 5 contains the model's results and analysis. Section 6 then discusses key findings and outlines our study's policy implications. Finally, Section 7 concludes the paper by addressing limitations and areas for future research.

8.2 Theoretical Background

8.2.1 Policy mixes for sustainability transitions and technology neutrality

An increased recognition that no single policy approach is sufficient to address the complexity and multidimensionality of sustainability challenges (Kivimaa and Kern, 2016; Schot and Steinmueller, 2018; Kanger et al., 2020) has given rise to the notion of policy mixes for sustainability transition (Kern and Howlett, 2009; Rogge and Reichardt 2016). In essence, the term describes a combination of multiple policy instruments and strategies that are strategically designed to target different aspects of a transition simultaneously (Rogge and Reichardt, 2016; Flanagan et al., 2011). Building on the work of Rogge and Reichardt (2016), a policy mix is made of three building blocks: (1) The policy process, which refers to the mechanisms of policy formulation and adjustment over time. (2) The elements of a policy mix, which include the specific instruments and strategic policy objectives. (3) The policy mix characteristics, including qualities such as coherence, consistency, and credibility, that affect the mix's effectiveness and efficiency. In this paper, we specifically focus on the influence of policy mix elements that are designed in a technology-neutral way on the adoption decision-making process of transport operation managers. These elements, as mentioned above, can be further broken down into the policy strategy, which represents a combination of policy objectives and principal plans, and the instrument mix, which outlines concrete tools (economic instruments, regulation, and information) to achieve the objectives (Rogge and Reichardt, 2016).

In the context of low-carbon transitions, technology neutrality has become a guiding principle for designing and implementing both the strategy and instruments of a policy mix (Kalkuhl et al., 2016; Skjærseth et al., 2023). However, the principle of technology neutrality already emerged in the late 20th century as a response to the challenges of rapidly changing technologies (Perez, 2002). It emphasises the need for a fair, competitive landscape among various low-carbon technologies to facilitate the most efficient technology pathway (Aldy and Stavins, 2011; Foxon, 2011; Styczynski and Hughes, 2019; Tongur and Engwall, 2017). In the last two decades, we have witnessed an expansion of innovation policy from mere technology push in the form of governmental R&D support towards various pull policies to accelerate the deployment of sustainable technologies (Flanagan et al., 2011; Anadón, 2012). The rationale behind this market-driven approach is rooted in the belief that open competition among low-carbon technologies can encourage the development and adoption of new technologies by creating a level playing field for various low-carbon options, ultimately enabling the most cost-efficient route to emissions reductions (Styczynski and Hughes, 2019; Jacobsson and Bergek, 2011; Acemoglu et al., 2012).

Despite these potential benefits, achieving sustainability goals has proven challenging in practice (Schmidt et al., 2012). Azar and Sandén (2011) highlight the elusive nature of technology-neutral policies, arguing that they often fail to accommodate the heterogeneity of low-carbon technologies and the influence of various externalities, such as environmental and social impacts. This shortcoming can be attributed to the fact that vested interests (Beland, 2018) and uncertainties regarding the future performance and costs of emerging technologies, coupled with the path-dependent nature of technological development, contribute to lock-in effects that may prevent the realisation of truly technology-neutral policies (Unruh, 2000; Arthur, 1989). Further critiques also point to the insufficiency of technology-neutral policies in addressing the complexities and context-specific barriers to low-carbon transitions, given the varied nature of these technologies (Stirling, 2014; 2008). In some cases, such neutrality may even impede the development of promising technologies by overlooking necessary considerations like differences in technology maturity, network effects, or economies of scale (Azar and Sandén 2011; Moe, 2012; Skjærseth et al., 2023). This oversight could lead to the exclusion of technologies that may be superior in the long term and diminish technological diversity (Del Río González, 2008; Schmidt et al., 2016), which is crucial for a resilient economy that can adapt to unanticipated shocks (Stirling, 2007, 2010; Van den Bergh, 2008; Kharrazi et al., 2013).

Additionally, a technology-neutral policy may lack predictability and thus be linked to contestations and uncertainties over future technological pathways for investors and innovation adopters (Hašcic et al., 2009; Geels, 2012). Deliberations about the most desirable low-carbon technologies often involve conflicting values, interests and visions, leading to uncertainties and political disputes (Geels et al., 2016). As policymakers refrain from endorsing technological solutions, stakeholders may face difficulties coordinating their actions and aligning their interests (Meadowcroft, 2009). This lack of coordination may prolong the transition process as stakeholders, particularly potential innovation adopters, remain divided over the most appropriate technological pathways to achieve emission reduction goals (Geels et al., 2016). In some cases, this is discussed as negatively impacting the adoption rate of low-carbon technologies. For instance, Nemet (2009) argues that genuine technology-neutral policies might not provide adequate support for emerging technologies that face significant barriers to entry, such as high upfront costs, uncertain market prospects or the need for complementary infrastructure. Especially in the context of sectors, such as road freight transport in which there is a need for rapid and large-scale deployment of low-carbon technologies and complementary infrastructure to achieve urgent climate mitigation goals, it might be more important for policy interventions to strategically support specific technologies with the potential for significant emissions reductions (Gallagher et al., 2012).

To summarise, the literature on technology-neutral policy design in low-carbon transitions paints a mixed picture of its potential impact on innovation adoption. While technological neutrality can spur innovation by fostering competition among various low-carbon options, this policy mix design practice might not always be sufficient to overcome the barriers faced by emerging technologies or to achieve the rapid deployment needed for effective climate mitigation. While many recent contributions to the transition literature have dealt with questions of how to design policy mixes most effectively (cf. Kern et al., 2022; Edmondson et al., 2019; Lindberg et al., 2019, for example), the potential effects of technology neutrality as a policy mix design principle on the innovation adoption process remain largely unexplored. Thus, this paper seeks to contribute to the ongoing academic debates surrounding this tension by exploring the relationship between technology-neutral policy mix design and innovation adoption.

8.2.2 Differences in policy mix perceptions and organisational innovation adoption

Previous research has revealed that the perceptions of a specific policy mix can vary vastly for individual decision-makers in different organisations (cf. Kern et al., 2022; Edmondson et al., 2019; Rogge and Duetschke, 2018; Rogge and Johnstone, 2017). This is because a policy mix produces interpretative effects (Edmondson et al., 2019; Edmondson et al., 2020), meaning that the information individuals obtain through a policy mix affects their patterns of cognition, resulting in differing perceptions and evaluations of the credibility or overall characteristics of a policy mix (Rogge and Schleich, 2018; Rogge and Reichardt, 2016). In the context of our study, this implies that while existing policy mixes to lower the emissions of a specific industry sector might be objectively designed in a technology-neutral way, the subjective perceptions of the level of policies' technology neutrality may vary amongst different individuals who are responsible for making technology adoption decisions for an organisation.

Moreover, as described previously, policies are rarely fully neutral due to different rates of technological development. An observed example is the development rate of different zero-emission truck powertrains (Craglia, 2022). The incentive-based policy instrument might be technology-neutral in the sense that it would theoretically subsidise both commercial battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) as well as their related infrastructure equally. Nevertheless, because BEVs have a higher market availability and rate of technical maturity and infrastructure, they are more frequently adopted than FCEVs. This, amongst some individual decision-makers in organisations, could lead to the impression that BEVs receive more substantial policy support. Furthermore, existing literature on policy interpretation and perception among individuals suggests that cognitive biases, namely, the tendency to favour information that confirms one's pre-existing beliefs, can lead individual decision-makers in organisations to interpret policy measures in ways that align with their interests and expectations (Tversky and Kahneman, 1974; Nickerson, 1998)—resulting in different interpretations of the same policy mix among various individuals (Rogge and Duetschke, 2018; Rogge and Johnstone, 2017). Lastly, managers' interpretations of policies are significantly influenced by the power dynamics and vested interests within their industries (Bendor and Moe, 1985; Stirling, 2019) and because their decisions are aligned with specific organisational goals and interests (Saydon, 2022), they may perceive the same policy mix differently (March and Olsen, 2010).

In addition to policy perception and the regulatory environment more broadly, other factors influencing innovation adoption in organisations, reported in the literature, include economic considerations, as well as innovation, and organisational characteristics. Economic factors such as cost savings, operational efficiency, and return on investment can be considered primary drivers for adopting more low-carbon technologies in an organisation because they directly impact the financial performance and competitiveness of a firm (Meleen and Schwanen, 2023; Bae et al., 2022; Mohammed et al., 2020). Additionally, innovation characteristics, including environmental performance, complexity and perceived advantage of an innovation, also affect the innovation adoption decision-making process in an organisation (Frambach and Schillewaert, 2002; Wikström et al., 2015). Organisational characteristics, such as size (Kennedy, 1983) and structure (Damanpour, 1991), determine the capacity to adopt new technologies. Larger firms with more resources are typically better positioned to absorb the risks and costs associated with low-carbon technologies, while smaller firms may face greater challenges due to limited financial and human capital (Seitz et al., 2015; Sierzchula, 2014).

The organisational innovation adoption literature acknowledges the role of individual actor-internal factors, understood in this paper as individuals' intrinsic qualities and characteristics, that influence organisational behaviours and adoption decisions. Such internal factors encompass a range of cognitive, affective and conative elements, including attitudes, beliefs and emotions (Mohammed et al., 2020; Wolff and Madlener, 2019). For instance, a manager's prior experience with a technological innovation may shape their attitude towards its future adoption (Schreyögg and Koch, 2009; Roberts et al., 2021). However, the effectiveness of policies in accelerating zero-emission transitions can be significantly influenced by the actor-internal factors of key individual decision-makers in organisations, as highlighted by Rogers' (2003) work on the role of individual perceptions in innovation adoption processes. While specific policies may create a conducive environment for innovation, manager's attitudes, beliefs and emotions play crucial roles in adoption decisions. For instance, even if a policy instrument incentivises the uptake of a novel technology through financial benefits, a manager's scepticism—stemming from past failures or industry anecdotes—might act as a barrier due to the perceived risk of adopting a novel technology (Rogers, 2003).

While internal factors of individual decision-makers in organisations, such as attitudes and emotions, have been recognised as influential in the behavioural process of organisational innovation adoption (Roberts et al., 2021; Makkonen et al., 2016; Roupas, 2008), their specific interactions with policy mix perceptions are still underexplored. The few examples focusing on this interaction so far have mostly explored its influence on the adoption behaviour of end-users or consumers (cf. Li et al., 2020; Xu and Su, 2016). Adding to that, to the best of our knowledge, no previous study has been performed that explicitly considered the potential effects of the underlying policy mix design, in the case of this research, perceived technology neutrality, on the adoption decisions of managers in organisations. As transitions towards low-carbon trajectories become imperative for most societal sectors, examining whether policy mixes anchored in technology neutrality propel or hinder such transition becomes essential. Since previous research on policy mix for sustainability transitions falls short of exploring how policy mix perceptions may influence individual actor-internal factors in an organisational context, we develop in the following section an extended research model to advance our understanding of how technology-neutral policy mix perceptions and individual actor-internal factors interact and mutually affect managers' innovation adoption decision.

8.3 Concept Development and Hypotheses

8.3.1 The effect of perceived technology neutrality on anticipated regret

The decision-making process for adopting low-carbon technologies in an organisation is frequently influenced by economic considerations. Managers might compare the expected costs of a decision to its expected benefits to determine its economic viability (Shahzad et al., 2022) or assess the uncertainties and potential adverse outcomes associated with the decision, helping managers understand and mitigate potential risks (Johnson 2010). However, previous work has shown that managers are not purely 'homo economicus'—rational agents who make decisions solely based on logical economic analysis—instead, their decisions are also influenced by emotions (Loewenstein et al., 2001; George and Dane, 2016). Emotions, thus, are recognised to play a significant role in decision-making processes, and particular emotions like anticipated regret (AR) can largely impact managerial decisions (Ng and Wong, 2008). AR occurs when individuals imagine the potential negative emotions they might experience if they make a decision that leads to an unfavourable outcome (Hetts et al., 2000). This concept is crucial in understanding why individuals might deviate from purely rational choices. AR is closely related to prospect theory (Kahneman and Tversky 1979), which suggests that people value potential losses more heavily than equivalent gains, resulting in decision-making influenced by fear of negative outcomes. AR, in essence, is the emotional response to potential losses and, thus, an important factor in decision-making (McConnell et al., 2000).

Accordingly, the concept has received considerable attention in consumer behaviour studies (see, e.g., Valor, Antonetti and Crisafulli, 2022), and it posits that individuals engage in mental simulations of possible outcomes before making a purchase decision, such as when upgrading from a DVD player to a Blu-ray (cf., Shih and Schau, 2011), to assess the potential regret that may arise from making the wrong choice (Zeelenberg, van Dijk, and Manstead 1998). During an upgrade decision in the context of technology, where individuals must decide whether to adopt new technology or stick with the old one, previous research has shown that individuals may experience higher levels of AR. This is due to the fear of prematurely adopting the current best technology and missing out on future technology when it becomes available (Shih and Schau, 2011). Applying this to organisational contexts, managers not only consider economic aspects but also experience AR, which can influence their decision-making processes (Ng and Wong, 2008).

Having established in Section 2.2 that the perceived technology neutrality (PTN) of the existing policy mix may vary amongst different individuals due to the interpretative effects produced by a policy mix, we suggest that the theory of AR can be extended from consumers to individuals in organisations who make technology upgrade decisions for their respective organisations. When PTN is high for individuals in decision-making positions in a transport and logistic organisation (i.e., individuals perceive no clear governmental guidelines on which ZEV technology will be the industry standard), counterfactual what-if scenarios to evaluate possible outcomes of choosing a specific ZEV technology are a way of coping with complex decisions. This increases the level of AR associated with adopting future ZEV technologies. Such increased levels of AR, in turn, lead to the decision to delay the adoption of available ZEV technologies for fear of making an unfavourable decision for the organisation and experiencing negative emotions in the future. Therefore, we propose the following hypothesis:

> ***H1:*** *Higher PTN of the existing policy mix is positively related to higher levels of AR associated with adopting future technology, which in turn positively influences ZEV adoption intention delay.*

8.3.2 Perceived rate of technological change

Additionally, previous research findings suggest an individual actor-internal factor related to the expectations about future technology changes, which can significantly influence their willingness to adopt new vehicle technologies (Pradeep et al., 2021). The perceived rate of technological change (PRTC)—consumers' understanding of the rate of technological change in a marketplace—is a crucial aspect of consumer decision-making processes in technology adoption (Shih and Schau, 2011). Furthermore, PRTC has been identified as a critical driver of AR in consumers (Tushman and Nelson, 1990). High levels of PRTC can engender the “new-obsolete paradox” (Mick and Fournier, 1998), which pertains to individuals' anxiety over the potential obsolescence of new technology due to a looming wave of innovations. This paradox often induces ambivalence, causing anxiety and uncertainty about adoption decisions. Evidence suggests that individuals can form perceptions of PRTC and consider the rate of innovation change in their adoption choices (Holak, Lehmann, and Sultan, 1987). As technological changes continue to occur at a rapid pace, individuals are faced with the challenge of making upgrade decisions that could have significant long-term consequences, which creates uncertainty about whether the new technology is the best option and if it will be quickly replaced by even better technology soon (Shih and Schau, 2011). Notably, the higher the PRTC is in an individual, the more likely this individual will choose to delay purchasing current top-end technology in favour of waiting for future advancements (Venkatesh and Brown, 2001; Shih and Schau, 2011) or choose to avoid deciding altogether to avoid decisions that will have negative consequences (Loewenstein, 1996).

We argue that this effect can be extended from consumers to individuals making technology upgrade decisions for transport and logistics organisations. When considering technology upgrade decisions in an organisation, decision-makers are also influenced by their perception of the technology's future evolution. They are less likely to adopt new technologies when they perceive they will continue to improve in a way that waiting for these improvements will benefit their organisation. Essentially, the continuous and rapid advancements in ZEV technology complicate adopting new vehicles, as transport managers are constantly uncertain about the imminent arrival of even more advanced technologies (e.g., driving range or re-charging rates). Consequently, when managers perceive a high rate of change of ZEV technology and its future performance (i.e. when PRTC is high), more counterfactual thinking occurs, resulting in higher levels of AR. While PRTC influences AR by emphasising the risk of rapid obsolescence, it functions as a moderator. High PRTC amplifies the effect of PTN by increasing the severity of the potential consequences of choosing the "wrong" technology, but it does not independently affect AR to the same extent as PTN. This distinction is crucial as PTN introduces a specific type of uncertainty related to policy directions, which has a greater direct impact on decision-makers anticipated regret than the general technological advancements represented by PRTC (Ha, 2018).

> ***H2:*** *The effect of PTN on AR is moderated by PRTC—the higher the PRTC, the higher the negative impact of PTN on AR.*

8.3.3 Controlling for attitudes of ZEV technological characteristics and organisational experience

Studies on ZEV adoption for commercial trucks are relatively scarce compared to BEV adoption of passenger cars (Melander et al., 2022). However, previous research by Bae et al. (2022; 2019) and Wu et al. (2023) have shown that the perception of technological characteristics represents another individual actor-internal factor that may influence fleet operator decision-making processes. In their study, they outline that during the decision-making processes in transport and logistics organisations, a variety of different attitudes towards technological characteristics of ZEVs are simultaneously considered, including perceived compatibility, which refers to how functionally suitable transport operation managers perceive ZEVs in terms of, for example, their vehicle power or driving range. Moreover, the perceived relative advantage for the organisation by adopting ZEVs influences the decision-making process, including monetary benefits in terms of a lower total cost of ownership (TCO) or non-monetary benefits considering the environmental impacts of ZEVs, such as lowered life-cycle emissions. Thus, in addition to the hypotheses presented above, controlling for the effect of managers' attitudes towards ZEV technological characteristics on the link between perceived technological neutrality and adoption intention delay is relevant.

Additionally, previous studies in the context of BEV adoption in the passenger car segment have highlighted that individuals with prior BEV experience generally show an elevated willingness to pay for these vehicles (Larson et al., 2014; Peters and Dütschke, 2014). Hahnel et al. (2014) and Herberz et al. (2020) similarly argue that first-hand experience can enhance the appeal of unfamiliar, sustainable technologies. These findings may also be relevant in the organisational context because learning curves and technological familiarity are not limited to individuals but also apply to organisations. Just as first-hand experience changes perceptions about BEVs and influences individual purchase intentions (Hahnel et al., 2014; Herberz et al., 2020), organisations that trial ZEVs can gain practical insights into their operation, benefits and limitations, thus potentially influencing their overall adoption decisions. Consequently, it is argued that prior experience with ZEVs through test drives or at exhibitions and trade shows may also affect perceived technological neutrality and adoption intention delay. Therefore, in addition to hypotheses H1 and H2, these other two individual actor-internal factors must be taken into account to control for the effect of ZEV technological characteristics, attitudes and organisational experience on the interaction between PTN, AR and adoption intention delay.

All hypothesised relationships between the key concepts described in this section are depicted in Figure 1 below:

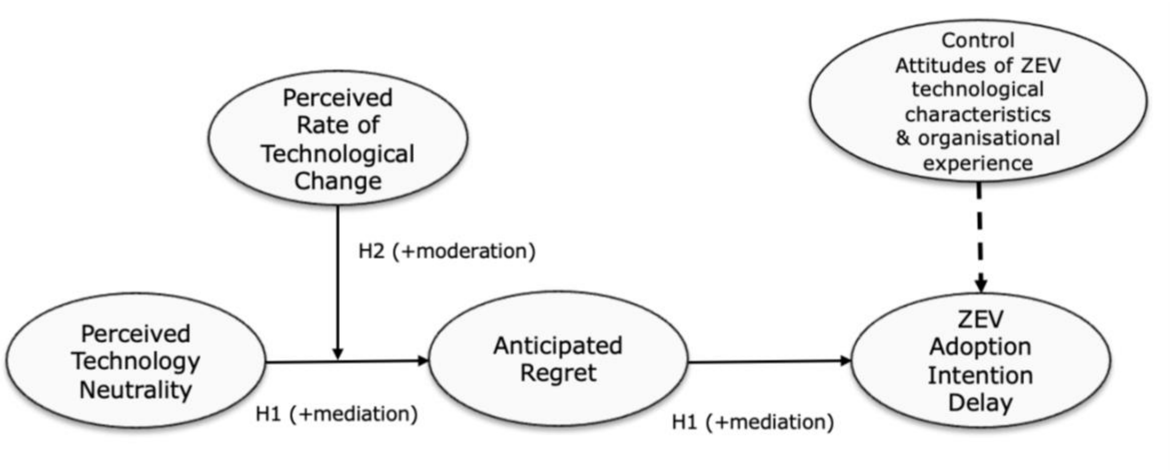

Figure 1. The hypothesised research model.

8.4 Methods

8.4.1 Case context

This study examines how different individual actor-internal factors of transport managers interact and together shape the innovation adoption decision-making process for ZEVs in the Swedish road freight transport sector. Road freight transport now plays a significant role in the Nordic country's economies, accounting for a sizable portion of Sweden's GDP (World Bank, 2021). The efficient movement of goods within the country and across borders can be considered essential for the growth of various industries, including manufacturing, agriculture and retail. However, its economic importance is also associated with significant GHG emissions, accounting for approximately 90% of the country's total transport sector emissions (SEI, 2021). Recognising this substantial environmental impact and the role that the sector must play in achieving internationally agreed climate targets, the Swedish government has set ambitious objectives for the decarbonisation of the road freight sector: a 70% emission reduction by 2030, compared to 2010 levels, with the long-term aim of net-zero emissions by 2045 (Regeringskansliet, 2021; Fossilfritt Sverige, 2019). To reach this objective, 50% of all trucks sold in 2030 should be ZEVs (Regeringskansliet, 2021). While the Swedish government sets no intermediate sales targets, a recent study by the International Council on Clean Transportation (2022) has indicated that an approximate sales share of 3-12% for medium-duty trucks (>=3.5-16 tons) and 2-9% for heavy-duty trucks (>=16 tons) by 2025 will be required to align the Swedish road freight sector with the Paris Agreement goals.

Three different ZEV drivetrain technologies, and mixes thereof, are currently being considered to decarbonise the road freight sector (Breuer et al., 2021; Regeringskansliet, 2020). The first solution is BEVs, trucks with an electrified powertrain with a large battery that is charged when standing still at a depot or en route via stationary chargers (Nykvist and Nilsson, 2020). The second is electric road system vehicles (ERSV), which also have an electrified powertrain but use an electric road system (ERS) for dynamic charging while driving (Tongur and Engwall, 2017). This charging technology is also available for stationary applications to enable a more seamless charging of trucks as they are being unloaded/reloaded at warehouses (Abrahamsson et al., 2020). The third, FCEVs, which also possess a fully electrified powertrain, are powered by hydrogen fuel cells refuelled at hydrogen fuelling stations (Çabukoglu et al., 2019).

The technological development rate of ZEVs has been extremely rapid in recent years, with all European legacy truck manufacturers committing to developing new zero-emission drivetrain technologies (Werner and Onufrey, 2022; T&E, 2023). Building on the early point of differences in technological maturity (Azar and Saden, 2011), it is essential to point to how the development stages of these three ZEV drivetrain technologies currently differ: BEVs have witnessed exponential progress in energy density, cost-effectiveness and charging infrastructure (Albatayneh et al., 2023). The improvements in lithium-ion battery technology, driven by economies of scale and advances in material science, have contributed to the increased range and reduced costs of electric trucks, making them viable options for various freight applications (Melander et al., 2022). Consequently, BEVs have seen a significant adoption uptake in recent years, especially in Sweden's light and medium-duty truck segments, where various vehicle models are readily available. Also, in the heavy commercial segment, Volvo Trucks and Scania, two of the world's leading vehicle manufacturers headquartered in Sweden, have launched several electric truck alternatives (Volvo Trucks, 2022). The Swedish government has also been investing heavily in expanding the charging infrastructure, intending to build 2,500 fast chargers by 2025 (Naturvårdsverket, 2023).

While Sweden is at the forefront of testing and developing ERS technology and ERSVs, ERS infrastructure on national roads outside of pilot test stretches has yet to be implemented. Nevertheless, stationary applications of the ERS technology exist due to several investments of transport and logistics companies into private charging platforms, and the Swedish government has a plan to build a 1000 km ERS network on public roads by 2030 (Regeringskansliet, 2021). Similarly, there is a growing interest in commercial FCEVs for long-haul transportation, where longer range and shorter refuelling time are required (Küffner, 2022). Currently, Volvo Trucks is testing its first model with Swedish transport and logistics companies. However, the truck model will only be commercially available in the second half of this decade (Volvo Trucks, 2023), hydrogen fuelling stations are limited, and registration numbers for hydrogen trucks from other manufacturers are still very low.

The successful deployment of commercial ZEVs is heavily connected to establishing a comprehensive charging and refuelling network, as all three ZEV drivetrain technologies require extensive infrastructure development to enable widespread adoption (Lajevardi et al., 2022). The availability of charging infrastructure, or lack thereof, thus, is frequently described as one of the main barriers to adopting ZEVs (Melander et al., 2022; Bae et al., 2022; Anderhofstadt and Spinler, 2019), and governments, as well as policymakers, play a central role in supporting the development of charging and refuelling networks (Galati et al., 2021). In Sweden, the existing policy mix to support the decarbonisation of road freight transport, next to monetary incentives for ZEV purchases, also includes a large variety of policy instruments such as financial incentives for infrastructure investments, regulatory support and public-private partnerships to stimulate the growth of such charging/refuelling networks and overall adoption rate of ZEVs.

The Swedish political landscape for the decarbonisation of the road freight sector can be described as technology-neutral in the sense that both policy mix elements of the policy strategy represented through official governmental roadmaps and plans as well as the instruments such as incentives and R&D schemes all broadly include and support all three different ZEV drivetrain technologies and their related infrastructure,[24] and aims to foster an environment where these different technologies can compete on a level playing field. However, despite the ambitious policy strategy for a low-carbon transition to ZEVs and instruments to promote it, progress is slow (Melander et al., 2022; Werner and Onufrey, 2022). According to the vehicle stock register of 2005-2023, a total of just over 480 ZEVs were part of the Swedish trucking vehicle fleet, making up only about 0.6% of all medium and heavy commercial vehicles registered in Sweden (Mobility Sweden, 2024a), with the sales share for medium-duty trucks (>=3.5-16 tons) laying at 1% and heavy-duty trucks at 3.6% of the overall sales of the respective categories between 2022-2023 (Mobility Sweden, 2024b). This gap between policy intention and real-world outcomes necessitates a comprehensive analysis that explores the relationship between individual actor-internal factors such as potential underlying transport and logistics companies' hesitations, uncertainties and the prevailing technology-neutral policy mix. Understanding this unique context might inform future policy adjustments within Sweden and serve as a relevant example for other countries striving to realise similar low-carbon transitions in their road freight transport sectors.

8.4.2 Data collection and sample

For the data collection, this study utilised a self-administered online survey targeted at transport operation managers working at transport and haulage companies in Sweden. We specifically targeted individuals in this role at transport and logistics companies because the decision to adopt ZEVs falls under a transport operations manager's purview, as they are responsible for evaluating and implementing strategies to optimise fleet performance, reduce operational costs and ensure environmental compliance. Moreover, we focused on organisations whose service portfolio included the type of transport assignments for which

[24]Information on the different elements of the prevailing policy- mix for the Swedish road freight sector and its technology technology-neutral stance can be found in Appendix A.

ZEVs are already commercially available, including distribution, waste, line and long-haul transport assignments. We aimed to survey companies with five employees or more to ensure our sample included businesses with a significant operational scale and economic resources. This criterion was set to allow our survey to better capture the perspectives of organisations that are more likely to engage in substantial fleet changes and have the financial and managerial capacity to adopt ZEVs. The sample frame for the study was derived from the email databases of two Swedish road freight transport industry associations. These databases provided a comprehensive list of members, ensuring representation from a significant portion of the Swedish road freight sector. A total of 397 email invitations to participate in the survey were distributed through the email databases. To increase the response rate, the researchers (1) pre-tested the survey using a small sample (n=10) amongst their network of transport operation managers to ensure that potential participants understood the survey questions and that the length of the survey was appropriate, (2) added a cover letter in the email invitation to explain the project that the participants would be contributing to and (3) based on the feedback received from the pilot, we included a text introduction explaining the study's rationale and asked respondents to provide their personal perspectives on potential organisational decisions and the development of ZEVs in the sector. Additionally, we provided a clear overview of all relevant ZEV technologies in the form of an infographic.

One hundred eighty-seven surveys were returned, which made the response rate 47%. However, only 83% of transport operation managers who began the survey also completed it, resulting in 155 completed answers. According to the statistical database of Sweden, 2973 road freight transport companies with a minimum of 5 employees were registered as of 2023 (Statistics Sweden, 2024). We thus surveyed just over 5% of this population. Considering established guidelines for determining sample size in organisational research (Barlett et al., 2001), this sample size can be considered robust, especially in the business-to-business contexts where the target population is relatively small, and panel data is not available. To further validate our sample, we performed a sample adequacy test (see section 5.1).

Table 1 gives an overview of the size of the transport and logistics companies of the respondents, the size of their vehicle fleet and the primary transport assignment type performed. Based on these results, our sample compares to the general characteristics of the Swedish road freight sector in that most of the companies are small to medium-sized enterprises (Statistics Sweden, 2023), and most transport assignments occur within Sweden (Trafikanalys, 2023), both in our survey and the total sector.

Table 1. Size of transport and logistics company sample by number of employees, vehicle fleet size and primary transport assignment type.

Characteristics		%
Size of transport and logistics companies (by number of employees)		
	<10 Employees	21.29
	10-20 Employees	38.06
	20-50 Employees	29.03
	50-100 Employees	7.74
	>100 Employees	3.87
Vehicle fleet size		
	<5 vehicles	3.23
	5-10 vehicles	28.87
	10-30 vehicles	20
	30-50 vehicles	29.03
	50-100 vehicles	16.77
	>100 vehicles	7.10
Primary transport assignment type		
	Waste collection	2.60
	Regional Distribution	39.61
	National long and line haul	51.95
	Timber transport	0.65
	International trailer transport	5.19

8.4.3 Instrument and measures

The survey instrument was comprised of two sections: The first part included all key concepts to test the relationships of the research model, while the second part included questions related to the transport company, including the size of the respondent's organisation (based on the number of employees), type of transport assignments offered and vehicle fleet size. All survey questions to measure critical concepts were close-ended, and participants were asked to indicate the extent to which they agreed to a particular statement describing a given concept on a seven-point Likert scale ranging from strongly disagree to strongly agree.

To measure the concepts of the research model, we employed the following established scales from the literature: For anticipated regret (AR), we adopted Tsiros and Mittal's (2000) regret scale as utilised by Shi and Schau (2011) to measure AR, and the perceived rate of technological change was measured by adopting Pradeep et al.'s 2021 perceived future technological change scale. Although these scales were originally applied to end-consumers, we adapted them for our study to measure these concepts within individuals in organisations (in the case of our study, transport operation managers working for road haulage companies). This adaptation is justified as the psychological processes underlying regret and perception of technological change are consistent across different contexts, including organizational settings. The remaining concepts of our research model, an individual's perceptions of the prevailing policy mix—specifically, perceived technology neutrality, attitudes of managers towards ZEV technological characteristics, previous organisational experience and ZEV adoption intention delay—have so far only been discussed conceptually and theoretically in the literature (Shih and Shau, 2011; Li and Wang; 2020; Bae et al., 2022; Wu et al., 2023). Therefore, we developed items based on previous academic literature and conducted validity and reliability tests, including Cronbach's alpha, exploratory factor analysis and confirmatory factor analysis. All measurement items for each concept can be found in Appendix B, and the full descriptive survey results for each in Appendix C.

8.4.4 Data analysis

The PROCESS macro in IBM SPSS (Version 24) was utilised to test the hypotheses of this study. This choice was motivated by several considerations. First, PROCESS demonstrated efficacy in addressing small sample challenges, even when the number of coefficients in a model is substantial. By employing bootstrapping, a resampling method, PROCESS generates multiple samples from the existing data, diminishing reliance on the assumptions of normal distribution and making it robust even for smaller sample sizes (Hayes, 2018). This approach has been shown to have high statistical power, permitting it to detect genuine effects with confidence even with smaller sample sizes while preserving a controlled Type 1 error rate (Preacher and Hayes, 2008). The flexibility of PROCESS allows for a comprehensive analysis of complex models, such as those involving moderation and mediation effects, without the need for a substantially larger sample. Additionally, applying bias-corrected 95% confidence intervals offers precise estimates of statistical significance, irrespective of the sample size (Hayes, 2018). Since the latent variables in our study were measured by multiple items, PROCESS (specifically, Model 7) proves compatible, ensuring the integrity and validity of the analysis.

Average scores were employed for variables represented by multiple items, as Hayes (2013) recommended. For instance, the value attributed to perceived technological neutrality was derived from the mean of five corresponding responses, assuming that these items accurately represented the latent variable in question. Principal component analysis (PCA) was used for the appraisal of the reliability and validity of constructs denoted by multiple items, and items with factor loadings below 0.5 were excluded from further analysis. The reliability was then assessed using Cronbach's alpha, and unreliable statements were eliminated. The Kaiser-Meyer-Olkin (KMO) measure was used to validate the adequacy of our sample size.

8.5 Results

8.5.1 Characteristics of measures and sample adequacy

The obtained KMO value was 0.846, which surpasses the recommended threshold of 0.6, suggesting a commendable degree of common variance among the variables. Additionally, Bartlett's Test of Sphericity was significant ($\chi^2(10) = 681.328$, $p < .001$), indicating that the correlation matrix is not an identity matrix and is thus appropriate for factor analysis. Additionally, as outlined in Table 2, the analysis of the reliability of measures based on Cronbach's coefficient showed that all the obtained factors were reliable (i.e., Cronbach's α >0.7).

Table 2. Characteristics of measures and factor loadings.

Latent variables and indicators	Mean	Cronbach's α	KMO measure	Loadings
Adoption intention delay (AID)	4.365	0.976	0.882	
AID1 Wait until dominant technology becomes clear				0.97
AID2 Wait until the dominant charging solution becomes clear				0.97
AID3 Wait until the government decides on technology				0.958
AID4 Wait until the government decides charging standard				0.966
Perceived technological neutrality (PTN)	4.776	0.891	0.852	
PTN1 Governmental policies for deployment				0.875
PTN2 Governmental investment support				0.842
PTN3 Governmental R&DD programs				0.891
PTN4 Policy strategy				0.819
PTN5 Climate policies				0.744
Anticipated regret (AR)	4.908	0.972	0.78	
AR1 Worried over wrong tech				0.948
AR2 Worried over wrong investment				0.962
AR3 Worried over wrong charging solution				0.962
AR4 Worried over wrong investment into charging				0.968
Perceived rate of technological change (PRTC)	4.654	0.948	0.775	

PRTC1 Improvement in vehicle purchasing costs	0.955
PRTC2 Improvement in market availability	0.951
PRTC3 Improvement in availability of charging	0.95

Before progressing to the regression analysis, a preliminary correlation analysis was performed to discern the relationships among the principal constructs. Spearman's rho was utilised, and the results are presented in Table 3. Notably, PTN demonstrated significant moderate positive associations with adoption intention delay (AID) and AR, while AID and AR also exhibited a moderate positive correlation. Conversely, PTR showed significant moderate negative correlations with PTN and AR and a high negative correlation with AID. This correlation analysis, thus, provides preliminary evidence of relationships between our constructs and the foundational insights necessary to advance the PROCESS analysis.

Table 3. Correlation matrix (Spearman's rho).

	PTN	AID	AR	PRTC
PTN	--			
AID	,582**	--		
AR	,645**	,745**	--	
PRTC	-,605**	-,727**	-,687**	--

** Correlation is significant at the 0.01 level (2-tailed). PTN = perceived technology neutrality; AID = adoption intention delay; AR = anticipated regret; PRTC = perceived rate of technological change.

8.5.2 Mediation and moderation analysis

First, the relationship between perceived technology neutrality (PTN) and anticipated regret (AR) was explored. As seen in Figure 3, the analysis found a significant relationship with a coefficient of 0.7492 (p=0.0116, LLCI = -1.3284; ULCI= -0.1699), thus indicating that an increase in perceived TN of the existing policy mix results in higher AR regarding the adoption of future technology. When analysing the direct effect of perceived TN on the intention to delay ZEV adoption, the results presented a marginally significant positive relationship. The coefficient was 0.1331 (p=0.0760, LLCI = -0.0141; ULCI= 0.2804), suggesting that higher levels of PTN might lead to a stronger intent to delay ZEV adoption. However, the indirect effect of PTN on ZEV adoption delay via AR was significant (coeff =0.6803, $p < 0.001$, LLCI=-0.8933; CI=-0.4922). Consequently, these results substantiate H1. As the PTN grows, so does the AR concerning future technology adoption, leading to a stronger intention to delay ZEV adoption.

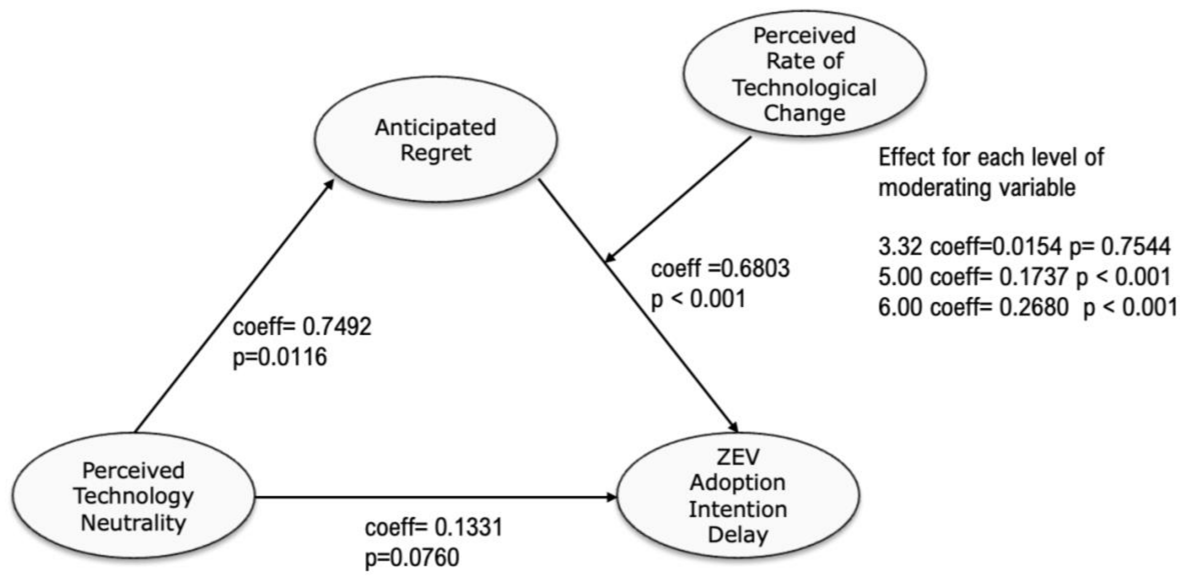

Figure 2. Measurement model.

However, the results suggest that the influence of PTN on the intention to delay ZEV adoption, when mediated by AR, is not uniform across different levels of perceived rate of technological progress (PRTC). Specifically, the strength of this indirect effect varies depending on how fast the managers believe technology is advancing. At a lower value (PRTC=3.3200), the indirect effect of PTN on the intention to delay ZEV adoption via AR is not significant (coeff=0.0154; p=0.7544; LLCI=–0.0758; CI=0.1429). Hence, as seen in Figure 3, lower perceived rates of technological progression diminish the indirect effect of PTN on ZEV adoption intentions through AR. At the median level of PRTC, which is a value of 5 on the PRTC scale, the indirect effect of PTN through AR on the intention to delay ZEV adoption was measured to be 0.1737. This effect was statistically significant, as indicated by the bootstrap confidence interval (p < 0.001; LLCI=0.0669; ULCI=0.3015). Hence, for transport operation managers who believe that the rate of technological progress is at an average pace, their increased AR due to perceived TN correlates significantly with the intention to delay adopting ZEV.

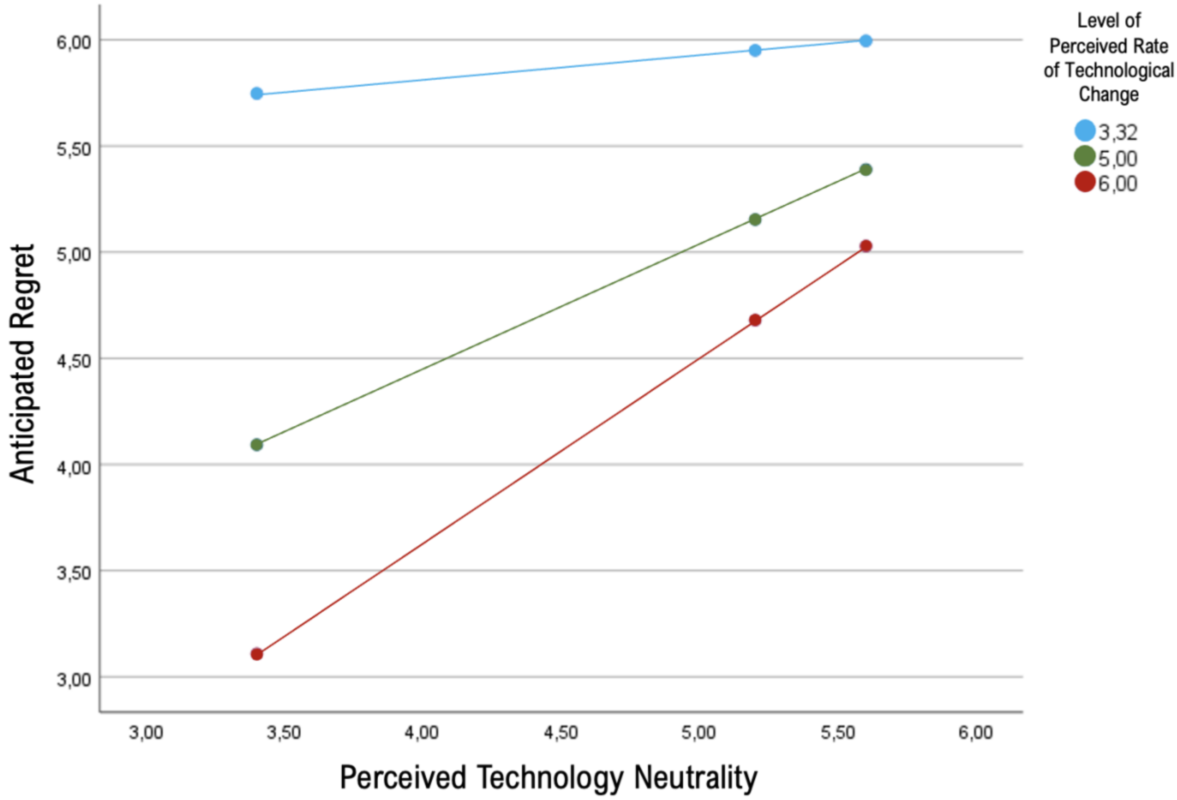

Figure 3. Effect of each level of the moderating variable perceived rate of technological change.

Interestingly, when we move up to individuals who perceive technology to advance faster, specifically at the 84th percentile or a PRTC value of 6.0000, this indirect effect becomes even more potent, registering at 0.2680. Again, this was statistically significant, as shown by the bootstrap confidence interval ($p < 0.001$; LLCI=0.1035; ULCI=0.4484). This indicates that those who believe we are in a period of rapid technological change anticipate even stronger regret due to high levels of PTN, amplifying their intention to postpone ZEV adoption. In essence, the perceived rate at which technology is evolving seems to accentuate the role of AR in mediating the relationship between PTN and the intention to delay adopting ZEVs. The faster one believes technology advances, the more pronounced this mediated relationship becomes, supporting H2.

8.5.3 Controlling for the effects of attitudes and experience

The mediation relationship between PTN, AR and AID was explored further by considering the effects of attitude towards ZEVs and prior organisational experience with ZEVs.

Table 4. Effects of Attitude and Experience on AR=Anticipated regret and AID=Adoption intention delay.

Variable	Coefficient	p-value	LLCI	ULCI
Attitude				
AR	-0.1680	0.2177	-0.4363	0.1002

AID	-0.2164	0.0116	-0.3837	-0.0491
Experience				
AR	-0.4403	<0.001	-0.6378	-0.2427
AID	-0.6051	<0.001	-0.7904	-0.4198

As seen in Table 4, the analysis revealed a significant influence of attitudes on AID. Specifically, as the attitude towards ZEVs became more positive, there was a decrease in the intention to delay ZEV adoption. However, the influence of attitudes on AR was not statistically significant. In addition, prior organisational experience with ZEVs had a significant negative impact on both outcomes. This indicates that individuals with more experience showed lower levels of AR and were less inclined to delay ZEV adoption. Notably, the coefficient for prior organisational experience with ZEVs was more significant than the coefficients for attitudes, signifying the former as a stronger predictor in reducing both AR and AID.

8.6 Discussion and policy implications

8.6.1 Key findings

Our findings show that when assessing the impact and effectiveness of policy mixes for sustainability transitions, it is important to consider how these policy mixes affect individual actor-internal factors. This includes understanding the cognitive and emotional responses of individuals in organisations, which can provide valuable insights into how organisations decide to adopt innovations. Building on the notion of interpretative effects (Edmondson et al., 2019; Edmondson et al., 2020) produced by a policy mix, our results highlight that such effects extend beyond previously discussed perceptions on policy mix credibility (Rogge and Duetschke, 2018) or acceptability (Kern et al., 2022). The underlying design principle of a policy mix, in the case of this study, technology neutrality, can also be cognitively processed differently by decision-makers in organisations. This varied cognition implies that while the intent of the policy mix might be neutrality, managers might interpret and perceive it in diverse ways. This, in turn, can lead to differing and potentially negative emotional responses; as revealed by the results of our mediation analysis, a significant relationship exists between the perceived technology neutrality (PTN) of the policy mix and the anticipated regret (AR) of transport operation managers concerning the premature adoption of new drivetrain technology. Essentially, increased PTN amplifies AR, leading to higher intentions to delay ZEV adoption. The results of this study on the role of AR in managers' behaviours towards technological innovations, hence, align with previous research on consumer behaviour towards innovations (i.e., Shih and Schau, 2011; Valor et al., 2022), as they indicate that transport operation managers may hesitate to adopt ZEVs because they fear potential adverse outcomes from adopting the "wrong" technology.

Moreover, these apprehensions grow stronger the more technology-neutral a policy mix is perceived by an organisation's decision-maker. Consequently, our findings suggest that technology-neutral policy mixes might have implications beyond merely affecting the technological trajectory of a transition, such as potentially locking out less mature technologies (Del Río González, 2008; Schmidt et al., 2016). Technology neutrality as a policy mix design principle also appears to have a pronounced influence on the cognitive processes and emotional responses of decision-makers in organisations, subsequently affecting their decisions regarding low-carbon innovation adoption. This is a important finding, showcasing the ripple effect of technology-neutral policy mix design on organisational behaviour.

Additionally, when analysing the moderating effect of a manager's perception of the rate of technological change, a distinct relationship becomes evident. Those who perceived a rapid pace of technological change exhibited stronger AR due to high levels of PTN, amplifying their intent to delay ZEV adoption. This underscores that managerial emotional responses are shaped not solely by the existing policy mix but also by overarching industry developments. Consequently, individual perceptions of a policy mix, in tandem with emotional responses and industry trends, jointly shape organisational decision-making, thus influencing the adoption rate of low-carbon innovations. Finally, our results also offer some mitigating factors. While, as described by Bae et al., 2020, a positive attitude towards ZEV technology can reduce the intent to delay their adoption, previous experience with ZEVs proved even more influential. Therefore, Hahnel et al. (2014) and Herberz et al.'s (2020) findings that individuals with previous experience with BEVs are more likely to adopt them also hold weight in an organisational context as managers with past ZEV experience showed less AR, emphasising the value of practical experience in decision-making processes related to ZEV adoption. This underscores the complex interactions of different emotions, cognition, experience and organisational behaviour in low-carbon transitions, offering a deeper understanding of organisational responses to policy mixes intended to foster rapid low-carbon transitions.

8.6.2 Implications for policy

From a policy perspective, the findings of our study consequently reveal an inevitable tension in the current policy mix for the road freight sector in Sweden. While intended to avoid favouring specific drivetrain technologies, technology neutrality might inadvertently hinder the rapid adoption of ZEVs. A technology-neutral stance can amplify uncertainties, especially in today's context, where technological change is perceived as fast, pushing transport operation managers to exercise caution and delaying adoption. Consequently, this research provides policymakers with insights into the interactions between perceptions of a policy mix design and individual actor-internal factors and their mutual influence on the pace of ZEV adoption. Instead of focusing solely on the technical and economic aspects, policymakers should consider the perceptual and emotional dimensions of individual decision-makers in organisations when designing policy mixes. In the context of emission-heavy sectors such as road freight transport, where ongoing decarbonisation processes are slow and require substantial investments in low-carbon technologies and complementary infrastructure, policymakers should reconsider the extent to which technology neutrality is emphasised for all elements of a policy mix to ensure they do not unintentionally deter industry progression towards net-zero goals. A three-pronged strategy, reflecting the current state of readiness for deployment of the emerging ZEV drivetrain technologies, might prove effective and would not require a complete shift away from technology neutrality but foster a more favourable environment for ZEV adoption, thereby aligning the road freight sector with Sweden's environmental and sustainability goals.

Firstly, augmenting the policy mix to reduce perceived risks associated with the early adoption of ZEVs can counteract heightened AR. This could be achieved by complementing existing financial incentives for ZEV adoption with a governmentally funded decision-making tool to guide the adoption decision-making process. Such a tool would provide accessible information on the different ZEV drivetrain technologies, for example, purchase costs, driving range and related infrastructure, including existing and planned charging and refuelling stations in Sweden, to alleviate concerns regarding the potential adverse outcomes of adopting the "wrong" vehicle technology.

Secondly, policymakers should recognise that in an era perceived to be marked by rapid technological change, some hesitation towards adoption is natural. Rather than solely promoting technology neutrality, policy measures could emphasise the robustness and longevity of current ZEV solutions, addressing obsolescence concerns. Hence, policymakers should formulate a long-term strategic plan for developing, deploying and supporting various ZEV technologies. This strategy should include clear targets, timelines and milestones, as well as input from relevant industry stakeholders and experts. To promote collaboration and knowledge sharing, policymakers could encourage open dialogue among diverse stakeholders, including transport operation managers, vehicle manufacturers, energy providers, and researchers. This aims to build consensus on the preferred decarbonisation pathway, which could lead to a more clearly defined governmental strategy for deep decarbonisation of the sector and mitigate concerns about potential policy shifts favouring a specific technology. Beyond the vehicles, our findings show that fears of rapid technological progression extend to supporting infrastructures such as charging and refuelling stations. Policymakers should, therefore, push for the development of infrastructure that is both compatible with current ZEVs and adaptable to future technological advancements. Assurances that today's infrastructure investments will not become obsolete tomorrow may significantly boost transport operation managers' confidence.

Thirdly, by leveraging insights from the influence of attitudes and prior experience, campaigns and initiatives that provide first-hand experience with ZEVs to transport operation managers and promote their benefits can help to encourage more decisive steps towards adoption. Policymakers, in collaboration with manufacturers, should consider establishing test centres where the latest ZEV models can be driven. These test centres could also house interactive exhibits that explain the technology, the economic, environmental and operational benefits of adopting ZEVs, as well as up-to-date information about the latest advances in ZEV technology and their expected commercial availability.

8.7 Conclusion

In this paper, we demonstrated the importance of the interactions between policy mix perceptions, emotions, attitudes, and past experiences in shaping organisational decisions to adopt low-carbon innovations. The findings underscore the complex relationship between the policy mix design, individual actor-internal factors and organisation's decision-makers, and resultant organisational actions. Notably, the psychological and emotional dimensions, previously less emphasised in the policy mix for sustainability transition literature, emerge as significant determinants of policy mix perception and effectiveness in the studied context. As a result, our study adds to this body of literature by emphasising the necessity of taking into account a broader range of factors when designing an effective policy mix. In doing so, it demonstrates how incorporating concepts and theories from psychology, behaviour economics and consumer behaviour studies into transition research can lead to a better understanding of how perceptions, attitudes, cognition and emotions influence transition processes.

While our research sheds light on the dynamics of policy mix perceptions and the slow ZEV adoption in Sweden's road freight sector, it does have limitations. First, our focus on individual actor-internal factors that influence the adoption decision-making process provides an initial set of relevant variables for the road freight sector. However, this approach may not capture the entire spectrum of factors influencing low-carbon adoption decisions. It is worth noting that, while our findings showed that established scales from consumer behaviour research could be applicable in an organisational context, it is important to recognise the need for careful validation and consideration of contextual differences when applying scales from a different context in organisational settings. Moreover, grasping the details of organisational decision-making presents ontological challenges because it is often a complex process influenced by multiple factors. Thus, our study is an initial exploration of how underlying perceptions, attitudes, and emotions can stall transition dynamics. Other socioeconomic, organisational or psychological determinants may also play important roles that warrant further exploration. We, thus, encourage transition researchers to consider a wide range of factors in future studies in order to gain a more pluralistic understanding of what shapes the choices, emotions and behaviours of decision-makers in organisations. Furthermore, given the interconnectedness of policy mixes, actors' internal factors and low-carbon innovation adoption, as exemplified by this study, a comprehensive, multi-disciplinary approach is required. We believe that integrating theories and concepts from longstanding disciplines such as consumer behaviour and psychology into transition research is a promising direction for future research to increase our knowledge of the interplay between individual-level factors, organisational-level decisions and industry-level transitions.

Second, the research's geographical limitation to the Swedish context may raise questions about the applicability and generalisation of findings to other national settings. While Sweden presents a distinct case, nuances in national policy landscapes, infrastructure and industrial dynamics may differ considerably elsewhere. As a direction for future research, cross-national comparative analysis, which includes a broader array of countries with distinct policy landscapes, may be useful because it can yield insights into overarching themes and region-specific nuances in innovation adoptions. Lastly, surveying only transport operations managers might provide a limited perspective into the organisation's adoption decision-making processes, as it is hard to account for strategic decisions made at higher levels.

To conclude, given the growing urgency of climate change, there is an undeniable emphasis on research that can advance knowledge on accelerating low-carbon transitions across industry sectors. Although relevant emission-reducing innovations may already exist, their swift adoption, as demonstrated by our study of the road freight sector, can sometimes be delayed by unidentified obstacles. Our research has contributed by identifying psychological and emotional barriers that might hinder organisations from adopting readily available low-carbon innovations. In light of our results, future policy mix research could benefit from adopting more inclusive approaches that consider both tangible and objective measures, as well as the subtle yet impactful emotional and perceptual nuances that shape decision-makers responses to low-carbon transition policies.

9. Emerging acceleration challenges of heavy-duty freight transport

Over the course of this PhD journey, the topic of net-zero transition acceleration challenges has gained increasing scholarly interest, and as a result of this, three new acceleration challenge types, namely *contestations*, *international dynamics* and *justice,* have been conceptualised (Rogge and Goedeking, 2024). In the following chapter, I discuss the applicability of these novel types to the empirical context of my work and introduce three additional acceleration challenges, which are illustrated with empirical examples of the net-zero transition of heavy-duty road freight transport.[25]

9.1 Contestation, international dynamics and justice

Contestations around building the new regime. This acceleration challenge describes the conflicts and competition of actors with varying backgrounds and interests over establishing new regime rules, such as market design or regulations, that influence the trajectory of net-zero transitions. These new rules are particularly contested because they determine how future gains among actors may be distributed and influence the growth and success of new technologies and associated business models (Rogge and Goedeking, 2024). Such contestations around building the new regime have been an integral characteristic of the investigated acceleration phase of the net-zero transition of heavy-duty freight transport: In Paper I and II, the analytical focus on contestation has allowed to reveal how power struggles between different incumbent actors but also new entrants play a central role in influencing the directionality and speed of the net-zero transition. By investigating the underlying cause of contestation, both Papers uncover different actors' varying economic interests and divergent priorities, highlighting how net-zero transitions are not just about technical feasibility but deeply political processes. These struggles are not merely about the adoption of (or the choice between) specific low-carbon technologies and new business practices but fundamentally about control over the emerging rules that have the potential to reconfigure the existing socio-technical system. Additionally, the results of both Papers show that contestations can evolve into conflicts and misalignment within and between regimes which result in a variety of different tensions that can either slow down progress, as exemplified through the conflicts over the prioritisation CE meta-rules amongst actors from different systems which has currently lead to fragmented efforts in the implementation of circular practices (Paper I); or accelerate net-zero transitions when for example new entrants challenge incumbent actors by pushing for more stringent environmental regulations, leading to faster development of low-carbon innovation as incumbents seek to maintain their market share (Paper II). The above highlights the importance for researchers and policymakers to acknowledge and further unpack the contested nature of regime change as it can enable a better understanding of why net-zero

[25]All additional acceleration challenges that are presented in this chapter are based on a qualitative content analysis of the empirical material (predominantly interviews and qualitative datums) that was collected for this thesis.

transition in certain sectors may be stalling as well as allow the design of more effective policies and strategies that can manage conflicts, align diverse actor interests, and ultimately accelerate the transition towards net-zero.

International dynamics. This acceleration challenge zooms out to bring attention to the complex global interdependencies that need to be considered for rapid emission elimination, including changes in global value chains, policy feedback, and international competition, which can significantly influence the pace of net-zero transitions (Binz et al., 2017; Rogge and Goedeking, 2024). While these international dynamics can drive faster adoption of low-carbon technologies, especially in export-oriented industries (Meckling and Nahm, 2019), they can also impede progress due to factors like critical material constraints (Gong and Andersen, 2024; Marín and Goya, 2021), industrial protectionism or trade disputes (Hughes and Meckling, 2017), and increasing geopolitical risks (Kivimaa, 2024). As outlined already in Chapter 3, the empirical context of this thesis research was the EU and Sweden; thus, international dynamics fall somewhat outside the scope of my work. Nevertheless, three international developments are worth mentioning here: First, the global market of heavy-duty trucks is undergoing rapid changes due to the emergence of Chinese manufacturers as dominant players in the EV sector (Gong and Hansen, 2023). Historically, European and North American manufacturers have led the market for conventional diesel trucks, but the shift to electric powertrains has created opportunities for new entrants, particularly from China (International Energy Agency, 2023). Companies, like Build Your Dream, have made significant advancements in BET technologies, benefiting from strong governmental support, vast economies of scale, and control over critical supply chains, including, most importantly, the battery production (Jolly, 2024). This rapid technological progress and cost reduction in Chinese BETs pose both a challenge and an opportunity for traditional Western manufacturers: The competitive pressure from Chinese manufacturers could act as a catalyst for Western companies to accelerate their innovation effort, thus accelerating the adoption of BETs globally. However, this raises concerns about the future of domestic truck manufacturing industries in Europe and North America, potentially leading to significant economic and political ramifications. If Western manufacturers fail to keep pace, we could witness a substantial shift in global market shares towards Chinese companies (BCG, 2023), mirroring the earlier trends in the passenger car market (Yang, 2023). This dynamic will likely drive further policy interventions in Western countries to protect domestic industries (Meckling and Nahm, 2019).

Second, the decarbonisation of heavy-duty freight transport, mainly through the accelerated adoption of BETs, heavily depends on the availability of critical raw materials, such as lithium, cobalt, nickel, and other rare earth elements. These materials are essential for the production of high-performance batteries. However, the supply chains for these materials are highly concentrated, often in regions with significant geopolitical risks (Koyamparambath et al., 2022). For instance, China currently controls a substantial portion of the global supply of rare earth elements and a significant share of the processing capacity for lithium and cobalt (Andersson, 2020). As geopolitical tensions rise, particularly between China and the West, in response to, for example, increased taxes on imported Chinese EVs, the security of supply for these critical materials becomes increasingly uncertain (Andersson, 2024; Nygaard, 2023). This could lead to supply chain disruptions, price volatility, and even potential shortages, which would have severe implications for the ongoing net-zero transition of heavy-duty freight transport. The EU has recognised these risks and actively seeks to diversify its sources of critical raw materials through strategies such as developing domestic mining capacities, investing in recycling technologies, and establishing partnerships with resource-rich countries outside of China (Brinza et al., 2024). However, these efforts are still in their nascent stages and may take years to impact global supply chains significantly. I, thus, argue that strategies that could reduce the resource intensity of heavy-duty freight transport electrification (as proposed in Paper IV) will play an important role in ensuring rapid emission reductions.

Third, while in the EU, stringent emissions regulations, substantial investments in infrastructure, and strong policy support have accelerated the adoption of BETs, in many other parts of the world, particularly in Africa, Latin America, and parts of Asia, this net-zero transition is barely in the emergence phase (Scott et al., 2023). One factor contributing to this difference is the narrow focus of European OEMs on meeting EU regulatory requirements and sales targets. While most of these manufacturers have committed to ambitious end dates for producing ICE trucks, these commitments are largely confined to the European market. Outside of Europe, these same manufacturers are not only continuing to sell ICE trucks but are, in some cases, actively investing in increasing their ICE production capacity to meet ongoing demand in these economically rapidly developing regions (T&E, 2023). Therefore perpetuating the reliance on fossil-fuel-powered vehicles in markets outside Europe. These investments by European OEMs in ICE production outside of Europe highlight the tension between regional net-zero goals and global business opportunities, potentially undermining international efforts to reduce greenhouse gas emissions from road transport (Emodi et al., 2022). If major regions of the world continue to rely on fossil fuel-powered trucks, it could undermine global net-zero targets and exacerbate inequalities between developed and developing regions (Alarcón, 2023). Therefore, international dynamics, such as trade policies, development aid, and international climate agreements, will play a crucial role in enabling the global transition to net-zero heavy-duty freight transport. Without significant international support, including financial assistance, technology transfer, and capacity-building initiatives, these regions will likely face significant barriers to reaching the acceleration phase.

Justice and equity. Lastly, Rogge and Goedeking (2024) have drawn attention to the inherent justice and equity challenges–the fair distribution of net-zero transition benefits and burdens across society–of the acceleration phase of net-zero transitions(Baker et al., 2021; Carley and Konisky, 2020; Heffron, 2021). Such challenges in the context of heavy-duty freight transport can be explored from the perspective of low-carbon innovation developers and manufacturers, as well as from the perspective of innovation adopters and users. From a manufacturing perspective, the challenge lies in securing the livelihoods of workers who have long been employed in the production of traditional ICE vehicles. As OEMs shift their production lines towards BETs and other ZEVs, there is a critical need to ensure that these workers are not left behind. Instead, they are offered retraining and reskilling programs to equip them with the skills necessary for a new EV manufacturing economy (Szabó and Newell, 2024). Moreover, many suppliers that currently provide parts for ICE trucks are likely to see their roles diminish or disappear altogether as OEMS focus increasingly on the production of BETs, which typically require fewer components and, thus, have a different supply chain structure (Rísquez Ramos and Ruiz-Gálvez, 2024). This could have profound implications for the economic livelihood of entire regions dependent on said supply chains (Galgóczi, 2008). Therefore, measures must be taken to enable these smaller suppliers to pivot to producing BET parts or diversify to other economic activities (Pichler et al., 2021a). Political support, such as financial incentives or technical retraining assistance, is most likely required (Szabó and Newell, 2024). Without such interventions, the net-zero transition of heavy-duty freight transport risks exacerbating economic inequalities, particularly in regions heavily reliant on the traditional automotive supply chain (Pichler et al., 2021b). Moreover, shifting production capacity from ICEVs to BETs demands the development of an ethically sound supply chain, particularly when sourcing critical raw materials like lithium, cobalt, and nickel for battery production (Rajaeifar et al., 2022). As discussed previously, these materials are often sourced from regions with significant socio-economic challenges, including labour exploitation and environmental degradation (Sovacool, 2021). Manufacturers have a responsibility to ensure that their supply chains are both environmentally sustainable to avoid problem-shifting effects and also socially equitable by protecting the rights and well-being of workers at every stage of the supply chain (Jannesar Niri et al., 2024). This could involve adopting stringent sourcing standards and collaborating with stakeholders across the supply chain to promote fair labour practices and community benefits in resource-rich regions.

From users' perspective, the net-zero transition of heavy-duty freight transport entails significant financial burdens, particularly for small businesses and independent truck operators, which make up the majority of the industry sector yet may lack the capital to invest in new low-carbon alternatives. The high upfront costs of BETs, coupled with the need for access to charging infrastructure, pose substantial barriers to entry for these users (Bohlin and Dahlin, 2023). Ensuring the affordability and accessibility of BETs is, therefore, a key justice concern. Governments and manufacturers must work together to develop targeted subsidies, financing options, and lower-cost vehicle models that make the transition to BETs feasible for all users in the upcoming few, regardless of their economic status or else the accelerated diffusion of these vehicles may be at risk. Moreover, the equitable development of charging infrastructure is crucial to ensuring that the benefits of the transition to BETs are shared across all regions. Rural and remote areas, particularly, are at risk of being left behind if charging infrastructure is concentrated in presumably economically attractive locations (Sovacool et al., 2022), such as in the case of heavy-duty vehicles, urban logistic centres or near truck stops. This could exacerbate regional disparities and limit the ability of users in less populated areas to contribute to decarbonisation efforts (Hardman et al., 2021; Hopkins et al., 2023). Additionally, the deployment of charging stations heavily depends on grid access and capacity, which can be limited in less developed or rural areas. Ensuring equitable grid access is vital to prevent disparities in charging availability. Upgrading grid infrastructure to support the increased demand from BETs, especially in regions where the grid is weak or underdeveloped, is essential (Brockway et al., 2021; Lin et al., 2022). This might involve targeted investments and incentives to build grid capacity in underserved areas. Adding to that, many independent operators also use their trucks for personal transportation and park them at home, making access to affordable home charging solutions a critical issue. Thus, support for installing residential charging stations or providing accessible public charging options near their homes is essential, alongside ensuring that local grids can support these additional loads without causing service disruptions.

9.2 Net-zero finance

Even though climate finance–financial resources (including public sector funding, private sector investments, and international financial mechanisms) directed toward supporting the transition to a net-zero, climate-resilient economy–has drastically increased over the last few years, the investment sums that are needed to avoid the worst impacts of climate change and reach broader net-zero goals are at least five-folds higher compared to what has been invested globally in recent years (Buchner et al., 2023). In line with previous contributions that call for more scholarly attention to the role of finance in transitions (e.g., Dordi et al., 2022; Hafner et al., 2020; Nykvist and Maltais, 2022; Penna et al., 2023; Polzin, 2017) , I thus suggest that this *net-zero finance gap* must be more explicitly considered a transition acceleration challenge. This challenge is especially relevant in the context of accelerating net-zero transitions of hard-to-abate industry sectors, which only receive approximately 1% of all global investments (IRENA, 2024) and, therefore, can be considered somewhat of a blind spot of climate finance (Warren, 2020). For heavy-duty freight transport, specifically, the costs associated with the development and deployment of ZEVs, infrastructure for charging and/or refuelling, and the scaling of renewable energy to power these trucks will require a substantial financial commitment of both private and public actors over the coming decades; even though no exact estimate of the total amount required exits. Viewing the net-zero transition of heavy-duty freight transport through the lens of the prevailing rules of financial investing, (Penna et al., 2023), it becomes clear why raising such substantial capital might become difficult: The financial regime prioritises investments that offer the highest financial returns in the shortest possible time span at the lowest quantifiable risk, and these rules thus contradict the long-term investments required to decarbonise heavy-duty freight transport, which involve high upfront costs without immediate financial returns, a substantial amount of technological uncertainty and frequently still unclear business cases.

Sweden, particularly through the collaborative efforts of its government, can serve as an insightful case of how to overcome these investment barriers and (at least partially) close the net-zero finance gap in the acceleration phase: Now that there is a range of commercially available ZEVs and related charging infrastructure the Swedish government has several targeted subsidy programs in place to foster cooperation between the public and private sectors that can stimulate investments in the net-zero transition of heavy-duty road freight. For example, Klimatklivet (Naturvårdsverket, 2024) offers up to 50% funding for projects aimed at reducing GHG emissions, including investments in heavy-duty ZEVs and the necessary charging infrastructure. By sharing financial risks, this program encourages private companies to invest in low-carbon technologies, stimulating demand and facilitating market growth. Similarly, the Regionala elektrifieringspiloter subsidy scheme (Energimyndigheten, 2024) supports the development of public charging and fueling stations in collaboration between municipalities, private investors, and technology providers. By subsidising a significant portion of the investment costs (up to 50%), the scheme reduces the financial risk for companies looking to invest in charging infrastructure. Thus, ensuring the infrastructure is in place to support widespread adoption of ZEVs even though the business case and model for truck charging stations remains unclear. Such funding programs are especially crucial for innovative technology providers, often smaller start-ups with limited access to capital, because they enable these providers to bring their technologies to market and contribute to the construction of charging stations without the need to carry all upfront costs.

However, the majority of these funds are paid out upfront, and despite an extensive application and review process, they are potentially vulnerable to fraud (Nylander, 2024). After receiving significant initial funding, the risk arises when recipients may divert these funds to unrelated or illegitimate activities, such as investing in other ventures or creating shell companies to secure further public funding. This could lead to a situation where funds are continuously cycled through different entities without any real progress being made on the original project. This practice could go undetected for extended periods. Additionally, there is the potential for recipients to manipulate their financial reporting, presenting false progress or inflating costs. This could lead to a situation where public funds are continually extracted without delivering promised infrastructure, thus delaying net-zero transitions. In conclusion, this transition acceleration challenge type is not only about closing the net-zero finance gap but also highlights the critical need to address how scaling up finance for net-zero initiatives during the acceleration phase may be vulnerable to fraud. Therefore, targeted strategies and control mechanisms are necessary to ensure that funds are not stolen, wasted or misused.

9.3 Premature lock-in

While lock-in is often discussed in the context of high-carbon technologies and represents effects that contribute to the path-dependent nature and change inertia of existing socio-technical systems, these effects (as highlighted in Paper V) can also be important drivers of the accelerated adoption of low-carbon alternatives (Lee et al., 2022; Stache and Sydow, 2023). By achieving lock-in, these alternatives can benefit from increasing returns, network effects, and standardisation, as well as reach the necessary economies of scale in production, reducing costs and making them more accessible to a broader market (Simmie, 2014; Sydow et al., 2012). However, previous work has indicated that lock-in tends to favour more mature innovations (Haelg et al., 2018; Schmidt et al., 2016), characterised by higher technological readiness and market availability. Once a new lock-in occurs, the entrenched socio-technical configuration surrounding the mature innovation creates barriers for newer technologies, potentially slowing the adoption of superior alternatives with greater emission reduction potential. I, thus, suggest that the *premature lock-in of inferior*[26] *socio-technical configurations* represents another challenge of the acceleration phase of net-zero transitions that deserves more theoretical and empirical attention.

The wording socio-technical configurations are used here on purpose to highlight that it is not solely about choices between different low-carbon technologies but also about the broader system elements such as infrastructure, regulations, practices, and societal behaviours that may shape and reinforce accelerated adoption of these technologies in an unfavourable way. As discussed in Paper IV, the lock-in of inferior socio-technical configurations can result from prevailing rules, such as the 'predict and provide' approach in transport infrastructure planning, remaining unchanged even as low-carbon technologies gain wider adoption and begin to reconfigure other elements of a socio-technical system. This premature lock-in can also extend to complementary technologies: In the case of electrified heavy-duty road freight, high-power stationary charging has become the new industry standard, with the EU having drafted plans to deploy mega-watt chargers along major transport routes supported by AFIR (European Comission, 2023). However, previous studies have indicated that while mega-watt chargers support the rapid

[26] When using the words inferior and unfavourable I refer to configurations that may be less effective in terms of their potential for reducing emissions compared to other available alternatives.

deployment of BETs, they may not be sufficient to meet the long-term emission reduction goals due to their limitations in reducing overall lifecycle emissions (Rogstadius et al., 2024). In contrast, electrification via a comprehensive ERS network across Europe would offer a much bigger emission reduction potential, as it not only enables continuous charging at lower power but could reduce battery size requirements, thus significantly lowering the lifecycle emissions of heavy-duty vehicles, thereby better aligning with net-zero ambitions (Plötz et al., 2024; Shoman et al., 2022). Similarly, semi-solid and solid-state batteries, which replace the liquid electrolyte in traditional lithium-ion batteries with a more stable material, could offer significantly higher emission reduction potential compared to their lithium-ion counterpart currently used in BETs (Janek and Zeier, 2023). These batteries are expected to enable more efficient energy use, lower lifecycle emissions, and reduce the overall environmental impact of EVs (Mandade et al., 2023). Nevertheless, lithium-ion batteries have become locked in as the new industry standard, leading European HDV OEMs to invest heavily in scaling their battery production and recycling capacity (Transport & Environment., 2023), with limited investment in R&D for the commercialisation of semi-solid and solid-state vehicle batteries. In both examples, it could be argued that stationary chargers and lithium-ion batteries have gained early dominance due to their current technological readiness. This early lock-in limits the adoption of potentially superior alternatives, which, despite offering greater emission reduction potential, are hindered by their relative immaturity and the positive reinforcing effects that these inferior complementary technologies are benefiting from. Consequently, as transitions across different systems accelerate and broader system reconfigurations occur, it becomes increasingly important to closely monitor how different socio-technical elements change and how new lock-ins might emerge.

9.4 Carbon-intensive technologies in use

The so-called flip side of transitions–the destabilisation, deliberate decline and eventual phase-out of carbon-intensive socio-technical configurations–has received increasing scholarly attention in recent years (Koretsky et al., 2023; Rosenbloom and Rinscheid, 2020; Turnheim and Geels, 2013, 2012). Previous contributions to the literature have highlighted that phase-out is an inherently political process entailing contested negotiations, power struggles, and conflicts among stakeholders with differing interests and priorities over the discontinuation of carbon-intensive technologies (Koretsky and van Lente, 2020; Rinscheid et al., 2022). Once a phase-out has been decided, the associated policy interventions can broadly be divided into two categories: use phase-outs and sales phase-outs (Trencher et al., 2023). Use phase-out policies mandate the gradual discontinuation of the existing technology in use. An example of such policies is Germany's nuclear and coal phase-out, where the government has committed to decommissioning all nuclear plants by 2022 and phasing out coal-fired power plants by 2038 (Hermwille and Kiyar, 2022; Markard et al., 2021; Rogge and Johnstone, 2017). On the other hand, sales phase-out policies focus on banning the sale of new units of carbon-intensive technologies while allowing the continuation of those already in use. For example, Norway's ban on the sale of ICE-powered passenger cars by 2025 is a policy that stops new sales to encourage a shift towards EVs, but it does not immediately ban already registered ICE vehicles from Norwegian roads (Meckling and Nahm, 2019; Zhou et al., 2022). Such sales bans, however, can hinder the timely achievement of net-zero targets by allowing existing carbon-intensive technologies to remain in use longer, resulting in a slower reduction of emissions over time. Thus, this approach often leads to an extended transition period, making it difficult to achieve the necessary rapid emissions elimination required to meet strict climate goals but also delays the accelerated adoption of low-carbon alternatives by maintaining demand for entrenched infrastructure, services, practices and other socio-technical elements tied to the old high-carbon technologies(Plötz et al., 2019). I consequently propose that not only decline more broadly but how to deal with *carbon-intensive technologies in use* more specifically should be conceptualised as an additional net-zero transition acceleration challenge.

At European-level currently, no concrete phase-out date for ICE-powered heavy-duty trucks exists (unlike for passenger cars); however, its target of a 90% reduction in GHG emissions from new heavy-duty vehicles by 2040 is often referred to as a de facto ban as it will only allow for a very small sales share of ICE trucks. Despite this target, emission reduction scenarios for the sector show that even if a sales ban on new ICE trucks were to be implemented, a substantial portion of the existing fleet would continue to emit GHG emissions for many years after 2040 due to the long lifespan of HDVs, which often remain in operation for up to two decades (Rogstadius et al., 2024). Such slow fleet turnover also does not create the strong demand signals needed to stimulate private investment for the development of a widespread charging network. Without sufficient market demand for BETs, the incentives to invest in and expand charging infrastructure remain weak, which in turn can further slowdown the adoption of low-carbon alternatives. This might create a situation where the lack of infrastructure discourages the purchase of new electric vehicles, thereby perpetuating the reliance on older ICE trucks. Thus, there is a need for additional policy interventions such as incentivising the early retirement of older vehicles or retrofitting existing ICE trucks with powertrains. Otherwise, the sector might struggle to meet the EU's GHG reduction targets and broader net-zero ambitions (Rogstadius et al., 2024). I would argue that this is not only a unique challenge of heavy-duty freight transport but is also applicable to passenger cars, gas and oil home heating systems, as well as the aviation fleet. Therefore, it must be explicitly addressed and strategically overcome in the acceleration phase of net-zero transitions.

10. Concluding discussion and contributions

This chapter integrates the insights from the five individual publications that represent the backbone of this compilation thesis and Chapter 9 to provide a meta-reflection on their findings and contributions in relation to the two research aims. It specifically focuses on their significance for understanding, analysing, and navigating emerging challenges in the acceleration phase of the net-zero transition in the heavy-duty road freight sector (and beyond). The discussion begins by outlining the conceptual contributions of this work for understanding endogenous change processes, followed by the methodological advancements for analysing the acceleration phase, and then the empirical findings in the context of heavy-duty road freight and their implications for both policymakers and managers. I conclude this chapter with a reflection on the limitations of this work and propose avenues for future research.

10.1 Conceptual discussion and contributions of this thesis

This thesis started with the aim of developing a better theoretical understanding of the possibilities and underlying mechanisms of how prevailing socio-technical configurations may be reconfigured from within. Answering previous calls to bridge and adopt theories and concepts from other disciplines to improve transition theorising (Hansmeier et al., 2021; Zolfagharian et al., 2019), my work has further developed and added to the evolving body of knowledge on system reconfigurations by integrating theoretical approaches and concepts from organisational studies into transition research. In the following subchapter, I attempt to summarise the key contributions of this thesis that enable transition scholars to gain an enhanced conceptual understanding of such endogenous change processes.

Conceptual contribution 1: Rule reconfiguration, diffusion and alignment and the role of tensions within and across systems

First, by building on previous applications of the organisational field concept to socio-technical regimes (Fuenfschilling and Truffer, 2014; Geels, 2020) and introducing the idea of regime fields to describe how regimes are comprised of multiple overlapping and interrelated fields of different practices, institutions, and rules, this thesis has extended the traditional understanding of regimes (Turnheim and Sovacool, 2020); thus, showing that they are not monolithic entities but rather dynamic and multi-dimensional spaces where the interaction of various sub-fields and a large variety of actors drive rule reconfigurations. This conceptualisation, additionally, places a stronger emphasis on regimes as arenas of ongoing negotiation and conflict, where different actors across regime fields vie for influence and control. Therefore, it contributes to a less harmonious view of actor interactions (Heiberg and Truffer, 2022) by theorising regime stability or change as the result of ongoing power struggles within these fields, where actors engage in strategic (inter)actions of differing natures (i.e., competitive, mutualistic, antagonistic) that can reproduce or reconfigure the status quo (Paper II). The work in this thesis further contributes to an increased understanding of how rules are reconfigured and diffused across systems by demonstrating that such processes are neither linear nor uniform. Instead, rule reconfiguration often involves negotiation and conflict, where actors seek to align new rules with existing practices or modify them to fit their specific contexts. Additionally, the findings of this thesis have allowed to overcome the previous overemphasise evolutionary convergence of rules (Kemp et al., 2022) by highlighting how rules are interpreted, adapted, and selectively implemented by different actors within the same system and across different systems depending on the strategic interests of the actors involved (Paper I). In consequence, rule alignment during a period of reconfiguration becomes a contested process that entails ongoing negotiations, conflicts and emerging tensions (Paper I; II). Instead of considering such tensions as a potential outcome of regime-change processes, the work presented in this thesis identifies them as an integral aspect of system reconfigurations. These tensions can emerge from incompatible ideas about new regulatory requirements, differing resource capabilities, or competing technological visions among incumbent actors. When navigated effectively, it can act as a driver of change, prompting a swift realignment of rules and the development of a new common meaning system. When tensions lead to prolonged negotiations and increased complexity, they act as barriers by preventing the development of common meaning systems, thus slowing down reconfiguration processes (Paper II).

Conceptual contribution 2: Incumbent actor reorientation dynamics

Second, this thesis contributes to an advanced understanding of incumbent actor agency (Galeano Galvan et al., 2020; Geels et al., 2016; Kump, 2023) for overcoming path dependencies and carbon lock-ins of prevailing socio-technical configurations by highlighting how incumbents are not merely passive entities reacting to external pressures such as the increased societal awareness of climate change but can be proactive agents capable of shaping and influencing system reconfiguration processes. By integrating path constitution approaches grounded in ideas of structuration theory to analyse such actor reorientations and proposing an alternative nested hierarchical structure of socio-technical systems, this work has revealed the continuous interactions between the existing structures (e.g., established technologies, regulations, and market conditions) and the actions of incumbents (agency), thus, demonstrating how incumbents in hard-to-abate industry sectors can leverage their entrenched positions, resources, and influence to actively accelerate net-zero transitions given the particular circumstances. In the studied context, such circumstances included increasing regulatory pressures, rapid technological advancements and diminishing returns from carbon-intensive technologies. These factors collectively enabled incumbent actors to reorient, further reinforced by targeted policy incentives and the development of complementary technologies that enhanced the viability of low-carbon alternatives (Paper III). This agency, however, is not homogeneous; different incumbents within the same sector may pursue diverse strategies based on their specific interests, resources, and interpretations of unfolding reconfiguration processes. Therefore, the research of this thesis has illustrated how incumbent actors also possess the ability to reinterpret emerging rules and influence and adapt them to their advantage, often engaging in selective rule adoption (Paper I). For example, they may choose to comply with emission regulations that align with their long-term goals while lobbying to modify or delay aspects that could threaten their established position (Paper III). This selective adoption allows incumbents to maintain control over the pace and direction of change, ensuring that net-zero transitions unfold on the most favourable terms to their interests, thus securing their continued dominance. To further understand how incumbents reorientate, this thesis has also developed a relational perspective on incumbency, which underscores that incumbents' actions are deeply embedded within their broader network of relationships, both within their system and across multiple systems (Paper II). Under this perspective, incumbency is not just about individual actors holding a dominant market position but also about their ability to mobilise resources jointly, influence other actors, and shape the institutional environment in their regime fields. Incumbents' reorientation strategies are therefore seen as relationally constructed, dependent on their interactions with other firms, regulators, and stakeholders, as well as on the specific configurations of power and resources within these regime fields.

Beyond contributing to an increased understanding of how large established economic actors that are deeply entrenched in carbon-intensive socio-technical configurations, such as OEMs, reorient towards net zero; this work has also made an effort to emphasise the diverse types of actors that can hold incumbent positions (Steen and Weaver, 2017; Turnheim and Sovacool, 2020). The results of this thesis highlight that incumbency is not limited to large, dominant firms but includes a range of actors such as small and medium-sized enterprises, industry associations, regulatory bodies, universities and local governments. These different types of incumbents bring varied perspectives, resources, and strategies, influencing how transitions unfold. For example, regulatory bodies and industry associations often play a critical role in shaping the regulatory environment of an industry, thus stabilising or reconfiguring regime rules. Similarly, universities and their research programs may also act as influential incumbents by aligning their research agendas with industry needs, which can either reproduce carbon-intensive arrangements or support the development of low-carbon alternatives (Paper II). Consequently, the more pluralistic view of incumbency put forward in this thesis challenges prevailing uniform understandings of incumbency by acknowledging that different actors, depending on their influence and role within the existing system, contribute to stability and change in distinct ways.

Conceptual contribution 3: Speed and scope of system reconfiguration

Third, in contrast to previous studies that have highlighted the gradual nature of system reconfigurations (Geels, 2018; Geels and Turnheim, 2022), the work presented in this thesis has demonstrated that under specific conditions, net-zero transitions can occur rapidly, resembling a punctuated equilibrium rather than a decade-long evolutionary process. This insight, thus, contributes to a better understanding of the varied ways in which system reconfigurations may unfold, as well as the underlying mechanisms that are responsible for this by theorising how trigger events and enabling conditions can lead to rapid reconfigurations (Paper III). Moreover, the work presented in this thesis has demonstrated that the scope of net-zero transitions can be significantly constrained when new rules are embedded into existing socio-technical systems without prompting broader reconfigurations of other socio-technical elements within these systems (Paper I; IV). The actual scope of net-zero transitions, therefore, depends not just on the diffusion of individual rules but on how these rules diffuse (e.g., rebranding of existing practices vs. transformation of existing practices) and the extent to which these changes to individual rules can catalyse fundamental reconfigurations of the entire system. Absent such broader reconfigurations, the capacity of novel low-carbon technologies or practices to drive rapid emission elimination is limited, as highlighted in Paper I and IV, ultimately narrowing the scope of net-zero transitions.

Conceptual contribution 4: Co-evolutionary nature of innovation and decline in system reconfigurations

Lastly, by following calls to examine the relationship between decline and innovation (Rosenbloom and Rinscheid, 2020; Schmidt and Sewerin, 2017) more closely, this thesis has contributed conceptually by highlighting the co-evolutionary dynamics between processes of low-carbon innovation and carbon-intensive technology decline as part of ongoing system reconfigurations. Its findings revealed that decline and innovation are interconnected and mutually reinforcing processes, and as the destabilisation of carbon-intensive configurations progresses, the adoption of low-carbon alternatives accelerates, creating feedback loops that further drive the decline of carbon-intensive technologies (Paper III). The work thus emphasises the importance of viewing innovation and decline as interlinked processes that must be managed in tandem in the pursuit of net-zero transitions in hard-to-abate industries.

10.2 Methodological discussion and contributions of this thesis

Next to conceptual contributions, this thesis also offers several methodological approaches and tools that can support transition researchers in analysing the acceleration phase of net-zero transitions. Overall, this thesis makes two methodological contributions.

Methodological contribution 1: Diversifying the data collection and analytical methods utilised to reflect the complexity of net-zero transitions better

First, the work presented in this thesis goes beyond more commonly applied data collection and analysis methods within the field of transition research, such as interviews and content analysis (Hansmeier et al., 2021; Zolfagharian et al., 2019). It incorporated a multi-method approach, integrating semi-structured expert interviews, a national survey, industry event observations, and field visits, alongside the systematic collection of secondary data from reports, policy documents, and media clippings. These different data sources were analysed using a diverse combination of analytical approaches, ranging from qualitative and quantitative content analysis as well as Social Network Analysis (SNA) to process tracing and mediation and moderation analysis. Especially by employing analytical approaches from other scientific disciplines to study net-zero transition, this thesis was able to generate novel insights: For example, making use of SNA in Paper I, originating from sociology, allowed to map and analyse reorientation activities and interactions of actors within and across multiple systems thus enabled the identification of key actors and prevailing power dynamics in ongoing system reconfigurations. Thus providing a clearer understanding of how the relational dynamics between actors of different systems influence transition processes. Similarly, by utilising a mediation and moderation analysis, commonly used in psychology and behavioural sciences, applied to the survey data in Paper V, this research was able to generate new knowledge on how internal factors (such as anticipated regret) and external factors (such as an existing policy mix) interact to influence the adoption of low-carbon innovations. Altogether, employing these diverse data collection and analysis methods has enabled this thesis to provide a more complete picture of the prevailing transition acceleration challenges of the net-zero transition of heavy-duty road freight and, therefore, highlights the importance of methodological pluralism to better capture the full complexities of socio-technical stability and change.

Methodological contribution 2: Leveraging quantitative and mixed-methods research for a more comprehensive understanding of transition acceleration challenges

Second, following previous suggestions on the possible benefits of employing quantitative and mixed-method approaches to study transition phenomena (Zolfagharian et al., 2019), this thesis has utilised such approaches to complement and enrich findings generated through qualitative methods. For example, the mixed-method content analysis employed in Papers I incorporated automated quantitative text analysis, enabling the identification of patterns in how the CE meta-rules are diffused and revealing the varied interpretations of CE meta-rules across different systems as well as how these interpretations evolve over time. Thus providing insights into the contentious meta-rule diffusion process that shapes the directionality of transitions toward circularity. Likewise, the process tracing method that was employed in Paper III, which combined qualitative narrative construction with quantitative statistical data analysis, enabled the identification of the sequencing and timing of events as well as the underlying mechanisms that have influenced historical industry trajectories and recent transition dynamics of the European HDV sector.[27] But the work presented in this thesis is also a testament to the value of purely quantitative methods, such as the moderation and mediation analysis discussed above, a method that clearly can generate valuable new insights into potential factors that are delaying transition processes when employed to answer specific research questions (such as innovation adoption decision-making in Paper V). To conclude, the new knowledge on transition acceleration challenges of heavy-duty freight that was gained throughout this thesis by using quantitative and mixed-method approaches should encourage transition researchers to venture out of the comfort zones of qualitative methods and explore what new knowledge can be generated through the integration and application of diverse methodological approaches.

10.3 Empirical discussion and implications of this thesis

Beyond conceptual and methodological contributions, this thesis also significantly improves our understanding of European heavy-duty road freight's contemporary net-zero transition dynamics. After decades of incremental improvements of ICE powered trucks and a short period during which multiple alternative vehicle technologies have competed to become the dominant low-carbon alternative, battery electric trucks (BETs) have emerged as the currently most viable decarbonisation technology. Within less than five years from their initial commercialisation, BETs have entered the transition acceleration phase, marked by falling total cost of ownership, ever-increasing market shares, and exponentially increasing new vehicle registration numbers across Europe. Despite these positive developments, the findings of this thesis have highlighted that previously conceptualised transition acceleration challenge types (Markard et al., 2020; Rogge and Goedeking, 2024) have high applicability also in the context of hard-to-bate industry sectors: whole systems change, the increasingly multi-system nature of net-zero transitions, managing the decline of carbon-intensive technologies, changes in demand patterns, net-zero transition governance, contestations around building the new regime, international dynamics as well as justice and equity concerns all present challenges that if not dealt with could slow down or limit the scope of the net-zero transition of heavy-duty road freight. Additionally, the empirical findings of this research also have contributed to extending the portfolio of transition acceleration challenges by proposing net-zero finance, premature lock-in and carbon-intensive technologies in use as additional challenge types.

[27] The SNA performed in Paper II is another example of mixed-method approaches used in this thesis but is not elaborated upon in this section to avoid repetition.

Despite the acceleration of the net-zero transition in heavy-duty road freight, low-carbon innovations are not equally embraced among incumbent actors such as vehicle manufacturers and hauliers. Vehicle manufacturers, especially those with significant sunk investments in perfecting ICE technology or those lacking the capabilities or resources to develop and produce ZEVs, remain committed to stabilising prevailing carbon-intensive configurations and often use their political lobbying power to for example weaken proposed CO2 standards of the European Commission. Nevertheless, driven by regulatory support and simultaneous pressure, the current net-zero transition dynamics are still characterised by drastic reorientations activities of incumbent actors towards low-carbon alternatives at all industry levels (i.e., OEMs, hauliers, fuel providers, gas station operators etc.). However, the growing involvement of incumbent actors from other systems, such as energy providers, introduces additional complexities, as these actors must align their operations, investments, and strategies with those of heavy-duty road freight to successfully reconfigure the system for electrification, often leading to coordination challenges, conflicting priorities and even new market competition.

Lastly, my research findings and the current pace of the net-zero transition of heavy-duty freight transport raise questions about its classification as a hard-to-abate sector. This classification, although useful to delineate the specific characterisations (see Chapter 1) that differentiate heavy-duty transport from other systems, should not be seen as a prescriptive label that inherently limits the pace of decarbonisation efforts but rather draws attention to potentially different transition dynamics (e.g., higher probability of endogenous change). Therefore, while recognising the heavy-duty freight transports' specific characteristics and challenges is important, the label hard-to-abate should not be used to excuse inaction or delayed action.

10.3.1 Policy implications

As highlighted throughout this work, the acceleration phase of net-zero transitions, especially in hard-to-abate sectors like heavy-duty freight transport, presents unique challenges and opportunities for policymakers. Therefore, in addition to the detailed policy recommendations provided in each of the papers (Chapters 4-8), this section aims to synthesise the findings from this thesis to highlight three overarching policy implications.

Policy implication 1: The acceleration phase of hard-to-abate industry sectors requires a distinctively different policy mix than the emergence phase.

Previous work has already highlighted that the acceleration phase of net-zero transitions calls for a shift from policies focused on niche support and experimentation to those that drive large-scale adoption and system-wide integration (Meadowcroft and Rosenbloom, 2023; Rosenbloom and Meadowcroft, 2022). Although this implication, thus, is not entirely novel, this work provides potential insights for *the how-to* in the context of hard-to-abate sectors by offering several new considerations for designing industry policy mixes to support the acceleration phase: First, instead of winding down low-carbon innovation incentives over the course of the acceleration phase (Meadowcroft and Rosenbloom, 2023), hard-to-abate industry sectors such as heavy-duty road freight might require policies that provide long-term economic stability and clear investment signals. Given the capital-intensive nature of these industries and the high upfront investment costs necessary to adopt low-carbon alternatives such as ZEVs, it might be crucial to maintain strong and consistent policy support to de-risk investments in low-carbon technologies and infrastructure. This could be achieved through mechanisms like long-term contracts for infrastructure providers that offer predictable returns on investment or sustained subsidies and tax incentives for innovation users that enable long-term predictability of operational expenses, such as the total cost of ownership for ZEVs.

Moreover, policies must be designed to address the acceleration phase's inherent contestation, conflict and resulting tensions. As highlighted in this thesis, the transition to net zero in hard-to-abate sectors like heavy-duty freight transport is not only a technical challenge but also a deeply political process. Contestation often arises from competing interests over the establishment of new market rules, standards, and regulatory frameworks. For instance, when new emissions regulations or technological standards are proposed, different incumbent actors but also new entrants may have divergent views on how these should be structured. To manage this, industry policies could include open, iterative stakeholder engagement processes where all relevant actors, such as manufacturers, regulators, and user groups, are involved early as well as continuously in the policymaking process. For example, creating sector-specific working groups or advisory councils could facilitate dialogue and build consensus on contentious issues like technology standards, as well as allow for revisions in response to emerging issues. This approach would ensure that all voices are heard and reduce the risk of prolonged tensions that can delay transition processes. As discussed in Papers I and II, conflict in the acceleration phase is often rooted in the redistribution of economic power and specific resources. Policies, therefore, must be able to manage such conflicts by fostering dialogue and negotiation among stakeholders and providing platforms for conflict resolution. This might include setting up neutral bodies or mediators to oversee the negotiation of standards and regulations in contested areas, such as the implementation of CE.

Additionally, as Paper III revealed, the diffusion of low-carbon innovation and the decline of carbon-intensive technologies in the hard-to-abate industry sector are interdependent processes that should be managed in tandem. Once a certain threshold of destabilisation of the prevailing carbon-intensive socio-technical configuration is reached, the mutual reinforcement between innovation and decline becomes a critical driver of rapid change.

Policymakers, thus, should account for and strategically leverage this coevolutionary dynamic and could more specifically focus on how the timing of regulatory interventions might play an important role here. For example, gradually tightening NOx and CO2 emissions reduction targets for newly registered heavy-duty trucks, timed to coincide with regulatory support for manufacturers in scaling up the production capacity of ZEVs, could ensure that as stricter standards are implemented, the market is fully equipped to meet the increased demand for low-carbon alternatives. Similarly, a long-term phase-out date could be timed to match forecasts about broad marker availability and cost parity of low-carbon technologies and further supported with adoption incentives, such as tax reductions and long-term commitments to infrastructure development.

While policies in the late emergence phase are often concerned with supporting innovators and early adopters of low-carbon technologies (Bianchi et al., 2017; Frenzel et al., 2021; van den Bergh et al., 2021), in the acceleration phase, the focus might have to shift to the opposite end of the innovation adoption curve (cf., Rogers, 2003). This means targeting policies towards laggards and the late majority, who may be slower to adopt due to, for example, higher perceived risks, uncertainty about technology maturity, and concerns about the total cost of ownership. Additionally, Paper V also identified that emotional and psychological barriers, such as fear of making the wrong investment, can also play a significant role in delaying adoption. Net-zero policy mixes could, therefore, include instruments to mitigate these concerns by offering decision-making tools that provide clear, up-to-date information on technology maturity, costs, and infrastructure development to encourage an accelerated adoption across all market segments and ensure that the eventual stabilisation phase is not delayed by adoption hesitance or worse resistance among the late majority and laggards.

Lastly, the effective coordination of policies (and their feedback) across multiple sectors and systems can be considered a crucial aspect of the acceleration phase, as highlighted throughout Papers I, II and IV. However, this is an important consideration and deserves a separate implication.

Policy implication 2: Initiating a policy paradigm shift towards multi-system net-zero governance approaches

A successful transition to net zero will require governance frameworks that go beyond traditional system boundaries and transcend single-system-focused approaches but instead can address the increasing interconnectedness of different systems as the acceleration phase unfolds (Markard and Rosenbloom, 2022). One of the main opportunities for developing such a multi-system governance approach would be its potential to enhance policymakers' understanding of how the diffusion of low-carbon innovation in one system can affect or is dependent on developments in other systems. For example, a recurring theme throughout all five Papers is the fact that the accelerated adoption of ZEVs is not only contingent on advancements in vehicle technology but also heavily reliant on the expansion of renewable energy capacity and grid infrastructure. By adopting a multi-system governance perspective, policymakers could anticipate potential bottlenecks, such as insufficient grid capacity, and plan for necessary developments early on before they start to affect the pace of the acceleration phase. Additionally, it would allow policymakers to address one of the main governance challenges that emerge throughout the work in this thesis: tensions that arise from the interactions between systems. As discussed in Paper I and II, such tensions often result from conflicting priorities, resource constraints, and different readiness levels across sectors. A multi-system governance approach could enable the alignment of regulations across systems. For example, this could entail integrating transport electrification policies with energy grid expansion plans to ensure that the increased demand for electricity from EVs does not overwhelm the existing energy infrastructure. This, however, would require close collaboration between transportation and energy regulators to harmonise the timelines and investment strategies as well as the development of monitoring and evaluation frameworks that can also account for policy feedback across both systems.

Policy implication 3: Addressing the more and the less obvious justice and equity implications of net-zero transitions

The insights of this thesis have also revealed several difficulties in ensuring a just and equitable transition to net zero for heavy-duty road freight that require further policy attention. Some of these difficulties, such as the geopolitical and resource-based inequities associated with the transition to electric mobility, have been widely acknowledged as well as are discussed in depth in Paper IV and elsewhere (e.g., (Koyamparambath et al., 2022; Marín and Goya, 2021; Sovacool, 2021) and, consequently, call for the development of robust, ethically sound supply chains that prioritise environmental sustainability and the rights and well-being of workers in of resource-rich but economically disadvantaged regions. Other difficulties, such as the potential economic inequities within transitioning industries, are only slowly gaining more awareness within the context of just transitions. Without proactive measures for workers and suppliers embedded in traditional automotive sectors, as suggested in Chapter 9, the net zero transition of heavy-duty road freight could lead to widespread job losses and economic decline in regions heavily reliant on the traditional automotive supply chain. Beyond these publicly discussed and researched difficulties, this thesis also brought to light some less well-acknowledged justice and equity concerns related to the accessibility and affordability of low-carbon technologies. Small businesses and independent truck operators, for whom a truck is not just a business asset but also a crucial means of personal mobility, are particularly vulnerable. The high upfront costs of ZEVs, coupled with the current lack of widespread charging infrastructure, create substantial barriers to adoption for these operators. This inequity threatens to exclude a significant portion of the industry from participating in the net-zero transition, potentially leading to a two-tiered system where only larger, well-resourced companies can afford to go net zero. To address these hidden inequities, targeted policies are essential, such as subsidies, financing options tailored to small businesses, and the equitable distribution of grid access and charging infrastructure. These measures would help ensure that the benefits of the net zero transition are shared broadly across society rather than being concentrated among those with the most resources.

10.3.2 Managerial implications

Additionally, this work offers implications for managers working for organisations that develop low-carbon innovations and for those who are faced with the decision to adopt such innovations in the heavy-duty freight sector.

Managerial implication 1: Navigating the multi-sectoral dynamics of net-zero transitions

The findings of this work have shown that the varying priorities and capabilities of actors across these different sectors can create significant challenges in achieving cohesive progress towards net-zero. Managers thus should focus on fostering cross-sectoral collaborations that can align these divergent interests. This could involve creating platforms for dialogue where different sectors can articulate their needs and constraints, facilitating a shared understanding of the net-zero vision of the sector. Additionally, managers should advocate for integrated policy frameworks that consider the interconnected nature the energy and transport systems, ensuring that regulations and incentives are designed to promote synergy rather than competition among the systems and its actors. Moreover, cross-sectoral innovation among technology producers should be encouraged, with managers supporting collaborative research and development initiatives that leverage the strengths of each sector. By building strategic partnerships and aligning objectives across systems, managers can help drive a more coordinated transition to net-zero, overcoming the resource limitations that often hampers isolated efforts.

Managerial implication 2: Strategic management of technological uncertainty and contested transition pathways

Despite the current dominance of BETs, a low-carbon alternative to ICE trucks, future net-zero transition pathways for heavy-duty road freight are still somewhat contested, and some technological uncertainty remains. For managers of organisations that produce ZEVs and those of organisations that should adopt them, a dual strategy might be beneficial: scaling up the adoption of current low-carbon technologies while remaining adaptive to future advancements. Manufacturers could prioritise the large-scale production of commercially ready ZEVs to achieve economies of scale and market availability, thus ensuring the current momentum of the net-zero transition does not slow down. Simultaneously, they should nevertheless continue investing in R&D to improve these technologies and develop alternative low-carbon technologies to avoid an early lock-in into a single technical trajectory. Hauliers and transport companies, on the other hand, should focus on integrating the available ZEV technologies as soon as possible into their operations to capitalise on near-term environmental and economic benefits. However, they must also remain flexible, recognising that the technology landscape is still in flux and might change significantly in another decade or two. Both manufacturers and end-users of low-carbon innovation thus need to stay open to emerging pathways and advancements, ensuring that their strategies can pivot as new, more efficient technologies become viable without remaining committed to carbon-intensive technologies in the meantime. To reduce the economic risks that such a strategy might entail, managers should advocate for strong government policies to achieve net zero, such as intermediate goals, subsidies and continued infrastructure investments.

10.4 Limitations and future research

This final section concludes the thesis and my PhD journey by reflecting on the inherent limitations of my work, some of which can inform future research. It is important to note that this section addresses the overarching limitations of the research endeavour as a whole. For detailed discussions of the specific limitations of each individual paper and the respective methods employed, please refer to the limitation sections within Chapters 4-8.

First, the use of five archetypical acceleration challenges, as proposed by Markard et al., 2020, to guide the analysis of the net-zero transition acceleration phase of heavy-duty road freight, may potentially introduce research bias. When researchers adopt predefined categories such as the five acceleration challenges, there is a risk that their analytical scope narrows, and they end up only focusing on evidence that supports or fits within these existing categories. Such confirmation bias may lead researchers to interpret data in ways that align with the archetypes, even if alternative interpretations might be more accurate. Researchers, consequently, might unconsciously seek out examples that confirm the presence of these archetypes, thereby reinforcing their relevance and existing assumptions about net-zero transition dynamics rather than challenging them. Several measures were employed throughout this thesis to navigate these limitations. Most importantly, I would argue that the five archetypical transition acceleration challenges to me resemble much more of a meta-level analytical framework rather than a framework that rigidly confines the research to predefined categories thus, leaving me with plenty of room to adapt them to fit the unique challenges of heavy-duty road freight. Moreover, the research of this thesis, rather than taking these acceleration challenges as a given, explicitly explored the empirical applicability of these archetypes to the acceleration phase of net-zero transitions in heavy-duty road freight. By maintaining a focus on assessing each archetype's relevance and context-specific manifestation, I, therefore, made a conscious effort to remain receptive to data that did not conform to the five archetypes. Finally, this thesis conceptualised three additional transition acceleration challenges to ensure that emerging challenges were not overlooked. This proactive step allowed me to incorporate new insights gained from my research, thereby minimising the risk of not including important, yet previously undefined, challenges, thereby contributing to the evolution of the transition acceleration challenge typology and ensuring a more comprehensive analysis of the net-zero transition acceleration phase challenges of heavy-duty road freight.

Second, several analytical choices of the research presented in this thesis limit the generalisability of its findings. Choosing heavy-duty freight as the empirical example to study transition acceleration challenges in hard-to-abate industry sectors inherently has narrowed the scope of applicability. While researchers and practitioners working on net-zero transitions of other hard-to-abate sectors with similar characteristics, such as maritime shipping or aviation, may find the insights presented in this thesis more relevant due to comparable characteristics and emerging low-carbon technologies options, those working on other hard-to-abate sectors with fundamentally different characteristics might not. For example, industries like steel, cement, or petrochemicals, characterised by distinct production processes, fewer viable low-carbon alternatives, and other infrastructure needs, may not benefit as directly from the findings. As discussed in related work, (e.g., Saygin and Gielen, 2021; van Ruijven et al., 2016), these sectors face unique process emission challenges that differ significantly from those encountered in the heavy-duty freight industry. As a result, the extent to which the findings from this research can be generalised across all hard-to-abate sectors is limited. Given that this thesis represents the first examination of transition acceleration challenges in hard-to-abate industry sectors, future research should expand the scope of the investigation to other sectors to allow for a more comprehensive understanding of the applicability of the challenge types and potential additional challenges across different hard-to-abate industry sectors.

Additionally, despite making an effort to include data from European representatives of the heavy-duty freight sector, much of the data collection took place in Sweden. The Nordic country presents a unique research context, as Sweden is a global leader in heavy-duty vehicle electrification, with the presence of leading OEMs of heavy-duty ZEVs (e.g., Scania and Volvo Trucks), supportive policy mix and advanced roll-out out of charging infrastructure. As a result, the findings presented in this thesis may reflect the specific conditions and advantages of the Swedish context, which might not be fully representative of the challenges faced in other European countries with different technological, regulatory, and infrastructural preconditions. Nevertheless, Sweden represents one of the handful of European countries that have actually entered the acceleration phase (measured on ZEV market shares), thus the insights generated in this thesis could still provide valuable knowledge on future challenges faced by other countries in Europe whose heavy-duty net-zero transition is on the brink of accelerating. Beyond Sweden and Europe, the generalisability of the findings to developing countries is even more limited: In many Global South countries, the heavy-duty freight sector is less formalised, often operates with older, less efficient vehicle fleets imported from the Global North and faces significant infrastructure challenges (Emodi et al., 2022; Mulholland et al., 2018). These differences suggest that the net-zero transition in these geographical contexts may follow a very different trajectory, potentially prioritising alternative solutions such as biofuels (Ghisolfi et al., 2024; Soliani, 2021), and once transitions enter the acceleration phase, emerging challenges might also differ significantly. Given that the transition acceleration challenge types have not been researched in the context of the Global South so far, future studies should, therefore, focus on understanding their applicability within the specific socio-economic and infrastructural constraints of these regions. However, due to the limited progress in the net-zero transition of heavy-duty road freight in developing countries, it may be more practical to start by examining systems where low-carbon transitions are already underway (e.g., the net-zero transitions of the African energy system).

Ending on a more theoretical note, one important direction for future research that emerged from the findings of this work is the need to better understand the absorptive capacity of existing socio-technical systems. Both Paper I and III highlighted that when existing socio-technical systems are faced with new rules, they might incorporate them into their existing socio-technical configurations by rebranding or substituting individual elements without broader systemic changes. While this can enable short-term adaptation to new market dynamics and compliance with increasing regulatory pressure, it poses a significant challenge for achieving more radical system reconfigurations such as those required to achieve net-zero goals. This absorptive capacity can entrench existing practices that contribute to environmental degradation (e.g., the predict and provide planning rule), possibly limiting net-zero transitions' scope and speed. Consequently, more research is needed to increase our conceptual understanding of the role of absorptive capacity in the context of system reconfigurations and endogenous change.

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