Cost and financing of the sustainability transition of the Swedish road freight transport sector

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To my beloved mother, Sanam,

my devoted husband, Mehdi,

and my caring sister, Irandokht

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Abstract

The cost and financing of the road freight sector's sustainability transition, driven by significant greenhouse gas (GHG) emissions and cost considerations, represent an urgent yet underexplored research focus. This study investigates the costs of fleet replacement with zero-emission powertrains, battery electric vehicles (BEVs) and fuel cell vehicles (FCVs), emphasizing cost variables that have been overlooked in transition research. It explores the financing dynamics of the transition for this sector at both the strategic and tactical levels, and it investigates circular economy (CE) transition barriers specific to BEV batteries. Six studies are developed, involving multiple sources of data and methodological approaches: systematic literature review, numerical modeling and scenario testing, data-driven agent-based simulation, network analysis, and interviews.

The findings reveal that charging strategies have a substantial impact on BEV costs, especially in scenarios with higher adoption rates. This is attributed to electricity price fluctuations based on charging location, timing, power, and source. High hydrogen prices in scenarios with a high number of FCVs lead to increased fuel costs. Interestingly, the impact on loading capacity for larger powertrains in both BEVs and FCVs is relatively minor compared to other costs. The capacity of batteries depends on charging ranges and temperatures, but their impact would not significantly affect cost savings through increased BEV salvage values where a CE initiative is in place. A set of regulatory, market, structural, technological, actor-related, and task-related barriers and their complex interactions are identified that hinder BEV transition from a linear to a circular system. The availability of financing is crucial for facilitating the transition and is highly contingent on the financial strength and creditworthiness of companies, particularly given the prevalence in the sector of micro and SMEs, which often encounter challenges in accessing financing.

Keywords: Sustainability transition, Decarbonization, Heavy-duty vehicles, Cost, Financing, Battery, Circular economy

List of abbreviations

ABS	agent-based simulation
BEV	battery electric vehicle
CE	circular economy
ERS	electric road system
FCV	fuel cell vehicle
GHG	greenhouse gases
GLM	generalized linear model
IAM	integrated assessment model
ICE	internal combustion engine
IPCC	Intergovernmental Panel on Climate Change
LIB	lithium-ion battery
PHEV	plug-in hybrid electric vehicle
R&D	research and development
SNA	social network analysis
TCO	total cost of ownership

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1. Introduction

The transport sector, an essential component of the economy, is the second-largest contributor to greenhouse gas (GHG) emissions (Islas-Samperio et al., 2019; Greene et al., 2010; Lamb et al., 2021; Yoro and Daramola, 2020) and plays a crucial role in exacerbating climate change and its environmental impacts. In 2017, 21.9% of Europe's GHG emissions came from the transport sector, showing an increase from 14% in 1990 (European Environment Agency, 2019). In Sweden, despite a decreasing trend in GHG emissions from the transport sector, the amount of emissions remains substantial, emphasizing the need to transition towards a more sustainable transport system. Road transportation is the biggest single source of domestic transportation sector's pollution in Sweden, with a 91.5% of the sector's emissions share (accounting for 24.7% of the total emissions in Sweden) in 2019 (SCB Statistical Database). Emissions from freight transportation also play a significant role in road traffic pollution in Sweden. According to data from the SCB, while passenger cars are the largest contributor at 67%, heavy-duty vehicles make up 21% of emissions from domestic road transportation (SCB Statistical Database). These figures highlight the crucial contribution of heavy-duty transportation to air pollution. Taking into account projected economic growth and an increase in demand for transportation, an even greater increase in GHG emissions is expected from this segment[5]. This makes the transition towards a sustainable transport system an urgent challenge, especially in the heavy-duty road sector, which is one of the hardest to decarbonize (Atkins et al., 2021; Van der Zwaan et al., 2013). Well-founded scientific evidence is needed to foster sound decision-making in this period of rapid transition.

In response to the escalating emissions output and its effects on global warming, the Intergovernmental Panel on Climate Change (IPCC) proposed a new agreement, the Paris Agreement, to limit the rise in the global temperature to less than 2 °C above pre-industrial levels and to pursue an effort to limit it to 1.5 °C by 2050 (UNFCCC, 2015). In accordance with the agreement, many

[5] For example, projections by the Swedish transport Agency of about 1.5% annual growth from 2017 to 2040 and 1.2% annual increase from 2040 to 2065 in road freight transportation in Sweden (Trafikverket, 2020b).

countries have established goals to reduce their GHG emissions[6]. However, the transition towards zero-emission transportation is by no means an easy one, and proceeding with the transition targets requires a great deal of investment. Although sustainability transition is a well-established area of research, little is known about the cost and financing of the transition (Sunio and Mendejar, 2022), which is currently attracting growing attention from policymakers through laws and regulations[7], from academics through research initiatives in areas such as sustainable finance and climate economics, and from society through the introduction of a variety of supportive initiatives[8].

Sustainability transition requires extensive investment in sustainable infrastructure across various sectors such as energy, public transportation, construction, water supply, and sanitation (Global Commission on the Economy and Climate, 2016) making the transition challenging from a financial perspective. The Global Commission on the Economy and Climate (2016), for instance, estimates the requirement for financial resources to transform global infrastructure in accordance with sustainability standards at approximately $90 trillion over the 15 years from 2015 to 2030, with 60% of this amount allocated to the energy and transportation sectors. Liu et al. (2021) expect this share to be around 90% of the total investment. Infrastructure Outlook (2017) projects a global investment gap in road infrastructure of about $8 trillion, with Europe facing an investment gap of $882 billion in this sector by 2040. These figures, although massive, do not include the cost of transitioning to sustainable operations for businesses, as they target public transportation for their projections (e.g., Infrastructure Outlook, 2017). Businesses, however, account for a significant share of emissions[9], requiring investigation into how they will face the transition and how much the transition will cost them.

The massive investment requirement is one of the major challenges for sustainability transition (Global Commission on the Economy and Climate,

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6 For instance, Sweden set a target for lowering emissions from domestic transport (excluding aviation) by 70% in 2030 compared to 2010 levels, with the ultimate goal of reaching zero emissions in 2045 (Trafikverket, 2020a).

7 For example, the regulations proposed by governments about sustainability reports in financial communities (Ng, 2018) or the introduction of the EU taxonomy of sustainable economic activities in Regulation (EU) 2020/852.

8 Several initiatives promote sustainability transition in transportation, such as increasing investment in green transportation under DHL's Send Green project in Sweden (DHL, 2020) and the Volvo Group's issuing of green bonds to finance its green projects, including production of fossil-free cars and trucks (Volvo Group Videos, 2020).

9 For example, 21% of emissions in the domestic road transportation sector in Sweden belong to the heavy-duty freight transportation segment, accounting for 5% of total emissions in 2021 (SCB Statistical Database, 2023).

2016), not least for private actors, who face difficulties in accessing external financing due to lower expected returns on investment in green projects and greater associated risks (Taghizadeh-Hesary and Yoshino, 2020). Within the road transport sector, most hauliers are micro and small companies with lower bargaining power for securing finance for their operations and investment. According to data collected from the Retriever Business database for active companies in Sweden's road freight transportation in 2021, about 53.55% of active hauliers are micro companies with fewer than three employees, and 43.65% of them are SMEs with fewer than 50 employees (according to the author's compilation of data from freight transportation companies in Sweden sourced from the Retriever Business database). Even with the current growing discussion on the transition of the financial system from a neo-classical economy to sustainability (Ryszawska, 2016), the lending practices of financial institutions continue to prioritize the creditworthiness of borrowers over considerations of sustainability (Sunio and Mendejar, 2022), making it difficult for such companies to access financing. Moreover, despite the criticality of financing as one of the main barriers to transition (Polzin et al., 2017), the financing allocated to emissions reduction adjusted in line with climate change considerations is still inadequate (Louche et al., 2019), and provision of finance from diverse sources is necessary (Global Commission on the Economy and Climate, 2016). Concerning risk evaluation, Louche et al. (2019) argue that a shift in the financial system from a short-term and retrospect-oriented approach to a long-term, climate-focused financing mindset is necessary to support this transition.

The focus of this thesis is on the costs and financial aspects of transition toward sustainability in the Swedish transport system. This can be studied through scenario analysis (Louche et al., 2019), which serves as the foundation for this thesis. This thesis also emphasizes that the transition is not a static phenomenon but a dynamic one. Its dynamism, both in scope (referring to the actors and networks involved in the transition) and duration, should be considered.

Sweden serves as a captivating and compelling case study in this thesis due to its extensive commitment to promoting sustainability and its pioneering role in numerous facets of sustainability. This is especially true when it comes to sustainability transition in the transportation sector and the green financing of that transition.

In the realm of sustainable financing, Sweden has etched its name in history with pioneering initiatives. Notably, its financial institutions have embraced a culture rooted in sustainability (Torvanger et al., 2021). This stands as a testament to Sweden's commitment to sustainability. Sweden also proudly issued the world's very first green bonds (Nordic Council of Ministers, 2016) and city and corporate green bonds (Climate Bonds Initiative, 2018). When it comes to transportation, the establishment of the first electrified road for heavy-duty trucks on public roads (Lindgren, 2020) and the introduction of the innovative mobility-as-a-service initiative called UbiGo (Smith et al., 2019) showcase Sweden's innovative approach to sustainability in this sector.

Sweden's commitment to sustainability is not confined to the past; it is an ongoing journey. The nation has set its sights on an ambitious target: achieving zero emissions by 2045 (Trafikverket, 2020a). This commitment is reinforced by Sweden's impressive track record in emissions reduction, which saw a significant drop from 72.5 million to 54.6 million tonnes (excluding international aviation and land use, land-use change, and forestry) between 1990 and 2018 (Eurostat, 2020). These efforts form a robust foundation for this research, providing valuable insights into the transportation sector's transition from both cost and financing perspectives.

2. Theory

2.1. Sustainability transition

As discussed in Section 1, humans must make a substantial transition in the ways we behave and act if we are not to deplete the very planet we live on. Transportation is a large part of this transition process, and so is the financial system. Large-scale transition processes have been studied from many different perspectives such as diffusion of innovations theory (e.g., Karakaya et al., 2014), social learning theory (e.g., Scholz and Methner, 2020), and a multi-level perspective on the transition of socio-technical system (e.g., Geels, 2005, 2011; Geels and Schot, 2007). This thesis is rooted in socio-technical systems theory, which views organizations, societies, or phenomena as complex systems composed of interconnected parts. It emphasizes the interdependencies and feedback loops within these systems and suggests that change in one part can have ripple effects throughout the entire system. It focuses on understanding the underlying dynamics and structures that drive change. To this end, sustainability transition has been employed as a foundation for this research, which defines the transition as a comprehensive transformation of a social-technical system from its current state to a new state that is economically, environmentally, and socially sustainable (Geels, 2011; Ryszawska, 2016).

The choice of sustainability transition as a theoretical lens in this thesis is based on its emphasis on the dynamic interactions among different components of a system. It defines the transition as an outcome of these complex interactions. The components encompass the roles of artifacts, actors, and institutions (Smith et al., 2010), while going beyond a narrow focus on social interactions. Geels (2005), for instance, argued that a transition in socio-technical systems happens through a multi-level change process sparked from complex interactions between different conceptual levels including niches, socio-technical regimes, and socio-technical landscapes. Similarly, Smith et al. (2010) asserted that a multi-level perspective examines how society functions through a hierarchy of niches, regimes, and landscapes.

In this perspective, the socio-technical landscape refers to the materiality and the exogenous environment that influence the transition process but will not be affected by the system (Geels, 2005; Geels and Schot, 2007). Change in landscape imposes pressure at regime level and provides an opportunity for niches to develop and speed up the transition from the dominant regime (Smith et al., 2010). The material and spatial arrangements of cities, highways, and electricity infrastructures (Geels, 2005) and external pressure coming from international communities to keep global warming below a certain point (Trippel, 2020) through institutional or informal channels (Falcone et al., 2018) are some examples of landscape pressures.

The socio-technical regime refers to all stable and dominant institutional and material structures (Smith et al., 2010) that coordinate social groups and their activities within the network. This level is stable at the first point but is affected by the niche level (the level that initiates the system's change) and pressure coming from the landscape, and therefore causes a change in the whole system (Geels, 2005). The dynamic nature of the regime level, which comes from heterogeneity in its configuration derived from landscape pressure or misalignments within the regime, creates a place for niche alternatives to penetrate into this level and compete with the existing regime (Smith et al., 2010).

Radical innovation emerges at the niche level (Smith et al., 2010) and develops in terms of creating a small niche market and initiating new rules. Thereafter, internal drivers in the niche level and/or external drivers from the regime and landscape levels push the radical technology to a wider breakthrough and create competition between the existing stable regime and the new technology. Eventually, in the last phase, social-technical change is followed by the replacement of the socio-technical regime (Geels, 2005). Not all niches have the chance to break through and penetrate the regime level; however, protective schemes like supportive policy instruments and subsidies can help more mature innovations to link up to the regime level and compete with the dominant regime. Figure 1 represents the interactions between different levels of a socio-technical system.

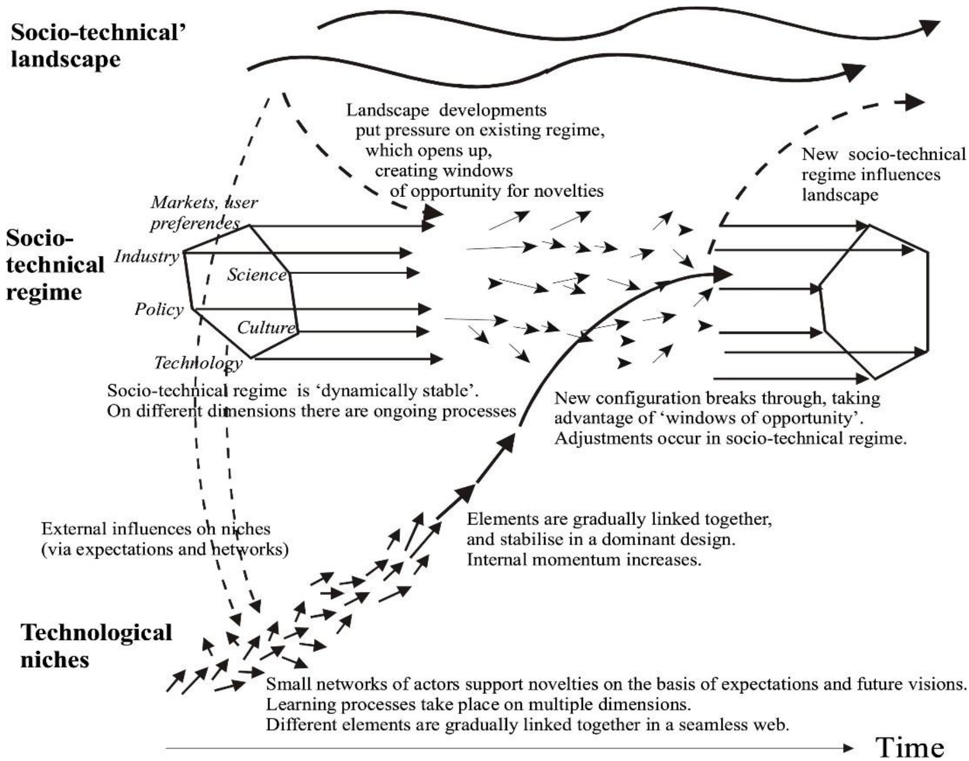

Figure 1 Multi-level perspective on transitions. (Source: F. W. Geels, 2011)

The shift in American urban passenger transport from horse-drawn wagons to automobiles between 1860 and 1930 is an example of the transition through a multi-level perspective discussed by Geels (2005). Landscape pressures, including urban development due to industrialization, caused an instability in the dominant regime in the transport system, leading to the emergence of new horse-drawn technologies such as omnibuses, taxis, and trams. Horse-drawn transport remained the dominant system until the late nineteenth century. However, rising problems such as increasing costs, traffic congestion, and health concerns provided an opportunity for niche alternatives, including electric trams, bicycles, and automobiles, to emerge and penetrate the market. Cultural and social changes, such as a shift towards electricity, helped drive the shift to electric trams. However, although electric and steam vehicles were being used extensively, gasoline-based automobiles ultimately became the dominant mode of transport due to advances in technology and regulatory and social factors. The transition was shaped by interactions between different niche technologies and the dominant regime and cultural attitudes, regulations, and landscape developments. Support from a particular niche innovation, namely gasoline cars, further influenced the transition. The financial challenges faced by tram companies, including rising costs and regulated fares, resulted in debts and limited funds for improvements, which intensified the competition between automobiles and electric trams (Geels, 2005). This example shows how important the availability of financial resources is regarding technological breakthroughs; without access to financial resources and financial support to direct a transition towards its target, a breakthrough simply will not happen.

The path of sustainability transition is influenced by interactions between actors, institutions, and materiality at the niche, regime, and landscape levels. Timing, in terms of the readiness of niche technologies, and the nature of the interactions (reinforcing or competing) of niche and landscape with the incumbent regime, determine the eventual pathway of the system (Geels and Schot, 2007). The five pathways for systems change introduced in the literature are reproduction, transformation, dealignment and realignment, reconfiguration, and substitution. Reproduction occurs when the current regime is stable and unchanging, and transformation occurs when external pressures force the regime to adapt. Dealignment and realignment is a rapid change in the landscape that creates competition among niche innovations, none of which is superior to the others, leading to a realignment of the current regime by the winner. Reconfiguration is the adoption of an innovation by the regime, creating a new form while maintaining most of the regime's architecture and rules; it takes place under pressure from the landscape and a symbiotic relationship between the regime and niche innovation (Geels and Schot, 2007). Substitution occurs when a radical niche innovation becomes dominant, replacing the previous regime.

2.2. Sustainability transition from a cost perspective

Within the sustainability transition, there has been a growing literature on how different sectors (including transportation) can transition towards zero emissions in an attempt to meet the target set by the Paris Agreement. These studies focus on changes in technology that lead to a system transition from the current state into a zero-emissions state: for example, in the road transport sector, battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), fuel cell vehicles (FCVs), and the electric road system (ERS) (e.g., Anandarajah et al., 2013; Brozynski and Leibowicz, 2018; Hagos and Ahlgren, 2020; and Islas-Samperio et al., 2019).

Regarding the cost of powertrains, two main approaches have been taken in these studies: implementation of different scenarios via integrated assessment models (IAMs), and comparative study of different powertrains based on total cost of ownership (TCO). These studies examine interactions across various socio-technical levels using financial measures, such as the TCO of different powertrains, and evaluate competition among various technologies based on their costs. Relatedly, they investigate how the government interacts with established and emerging technologies through a range of policies, including offering subsidies for zero-emission drivetrains (e.g., Axsen and Wolinetz, 2018; Blanco et al., 2019; Lam and Mercure, 2021) and imposing higher taxes on internal combustion engines (ICEs) (e.g., Lam and Mercure, 2021).

Two main classes of models have been employed in studies using IAMs: optimization IAMs (e.g., Böttger et al., 2018; Dhar et al., 2018; Hagos and Ahlgren, 2020) and simulation IAMs (e.g., Connolly, 2017; Bramstoft and Skytte, 2017; Skytte and Bramstoft Pedersen, 2018). The former strive to determine the best possible policy (that is, the ultimate pathway or, in other words, the market share of different technologies over a specific horizon) through an endogenous approach based on a cost optimization method. Conversely, policy evaluation models (i.e., simulation models) evaluate the impact of an exogenous policy on the system (Kelly and Kolstad, 1998). In this approach, identified pathways are a consequence of designed scenarios which later help the researcher to measure the transition costs based on the pathway taken.

The literature also discusses the transition from current production and supply chain norms towards a circular economy (CE) business model for newly emerged technologies, especially in relation to the huge increase in global demand for lithium-ion batteries (LIBs) due to a high penetration of EVs (Rajaeifar et al., 2022) and their potential environmental consequences (European Commission, 2020; Giosuè et al., 2021). A scant body of literature has highlighted the potential cost savings through circular economy (CE) schemes for LIBs, such as reusing, remanufacturing, repurposing, and recycling batteries (e.g., Kampker et al., 2016; Standridge and Corneal, 2014).

As discussed in each of the papers in this thesis, in a socio-technical system change process the financial mechanisms and incentive structures have significant effects on the capacity for or resistance to transition. If we understand these mechanisms better, we can develop solutions, policies, and incentives that are better aligned and help speed up the transition. To this end, this thesis first conducts a systematic literature review to identify a set of factors that influence transition costs. It then provides a framework for predicting potential technology and system costs through a set of numerical analysis and calculations. In this way, the sensitivity of the technology and transition costs are tested by taking into account different policies and incentives.

2.3. Sustainability transition from a financing perspective

Financing is crucial for the sustainability transition, and yet it has mostly been ignored in academic studies (Sunio and Mendejar, 2022). It is one of the main barriers to the breakthrough and diffusion of niche innovations and is referred to by Polzin et al. (2017) as one of the most significant "silent" barriers. The transition from electric trams to automobiles in the 1920s and 1930s is an example of finance acting as a barrier to technology diffusion (Geels, 2005). Niche actors need financing, especially in their research and development (R&D) and commercial phases, to facilitate their destabilization of the dominant regime and penetrate the market. The current system suffers from a lack of sufficient investment in clean R&D compared to fossil-fuel-based technologies and given the immaturity of innovative clean technologies (Polzin et al., 2017).

Green financing solutions, particularly green bonds, have gained significant attention for their substantial contribution (Maltais and Nykvist, 2020; Sartzetakis, 2020; Wang and Zhi, 2016). However, fiscal instruments alone cannot cover all the costs of sustainability transition (Sartzetakis, 2020), and to facilitate the transition it is essential to redirect cash flows from private actors. In this connection, Campiglio (2016) suggests three sources of external transition financing: bank lending, market debt, and market equity.

In the existing financial system, bank lending, the main source of external financing (Campiglio, 2016), is based on borrowers' creditworthiness rather than their sustainability status (Sunio and Mendejar, 2022). This credit-oriented structure enforces a lock-in of fossil-fuel-based technologies. In addition, the introduction of restrictive policies, such as Basel III, hinders banks from offering external green financing (Polzin et al., 2017; Campiglio, 2016), especially for responsible SMEs (Durst and Gerstlberger, 2020) considering their stricter standards on both asset liquidity and capital robustness (Campiglio, 2016).

For transition to occur, both landscape and niche actors need to interact with the current regime through either a symbiotic relationship or a competing approach (Geels and Schot, 2007). In competitive interaction of the niche market with the regime, external support from the landscape level is required, especially in the R&D and commercialization phases, to help the technology mature and become competitive. In a symbiotic relationship between the niche market and the dominant regime, however, an eco-innovation transfer opportunity to the regime is exploited, providing a chance to bring funding from the regime for advancing low-carbon niche innovation (Polzin et al., 2017). A limited body of literature has discussed the application of grants from public institutes, universities, and internal funding by private firms in the R&D

phase, and the deployment of private financiers, such as venture capital family offices, and crowdfunding in the early commercialization phase, especially for less mature innovative actors, as well as financing from institutional investors for complementary assets like projects and infrastructure (Polzin et al., 2017).

Government support, especially regarding policy uncertainties, legal insecurity, and prolonged administrative processes, is required to redirect financing actors' investment away from fossil-fuel-based technologies and toward sustainable technologies (Polzin et al., 2017). Therefore, a transition in the financial system itself is necessary (Falcone et al., 2018). Incentives from the landscape, through a set of policies including R&D subsidies and grants or tax credits for clean technologies (Santos, 2017; Durst and Gerstlberger, 2020; Polzin et al., 2017), withdrawal of subsidies for fossil-fuel-based technologies (Polzin et al., 2017), fiscal incentives like tax relief and flexible taxation for investors (Durst and Gerstlberger, 2020), production support such as production tax credit as a signal to the financial market, providing combined public-private investments (Polzin et al., 2017), introduction of carbon pricing (Campiglio, 2016; Louche et al., 2019), promotion of sustainable investment and portfolio composition for pension funds (Polzin et al., 2017), and easing of lending conditions (Campiglio, 2016) can rapidly scale up their diffusion for innovative technologies.

Keeping all these financing solutions in mind, we need to evaluate the system in terms of the accessibility of different types of financing. The abovementioned supportive policies mostly target niche technology providers, but technology users, hauliers in this case, also need further support. Providing subsidies for purchasing green powertrains has been one of the supportive policies widely applied as an instrument to increase the share of newly registered green powertrains[10]. Such fiscal policies incentivize purchasing decisions. However, the high initial investment in purchasing green powertrains requires more investigation into the source of funding to see from which sources hauliers are able to finance their fleet replacements and whether they are eligible to use such resources to finance the transition. Support from the financial system seems to be essential, especially in the freight transportation sector, where the majority of actors are micro companies. In light of this, supply chain finance solutions might do better to help the transition of small traditional actors that have difficulty accessing external financing. Accordingly, this thesis develops a simulation model to identify the sector's potential for transition, taking into account the financial strength of the

[10] Providing a bonus of either 20% of the purchase price or 40% of the difference between the purchase price of a battery electric truck and that of a diesel truck (whichever is lower) (Energimyndigheten, 2021).

actors within the sector and the potential advances in response to supportive policies. A network analysis is then conducted to investigate the accessibility of short-term external financing at a tactical level.

2.4. Socio-technical system change

Socio-technical systems are complex and involve actors, institutions, material artifacts, and knowledge. Transition of socio-technical systems involves not only technological change but also change in other dimensions and interlinked systems (Markard et al., 2012). This comprehensive change throughout the system places an emphasis on dynamic interactions among actors and on the interlinkage between barriers and solutions (Polzin et al., 2017).

Leavitt (1965) developed a theory of system change that identifies the four primary components of socio-technical systems: task, technology, actor, and structure. The theory explains how these components are interdependent and their interactions determine the mechanisms and outcomes of organizational change (Leavitt, 1965). Therefore, modifying one component within the system can lead to an improvement in the system's overall performance (Leavitt, 1965).

By connecting the theory of sustainability transition and socio-technical changes, it can be argued that transition occurs not only through an introduction of niche and disruptive technologies but also through changes in actors' attitudes and norms and regulations within a system structure. Therefore, to accelerate transition, it is essential to establish interlinkages between the barriers in all these categories to see how removing one barrier can have a positive impact on the entire system and expedite the transition process.

3. Research gaps

3.1. The cost of sustainability transition

Research on the theoretical foundation of sustainability transition is gaining momentum (e.g., Markard et al., 2012; Geels and Schot, 2007; Rogge et al., 2020; Lindberg et al., 2018), especially in the energy sector. However, research on financing the transition is scant (Sunio and Mendejar, 2022). To project the financial implications of the transition and assess its feasibility from a financial perspective, cost analysis is a necessity.

In the literature on sustainability transition, cost analysis under different transition pathways has been outlined (e.g., Blanco et al., 2019; Hagos and Ahlgren, 2020; Statharas et al., 2019). Different approaches have been taken in calculating the potential cost of transition. Some studies have focused on the cost of infrastructure change, such as charging stations (Colbertaldo et al., 2020); some have highlighted the cost of vehicle manufacturing (García-Olivares et al., 2020); and some have focused on energy costs by calculating the cost of energy production through expansion in the general network (e.g. Taliotis et al., 2020; Spittler et al., 2020) or grid upgrade and power over-generation to support the hydrogen fuel required (Colbertaldo et al., 2020). Several studies have given their attention to cost analysis that considers different types of fuels, including electricity (Spittler et al., 2020), biofuel, and hydrogen, or a mix of different fuels for different powertrains and vehicles (e.g., Colbertaldo et al., 2020; Taliotis et al., 2020; García-Olivares et al., 2020).

The investment needs, fuel expenses, and maintenance costs have been discussed widely in the literature (e.g., Ajanovic and Haas, 2021; Connolly, 2017; Gambhir et al., 2015; Nanaki et al., 2016; Wietschel et al., 2019). Some critical variables, however, have been neglected, and the cost projections may be correspondingly incomplete. The cost of charging/refueling strategies (Teoh et al., 2018), time spent charging vehicles (Ahmadi, 2019), lost loading capacity as a result of greater weight and volume for some powertrains (Karlström et al., 2019; Ruf et al., 2020), and financing costs (e.g., Bhosale et al., 2022; Hagman et al., 2016; Mansour and Haddad, 2017; Scorrano et al., 2020; Zhao et al., 2015) are some of the variables that have received less attention in the literature.

In the context of circularity, the literature appears somewhat disconnected from the discussion of transition costs. However, circularity is closely related to costs, especially when considering the value created through product circularity. This value extends not only to manufacturers, who can recover used materials, but also to end users, who benefit from higher salvage rates. In the case of batteries, a prominent green technology in the transportation sector, the importance of CE schemes becomes even more apparent due to the significant cost savings projected in various models.

Although the literature on transition costs has included salvage as a component of cost analysis (e.g., Blanco et al., 2019; Perera et al., 2017; Schmid et al., 2021), the salvage value of batteries has often been determined without considering the remaining capacity and state of life of the batteries, which are crucial factors in the valorization of end-of-life batteries. Lack of valorization of used batteries has been mentioned as one of the main barriers to CE transition of LIBs (Giosuè et al., 2021; Rajaeifar et al., 2022). This creates a gap in the literature, prompting us to ask *what the cost elements are and how they can be modeled to provide precise analysis of the system cost over the transition period.*

CE strategies offer advantages not only from an environmental perspective but also from a financial standpoint[11]. Their adoption, however, remains limited[12], leading us to ask *what keeps companies from implementing CE and how this transition can be facilitated.*

3.2. Financing sustainability transition

The necessity of reformulating the financing system to redirect the flow of private financing has been acknowledged within the literature (Global Commission on the Economy and Climate, 2016; Trippel, 2020; Falcone et al., 2018). However, little attention has been given to this area (Sunio and Mendejar, 2022). Polzin and Sanders (2019), for example, studied different financing solutions in the energy sector and provided a financing framework for different stages of operation for energy-innovative companies. The potential applications of corporate and government R&D grants, venture

[11] Kampker et al. (2016), for instance, measure a cost saving of approximately \$60/kWh from remanufacturing end-of-life batteries. Standridge and Corneal (2014) suggest a 40% cost saving, equal to \$83/kWh to \$114/kWh, from repurposing waste batteries.

[12] For instance, in the USA, there is a recycling rate of approximately 5% for manufactured EV batteries (Seltzer, 2022)

capital, crowdfunding platforms, banks, institutional investors (Polzin and Sanders, 2019), and green debt financing solutions such as green bonds (Wang and Zhi, 2016; Sartzetakis, 2020) have been highlighted as sources of finance for niche innovative technologies. However, the research remains rather abstract and lacks analysis of a specific financial framework (Steffen and Schmidt, 2021), especially within the transport sector, that would demonstrate the sector's financial readiness for such a transition.

The literature has discussed how to finance the innovative niche market, but it is silent on how users of the technology should deal with and finance their transition. This gap has been identified by Kanger et al. (2020) as a point of intervention for policymakers in assisting the transition process. Niche innovative markets, although they have to cope with barriers like credibility, access to collateral, and restrictive financing regulations (Polzin et al., 2017), might still be attractive for private equity, venture capital, crowdfunding, and junk bond investors.

SMEs in the freight transportation sector, the sector chosen for this research, are in the middle of this transition and may appeal less to investors, not only because of restrictive and uncertain policies (Polzin et al., 2017; Campiglio, 2016), lower expected rates of return, and associated risks (Taghizadeh-Hesary and Yoshino, 2020), but also because they do not offer a disruptive technology with the capacity to grow and take the future market. In this connection, there is a gap in exploratory research about green financing of sustainability transition (Wang and Zhi, 2016), and the literature has omitted to examine how well existing financial policies advocate transition of the financial system as a socio-technical system (Falcone et al., 2018).

In this thesis, financing is approached from two main levels: strategic and tactical. Strategic financing and strategic financial planning include long-term decisions related to risk appetite, capital structure, growth plans, and investment opportunities. Strategic financing aims to optimize the allocation of financial resources to support sustainable growth, profitability, and value creation over an extended period. Tactical/operational financing, on the other hand, has a shorter-term focus and deals with specific operational or immediate financial needs. It involves day-to-day financial management activities, short-term cash flow management, working capital optimization, and responses to immediate funding requirements. Tactical financing addresses the organization's short-term financial challenges and ensures the smooth functioning of its operations.

4. Research design

4.1. Purpose

On reviewing the literature on sustainability transition within the transportation sector, it became evident that there is insufficient research on cost analysis, financing of the transition, and the barriers that keep the system from transitioning, especially regarding the circularity of zero-emission technologies. Consequently, the main objective of this thesis is to explore the issue within the road transportation sector. The purpose of this thesis is therefore as follows:

> *to identify the costs of sustainability transition for actors within the transport system, how the current financial strength of actors and financial supports impact the transition, and how we can achieve systematic change by overcoming the potential barriers.*

There are three parts embedded within this general purpose. The first sub-purpose is to extract different costs related to the transition for the selected actors and analyze those costs at both the technology and system levels. The second sub-purpose is to explore sustainable financing solutions and assess to what extent the current financial system can support the transition through various financial policies. The third sub-purpose is to focus on CE as a cost-saving solution for battery-dominated technologies, identify the barriers preventing companies from transitioning to circular economy, and explore the interconnections between these barriers that may hinder change in this socio-technical system.

For the purposes of this research, and relying on the theory of transition for socio-technical systems, sustainability transition is defined as the replacement of existing powertrains within the fleet with new low-carbon technologies. Here, the landscape is considered to include all social and cultural changes and exogenous environmental factors that may exert national and/or international pressure regarding climate change and meeting the Paris Agreement, or in support of the existing dominant regime. In other words, from a practical perspective, landscape refers to all policies (fiscal and financial) concerning the transition and change in technologies within the fleet. The regime is defined as the dominant ICE powertrains in the market, which contribute the most to carbon emissions within the transport sector. Niche is defined as all new low-carbon-emission technologies (powertrains), including BEVs, PHEVs, FCVs, and ERS.

Actors are classified into two groups: direct and indirect actors. For the purposes of this research, direct actors are defined as those that conduct transportation operations directly, such as logistics service providers. Indirect actors are those connected to the transportation sector, such as battery manufacturing companies. Based on the research gaps and questions, the focus here is sometimes on direct actors and sometimes on indirect actors.

The transport system in this research is limited to the road transportation sector. We focus on the heavy-duty fleet, which is a part of the sector that is hard to decarbonize. Following the European Commission (2018), we define a heavy-duty fleet as freight vehicles of more than 3.5 tonnes (lorries). In some of the papers, following Lindgren (2021), these trucks are classified according to their operational distances: local distance, with weight between 3.5 and 16 tonnes; regional distance, with weight between 16 and 26 tonnes; and long-distance, with weight more than 26 tonnes.

Regarding, identification of barriers to CE, we focus not on heavy-duty trucks but on the circularity of high-voltage batteries. The case study company's targeted segment is special vehicles, including trucks for material handling and warehouse logistics, mining vehicles, airport logistics vehicles, and port material handling vehicles.

In relation to sustainability transition costs, charging locations are categorized as depot, semi-public, and public. Depot charging takes place at truck owners' terminals; semi-public charging takes place at locations where vehicles load and unload, like warehouses and terminals; and public stations are open to the general public. The power capacity at each type of station is assumed to be low (50 kW), medium (150 kW), and high (600 kW), respectively, based on a report by the Swedish transportation agency (Lindgren et al., 2021).

4.2. Research questions

4.2.1. Research question 1 (RQ1)

To address the initial aspect of the research purpose outlined in Section 4.1, and revisiting the research gaps highlighted in Section 3.1 on determining the cost elements, the subsequent research question arises:

> *What has been done so far on measuring the cost of transition and transition financing?*

Paper 1 was conducted to address RQ1 and investigate existing knowledge on cost analysis and the financing of sustainability transitions in the road transportation sector. With the aim of providing a foundation for subsequent papers within this thesis, Paper 1 conducted an in-depth systematic literature review to gain an understanding of the current state of the literature on the topic and to identify influencing cost elements related to different powertrains.

4.2.2. Research question 2 (RQ2)

To further address the first part of the research objective, as delineated in Section 4.1, and to revisit the research gap highlighted in Section 3.1 on how the cost can be modeled to provide a precise system-level analysis, the following research question emerges:

> *What are the relevant sustainability transition cost factors, and how can these factors impact transition costs?*

Paper 2 addresses RQ2 by building upon the results and theoretical foundation established in Paper 1. This is achieved through the development of a numerical cost model that incorporates the cost elements suggested by the literature reviewed in Paper 1. The model places a particular emphasis on charging strategies and the cost of financing (which connects the first and second research gaps) and tests various policies to explore the role of external pressure on and supports for the system cost at landscape level.

4.2.3. Research question 3 (RQ3)

Returning to the initial part of the research purpose in Section 4.1 and the research gaps emphasized in Section 3.1, RQ3 moves forward with a progressive stance:

> *How much does transition cost?*

Paper 3 responds to RQ3 by utilizing the model established in Paper 2. The model is tailored to a novel context and enhanced through the incorporation of fresh variables, placing particular emphasis on circularity as a pivotal cost function, as previously discussed in relation to the third research gap.

4.2.4 Research question 4 (RQ4)

To address the third part of the research purpose mentioned in Section 4.1 and the research gap discussed in Section 3.1 regarding CE transition and its barriers, the following question arises:

> *What are the key barriers to implementing CE for EV batteries, and how do they interact to reinforce the system and prevent changes towards CE?*

Paper 4 explores RQ4 by focusing on one of the main uncertainties in cost analysis for sustainability transitions: salvage value. The paper draws inspiration from Paper 3 and places particular emphasis on CE strategies, highlighting them not only for their ability to mitigate environmental impact, market uncertainties, and shortage of raw materials, but also for the value they bring to the vehicle owners through increased salvage values and manufacturers through saved costs. Paper 4 delves more deeply into the topic by identifying barriers that hinder battery manufacturers from implementing circular schemes, resulting in both the end users and the manufacturers being unable to capitalize fully on the potential cost savings. The paper takes a system perspective to depict the complexity of the interconnections between barriers.

4.2.5. Research question 5 (RQ5)

To address the second part of the research purpose discussed in Section 4.1 and the gap highlighted in Section 3.2, the subsequent research question arises:

> *How do the financial strength of transportation actors and the financial system's support for them affect the transition of the sector?*

Paper 5 addresses RQ5 in light of the research gap on financing sustainabity transition. It has been written in response to the lack of research in transition financing found in Paper 1, and to explore further the impact of financing availability and financing cost addressed at a strategic level in Paper 2. Paper 5 explores the decision-making of hauliers on the source of financing (retained earnings, external financing and/or equity) to see to what extent the current system can transition based on these sources of financing. It also examines how different financing policies support the transition at the strategic level for the heavy-duty sector under different scenarios and assumptions. It investigates how financing decisions are influenced by a company's financial position and creditworthiness, including all the dynamics on the balance sheet as a result of decisions about replacing vehicles over time.

4.2.6. Research question 6 (RQ6)

Returning to the second part of the research purpose set out in Section 4.1 and the research gaps emphasized in Section 3.2 with a focus on the tactical level of financing, the following research question emerges:

> *How does a company's bargaining power impact its access to financing and, more specifically, the supply network's financing at a tactical level?*

Paper 6 addresses RQ6, examining financing at a tactical level by looking into the network of actors in a supply chain and their interrelationships. Paper 6 is based on the discussion in Paper 5 about the majority of companies within the freight transport sector being micro hauliers and SMEs with only limited bargaining power and creditworthiness; thus, they face difficulties in accessing external financing. Paper 6 takes a step down from the strategic to the tactical level, with a specific focus on one of the main, widely used sources of tactical-level financing: trade credit. It examines different proxies for bargaining power and their impact on a company's trade credit.

The paper explores the dynamics within a supply network to show how the financial decisions of individual actors can impact the whole network of actors' financial decisions. It addresses the potential network-wide impact of receiving trade credit from a buyer, and it explores how the decisions of upstream suppliers about offering trade credit are associated with the choices of downstream suppliers. The findings create a platform for future discussion of the impact of such dynamics within a supply chain network on network-level transition.

Figure 2 depicts the research questions and their relationship to the papers.

4.3. Delimitations

Road transportation is under study in this research, with a main focus on heavy-duty vehicles. However, there are some exceptions regarding the targeted segments. For example, in the literature review, the entire road transport sector is targeted to gain a better insight into all possible measures for transition, as heavy-duty vehicles have been studied less in the literature. Similarly, when analyzing trade credit in a supply network, the selected case is not focused on the targeted sector. Regarding circularity barriers, although the selected case concerns heavy, high-voltage batteries, the targeted customers are in the special vehicle segment. Additionally, in the analysis of transition costs and financing, no particular delimitation is made in terms of types of goods.

For the purposes of cost analysis, it is assumed that all trucks are loaded to their maximum capacity and work one shift of eight hours during the day. Assuming that BEVs and FCVs have a lower loading capacity due to their heavier and bigger powertrains, this impact on the potential opportunity cost is considered. However, the transportation demand is based on the projections of the Swedish transportation agency (Trafikverket, 2020b), and the impact of this lost loading capacity due to BEV and FCV powertrains on the demand for more trucks has therefore been excluded from this study.

Although zero-emission powertrains, including BEVs and FCVs, have been studied in various settings from transition cost and financing perspectives, there is no assertion that these powertrains are the most sustainable options. This research aims to assess the cost and evaluate the financial potential of the sector for such a transition under different anticipated scenarios, drawing on the literature and interviews with experts in the Swedish context. While modal shifts from road to rail and sea might be perceived as more sustainable options, this examination is limited to the sustainability transition of road freight transportation and does not consider the potential dynamics of demand for trucks in response to intermodal shifts.

The cost and financing of the sustainability transition in the road freight transport sector has been approached in this research from various perspectives. Therefore, in different parts of the study, the unit of analysis changes from the individual truck (when comparing powertrains in terms of TCO) to the heavy-duty transport sector (when examining system-level costs and financing). In Paper 4, with its focus on circularity transition, the unit of analysis is the circularity of lithium-ion batteries (LIBs), making it possible to address a related question and explore the transition from an after-first-life angle.

Sweden has been chosen as the context in which to study the cost and financing of the transition in a particular geographical location. Although this choice might affect the generalizability of the results because of differences in demand and technological development across countries, the cost of transition will differ for different cases, making the topic inherently context-dependent. An international level of analysis would not provide a straightforward direction for policymakers at a national level to reformulate the financial system within their country and facilitate the flow of financing in support of sustainability transition.

4.4. Bridging theory and methodology

This section explains the interconnections between the different papers in this thesis. To provide practical recommendations, a detailed analysis of the cost and financing aspects of sustainability transition was conducted, with the aim of exploring some less discussed areas and gaining a better understanding of the topic. Therefore, Paper 1 was the initial step in this research, providing a systematic review of the literature on the cost and financing of sustainability transition, with a focus on the transportation sector. A set of crucial, mostly overlooked variables were identified, leading to the next step, taken in Paper 2, of designing a numerical model for transition cost analysis that includes these variables (depicted in Figure 2).

The concept of sustainability transition has been examined from a cost perspective, asking what the costs of transitioning to green powertrains are for truck owners. Would they take the first steps to replace their fleet based on these costs compared to the cost of conventional options? What strategies and policies can help make green powertrains more competitive when it comes to strategic decisions on charging, government intervention through supportive policies (such as offering subsidies or providing discounted interest rates for financing green powertrains), or measures taken by the industry as a whole (such as adding to the value of scrapped batteries through circularity strategies)?

In this context, Paper 3 tests various scenarios of freight transportation pathways to address these questions. It extends the model developed in Paper 2 by incorporating more aspects into the analysis, thereby integrating circularity with sustainability transition from a cost perspective. Besides, the limited circulation of end-of-life batteries leaves the question of what impedes the system's transition to CE and why. This matter is explored further in Paper 4 by looking at the circularity barriers in the EV battery industry at a system level.

In the next stage, in response to the call from Paper 1 for more research on financing the transition, and given the impact of financing policies on technology costs discussed in Papers 2 and 3, Paper 5 focuses on the strategic level of financing. The strategic level concerns a company's capital structure and investment planning. Paper 5 also examines the replacement capacity of the sector based on its earnings, access to finance, and financial strength under different policy scenarios. We delve further into the actors within the sector and demonstrate that the majority of these entities are micro companies and SMEs struggling because of their credit scores to access external financial resources.

Paper 6 departs from Paper 5's focus on the strategic level of financing, moving to the tactical level and focusing on working capital financing solutions. It argues that companies with higher bargaining power will be able to ask for more trade credit from their suppliers to finance their operations. It discusses the dynamics of financing within a supply network, as well as the association between a company's financial decisions on the level of financing and its upstream supply network partners. The results provide an understanding of how companies will be able to access financing and what impact such financing will have on their upstream supply partners.

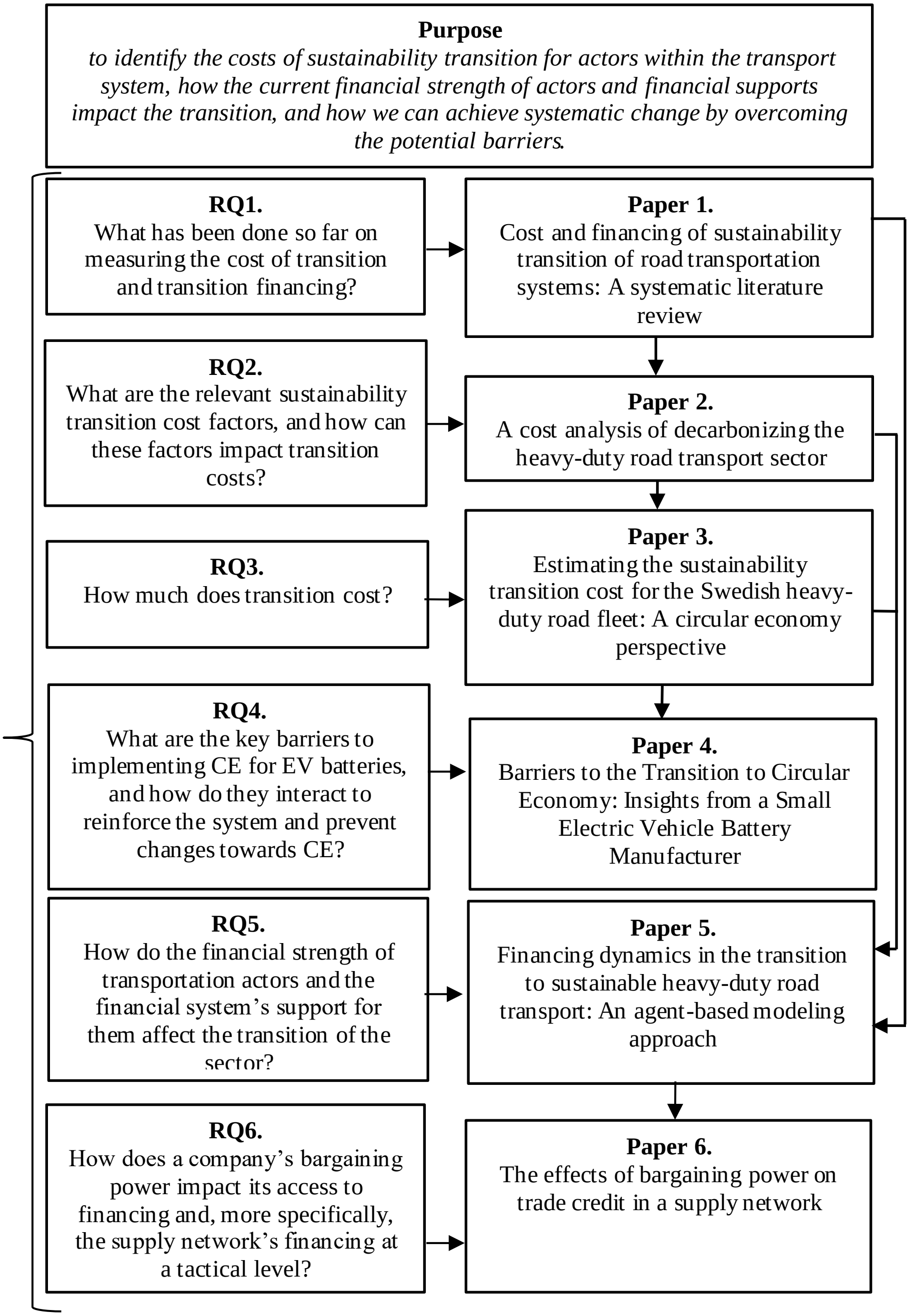

Figure 2. Relationships between the research purpose, research questions, and papers

5. Methodology

5.1. Methodological anatomy

This research is based primarily on a case study analysis, given the research questions and the philosophical approach adopted. A case study methodology is typically used to address how and why questions, considering the contextual conditions under which the phenomenon occurs (Baxter and Jack, 2008; Thomas, 2021). Simons (2012, p. 9) defines a case study as "an in-depth exploration from multiple perspectives of the complexity and uniqueness of a particular project, policy, institution, programme or system in a 'real life' context. It is research-based, inclusive of different methods and is evidence-led. The primary purpose is to generate in-depth understanding of a specific topic (as in a thesis), programme, policy, institution or system to generate knowledge and/or inform policy development, professional practice and civil or community action." The application of case study analysis in understanding complex, contextualized situations has been widely argued (Thomas, 2021). Therefore, this approach was applied in all phases of this research, given the complexity of the phenomenon, the need for an in-depth understanding of the topic from various perspectives, and the different elements involved in sustainability transition of the transport socio-technical system.

Case study research is a common method in social science research. Depending on the nature of the research, a case study can be explanatory, exploratory, descriptive, multiple, intrinsic, instrumental, or collective (Baxter and Jack, 2008). The unit of analysis is important, and it can be an individual, program, process, or difference between organizations that is of interest to the researcher (Baxter and Jack, 2008). Case study analysis can also employ both qualitative and quantitative methods as tools for answering the research question. Here, different approaches have been taken regarding the nature and methods of the research. Both exploratory and explanatory case study analysis were used, considering the nature of the research questions and whether more understanding about the phenomenon is required or whether the case can explain a predefined causal relationship between variables. Thomas (2021) calls a case study not a method or methodology but a focus on one thing and looking at it from different perspectives. To study a particular phenomenon with a case study approach, both qualitative and quantitative methods can be applied.

Paper 1 applies a systematic literature review to uncover prior knowledge on the cost and financing of sustainability transition. When the research question is specific, a systematic methodology is appropriate for identifying related resources and answering the research question (Rother, 2007). A literature review can help to understand the area of research, especially when that area is interdisciplinary; a review also helps to synthesize the existing body of literature and discover the gaps to be filled in future studies (Snyder, 2019). Conducting the review in a systematic way helps the author to avoid a selection bias towards studies that the author aims to build assumptions on instead of presenting all existing knowledge in the area of research (Snyder, 2019). Therefore, in order to answer the first research question and identify the main cost items for sustainability transition in the road transport sector and its sustainable financing, Paper 1 systematically selects related studies by searching relevant publications in Scopus and the Web of Science. The collected studies are then filtered based on procedures explained in detail in the paper. We collaborate with experts and librarians to choose database search keywords; because of the limited full-text search capabilities, we query titles, abstracts, and designated keyword sections. This aligns with the need for precision in a systematic review. An in-depth analysis confirms the appropriateness of the structured keywords based on the frequency of authors' keywords.

To answer the second research question, Paper 2 develops a numerical model that better depicts the system costs under different assumed scenarios. This paper also provides a suggestion for further research and factors that could be added into the cost analysis in future research. Python 3.8.5 is used to design the model. Technology evaluation is applied by measuring the TCO of different powertrains; the system annual costs cover all timely operational expenses, investment in purchasing new powertrains, and financing costs; the salvage value for all scrapped vehicles is subtracted from total annual costs.

Paper 3 is based on a combination of qualitative and quantitative methods. This is achieved by investigating the effects of different charging range patterns and battery temperatures on the remaining useful life of batteries in BEVs at the end of their lifespan, and the subsequent impact on their salvage value. Incorporating determinants such as charging strategies and financing policies similar to those outlined in Paper 2 is essential in assessing the cost of decarbonizing the road transport sector for heavy-duty vehicles. Limited literature exists on the impact of leasing models on TCO for BEVs (Desreveaux et al., 2020; Franzò et al., 2022) and customer preferences compared to purchasing (Hoogland et al., 2022; Liao et al., 2019; Gonzalez-Salazar et al., 2023). Research indicates that, in a perfect market, there is no significant difference between leasing and loans in the net present value of the total cost (Berk and DeMarzo, 2020). Leasing with a fair market value cap leads to lower monthly payments, whereas loans involve a residual value. In a finance lease, the payment is similar to a loan (Berk and DeMarzo, 2020). Due to the similarity in results, BEV leasing is excluded from the cost analysis in Paper 2. Multiple tools are used to collect the required information. Secondary data are used to collect input data for the model from existing literature, related reports, and documents. Considering the context-based nature of the phenomenon and the different perceptions of various actors in this socio-technical system, qualitative research can provide better insights and in-depth knowledge about the phenomenon (Yamahaki et al., 2020). Therefore, due to the explorative nature of questions about the future penetration of different technologies, multiple explorative, semi-structured interviews are conducted to collect information from experts in academia, industry, and public authorities to determine how they perceive the future of these technologies. Scenario testing is then applied on a quantitative approach with the aid of the model developed in Paper 2.

Inspired by Paper 3, Paper 4 explores the barriers to the circularity of EV batteries through a case study analysis of a battery manufacturing company. The potential cost saving in circular economy manufacturing is discussed, addressing the CE barriers and their interconnections that reinforce the system. To this end, both primary and secondary data are collected to understand the state of the company through its CE activity, its relationships with customers and financiers, and its financial data. Document analysis (of the company's financial statements and documents) is also applied. A quantitative approach and cost–benefit analysis is conducted to measure the potential cost saving for the manufacturing of batteries and, therefore, for BEVs.

Paper 5, which addresses the fifth research question, is designed to explore how the current financial system supports the transition for the heavy-duty freight transportation sector. An agent-based simulation (ABS) model is developed focusing on each actor's decision about how to finance replacement of their fleet. Three sources of financing are included: internal financing through retained earnings, debt financing, and equity financing. An ABS method is the ideal methodology for this research question due to its suitability for cases where individual behavior is nonlinear, diverse, complex, and responsive to changes (Bonabeau, 2002). These individual independent agents interact to decide on the topic of interest based on a set of predefined rules and possessing unique characteristics (Bonabeau, 2002). Accordingly, a set of rules and scenarios is designed, and through an ABS the system's response to the financing policies is examined depending on the financial strength and creditworthiness of each agent (i.e., haulier), as a criterion for being offered external financing. All replacements are assumed to involve long-distance heavy-duty BEVs to prevent subjective impacts on the agents' balance sheets. The scenarios are based on maintaining the same purchasing investment for each replacement, and the assumption is that most small companies operate over long distances. This cautious approach prevents overestimation in respect of transition by taking into account the higher cost of long-distance trucks compared to regional and local ones.

Paper 6 discusses one of the private financing methods identified in Paper 1 as a research gap for cash flow financing. It addresses RQ6 and is designed to explore how different factors representing the bargaining power between buyer and supplier in a transaction lead to an extension in the buyer's trade credit, and how the buyer's extended trade credit can incrementally grow upward in a supply network and expand the financial stress to other actors in the upstream supply network. This design helps us to understand the critical role of companies in controlling the financial well-being of the whole network as an aspect of sustainability; it also opens up the opportunity to discuss the role of supply chain finance (SCF) solutions, not only for the economic aspect of sustainability but also for the environment. In this regard, a case study approach is taken and a quantitative methodology used to answer the research question. Social network analysis (SNA), combined with the generalized linear regression modeling (GLM) technique, is the method applied to discover the causal relationship between bargaining power representatives and the buyer's trade credit, as well as the contingency effect of upstream suppliers and the different paths that connect each pair of companies in the relationship between the buyer's and the supplier's trade credit.

Figure 3 summarizes the purpose of this study and the research questions addressed in each paper, as well as the methodology and methods used.

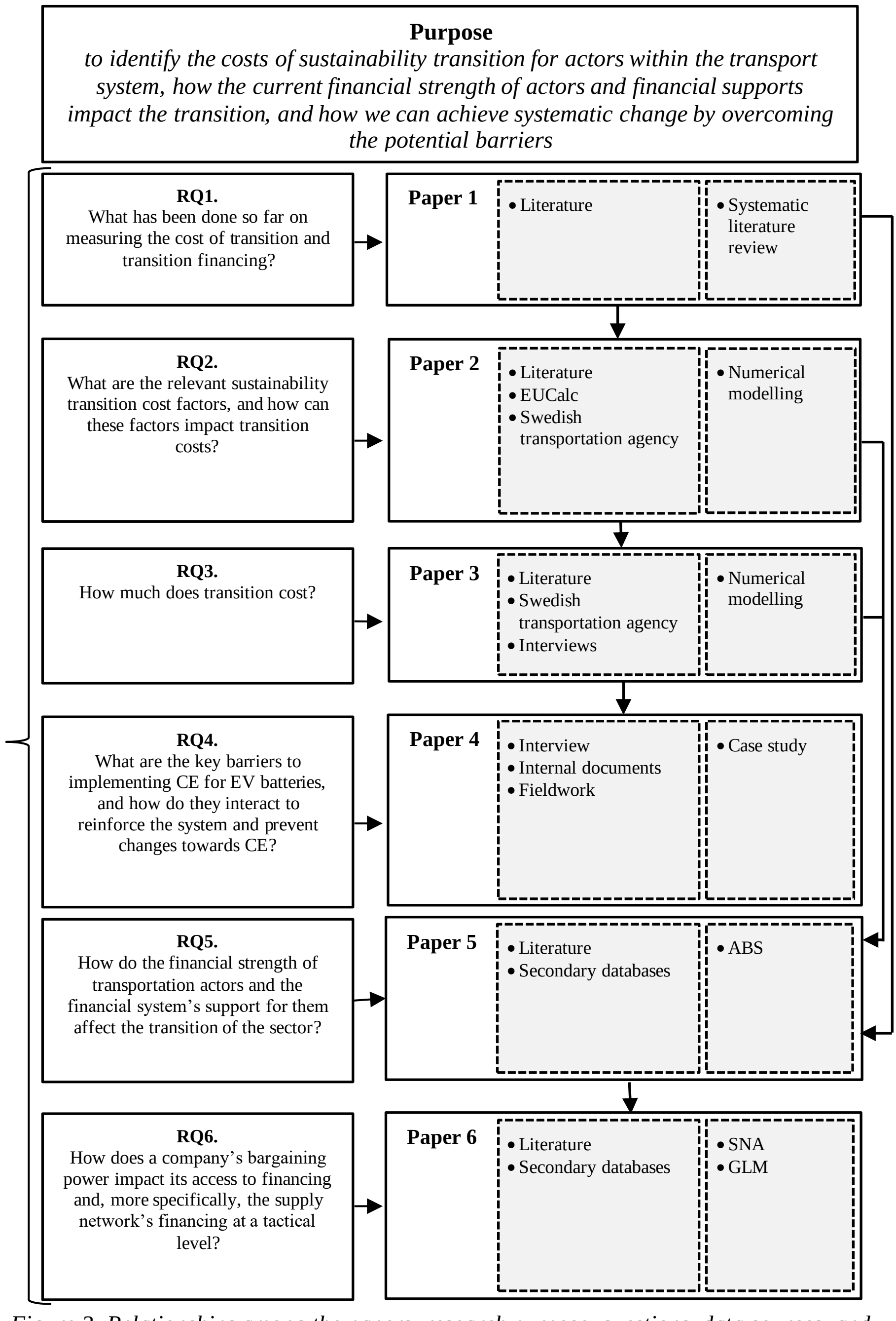

Figure 3. Relationships among the papers, research purpose, questions, data sources, and methodology

5.2. Credibility and quality of the research

Reliability, validity, and generalizability are essential parts of research quality assessments, and they are defined depending on the nature of the research and the research paradigm (Golafshani, 2003). In quantitative studies with an explanatory approach, reliability refers to the consistency and replicability of the results, while validity shows to what extent the research is accurate in measuring the phenomenon (Heale and Twycross, 2015). Some scholars argue that reliability may be irrelevant or even misleading in qualitative studies with the purpose of generating an understanding instead of measuring anything (Stenbacka, 2001). When it comes to validity, having "good data" (that is, collecting high-quality data through effective interaction between the researcher and the respondent) will help in validating the results (Stenbacka, 2001). Other scholars emphasize the importance of both reliability and validity in evaluating research quality (Golafshani, 2003). The quality of the research can be judged on its trustworthiness, credibility, confirmability, and consistency or dependability in the form of four tests: construct validity, internal validity, external validity, and reliability (Yin, 2014).

5.2.1. Validity

Validation is one of the main tasks in understanding the quality of research. Models can be validated in three steps: verification, validation, and testing (Balci, 1998). Validation can be carried out through face validation, sensitivity analysis, validation of the assumptions of the conceptual model, and validation of input–output transformations (Bergqvist, 2007).

The face validity of the models used in Papers 2, 3, and 5 was assessed by presenting them to experts in the transportation and financing industries, who provided feedback on the structure and logic. Multiple researchers participated in the development phase. The models were also showcased in the form of research papers delivered at various conferences and events or submitted for review to scientific journals. The model-based papers incorporate several sensitivity analyses to examine the impact of various changes in model variables on the results. For instance, Papers 2 and 3 conduct sensitivity analysis on different charging strategies, electricity prices, financing interest rates, and charging states to evaluate the model's sensitivity to these variables. The initial conceptual model is validated by conducting a systematic literature review and analyzing the relevant literature to determine how different costs have been measured in evaluating sustainability transition costs. Regarding input–output transformation validation, several tests are conducted, including conversion of the total system costs to cost per vehicle to assess the logic of the code and whether it correctly calculates the costs according to the conceptual model. Comparing the outcome with real-world data is not possible, as the model projects future costs under different scenarios.

Several other techniques are used to verify the model, including structural programming, heuristic approaches, self-documentation, code inspection, input data checks, and animation, as suggested by Balci (1998) and Bergqvist (2007). To ensure the structure of the program is appropriate, a detailed plan of the model is developed before coding (i.e., the flowchart presented in Papers 2 and 5), as suggested by Balci (1998). In the coding process, a description of the model and the logic is written in each module of the code. The code is audited several times to identify deficiencies and to test whether the computer code is proceeding according to the developed plan. The input data are checked to ensure consistency with the data source. Different parts of the model are designed to provide graphical output used to detect illogical results, as suggested by Balci (1998) and Bergqvist (2007).

Regarding the qualitative approach in the case study research, the validity of the research is checked using three tests suggested by Yin (2014): construct validity, internal validity, and external validity.

Construct validity concerns whether the operational measures relate to the concepts under study (Yin, 2014). Yin (2014) proposes three techniques for ensuring construct validity in qualitative studies, namely incorporating multiple sources of evidence, establishing a chain of evidence, and obtaining feedback from key informants on the preliminary case study report. This research employs various methods to carry out these strategies. For example, in one of the qualitative studies (Paper 4), data triangulation is used to cross-validate information gathered from multiple sources such as the literature, interviews, observations, company documents, reports, and websites. A mixed-method approach is also adopted to address the research questions via an analytical scenario analysis of the company's business model in terms of financial profitability analysis for different CE strategies, which involves the application of both qualitative and quantitative methodologies.

Internal validity concerns explanatory research that examines the causal relationships between different variables. In this case, the relationship between X and Y is inferred based on interviews and documentary evidence. To ensure that the conclusions and identified causalities are correct, the validity of the results can be tested through pattern matching, explanation building, addressing rival explanations, and using logic models (Yin, 2014). Pattern matching is applied by comparing the theoretical pattern of the relationship between identified barriers with the observed pattern based on empirical data (Trochim, 1989) and falsifying alternative patterns of predicted values (Yin, 2014). The theoretical pattern can come from traditional theorizing or the investigator’s ideas and hunches (Trochim, 1989). In explanation building, the investigator makes an initial theoretical statement, compares findings with initial propositions, and revises expectations in an iterative manner based on other details within the case (Yin, 2014). In Paper 4, which takes an explanatory approach to identifying the causal relationship between barriers to CE transition, an initial conceptual model is designed based on the literature and on logical inferences about the interconnection between barriers. This model is then compared with the results of analysis from interviews. An illustrative logic model of the interactions between barriers is provided that represents the initial theory of the case under study and the systematic effects of barriers.

External validity concerns the generalizability of the results (Yin, 2014). When it comes to generalizability, analytical and statistical generalizations should be differentiated. In qualitative studies, such as this case, empirical material is lifted to a general level and related to theory, instead of drawing conclusions based on a statistical sample as in quantitative studies (Stenbacka, 2001). Yin (2014) suggests drawing on proper theory or theoretical propositions in the research design phase to deal with the generalizability and external validity of research, especially where a single case study is used. When it comes to modeling (as in Papers 2, 3, and 5), the model is designed, based on the available literature, to be replicable in different scenarios and geographical contexts for pathway analysis and for cost and financing of sustainability transition. However, in Paper 4, with its single case study analysis of the CE transition barriers and their interconnections, a socio-technical system change theory is borrowed and evolved to direct the analysis and to frame the identified variables and their interconnections, helping to meet the external validity of the research.

5.2.2. Reliability

Rigor and transparency in data collection and analysis is crucial as a means of ensuring reliability (Davies and Dodd, 2002), with the goal of minimizing errors and bias in the study (Yin, 2014). Yin (2014) suggests using a well-documented protocol for the case study to enhance the reliability of the research. Regarding the models developed here, the mathematical expressions provided in Paper 2 and 3, and the detailed structure of the model presented in Papers 5 and 6 provide the possibility of rerunning the models to ensure the reliability of the results. In Paper 4, the reliability of the results is met through a detailed explanation of the data collection, coding procedure (first- and second-order coding, as recommended by Gioia et al., 2013), and analysis, as suggested by Yin (2014).

6. Results

This research underscores the critical role of charging strategies in projecting transition costs, encompassing charging expenses and time lost. The negligible opportunity cost of capacity loss in green powertrains contrasts with the significant impact of fuel and financing on overall technology costs. Although not being significantly influencing from a cost perspective, realizing savings through salvage value relies on a CE model that is subject to system-level barriers and their interactions. Financing costs, though smaller than fuel expenses and initial investments, are pivotal. They are not merely an antecedent for transition of freight; rather, the availability of financing, particularly in this micro-based sector, is a critical factor. This significance applies not only to strategic financing and investment planning but also extends to the operational level, where bargaining power significantly influences financing levels. As sustainability transition occurs at a systemic level, it becomes imperative to consider the dynamics of actors' networks, especially in financing, as the financing level of each actor in a supply network can impact the financing choices of the others.

RQ1: What has been done so far on measuring the cost of transition and transition financing?

Two main directions in research on the sustainability transition of the road transport sector have been identified. The first direction was discussed in Paper 1 through an in-depth systematic analysis, while the second direction was presented in Paper 2, which focused on developing a cost model. The literature review reveals two main streams of research on the sustainability transition of the transportation sector:

- Employing IAMs with simulation or optimization approaches to determine the effect of policies on the future pathway for transition or the most cost-optimized path for transition.
- Applying a TCO/life cycle assessment (LCA) analysis to compare technologies based on their overall costs.

Common variables used in these studies include initial investment in the technology, maintenance costs, insurance costs, taxes and subsidies, and salvage value for end-of-life vehicles. The impact of technology-related variables such as charging strategies and battery degradation on cost in technology and system level costs has been inadequately explored. In terms of the future pathway of sustainability transition, there is no consensus on the dominant technologies. Scenario testing and sensitivity analysis have been conducted, exploring different variables such as the share of different powertrains, fuel economy improvement, learning rate, effects on vehicle prices, changes in taxes and subsidies, restrictions on carbon emissions, infrastructure availability, competitiveness of transportation modes, and user lifestyle.

RQ2: What are the relevant sustainability transition cost factors, and how can these factors impact transition costs?

To answer this question, a cost analysis model was developed in Paper 2, incorporating important variables that have been less discussed in existing cost and pathway analysis models. This research highlights that the extent to which sustainability transition costs can proceed depends on several variables. One key factor is the strategic choice of fueling and charging, which determines the economic viability and competitiveness of electrification or different powertrain options. For instance, by charging trucks in terminals with low power consumption during off-peak hours, electric trucks can compete with ICEs in terms of TCO, even today. However, it is not always possible to charge in terminals, and in such cases, having the option to charge in warehouses during loading and unloading can help avoid additional time costs associated with charging. Our results demonstrate the significant sensitivity of costs to charging strategy, particularly because of dynamic electricity pricing based on charging location, time, power consumption, and electricity supply. We also found that the cost of capacity loss is negligible. When it comes to financing, we found system cost to be sensitive to the financing interest rate, especially in the case of high penetration, where a lower interest rate is applied on debt financing for green technologies.

RQ3: How much does transition cost?

To answer this research question, Paper 3 adopted a mixed methods approach, applying a set of interviews to develop scenarios on the future penetration of the technologies in the heavy-duty road transportation segment. The cost model was adapted from Paper 2 and further developed by linking the charging range behavior and battery temperature, and their impacts on batteries remained capacity, to batteries' salvage value and the potential costs of transition. Four different scenarios were set based on the speed of transition and the mix of penetrating technologies, and the costs related to each scenario were calculated and compared. The model was improved by adding a CE perspective to the cost analysis through the valorization of end-of-life batteries and the sensitivity of this value and other costs to the factors influencing the batteries' remaining capacity. Our results show that while the charging/discharging pattern and the cell temperature significantly impact the remaining capacity of the end-of-life battery, their impact is negligible considering the salvage value of a whole powertrain. However, charging patterns influence charging strategies through the effective capacity of different batteries and driving ranges and the amount of charging that must be done at higher prices in public stations.

RQ4: What are the key barriers to implementing CE for EV batteries, and how do they interact to reinforce the system and prevent changes towards CE?

Considering the incremental growth in the number of electric vehicles, along with potential challenges related to material scarcity (Giosuè et al., 2021) and the environmental consequences of waste batteries (Neumann et al., 2022), the circularity of LIBs has gained momentum. Moreover, in terms of cost analysis, batteries constitute a significant portion of the initial investment for BEVs (Safari, 2018), making CE operations cost-effective. However, progress in implementing CE business models appears to be very slow (Seltzer, 2022).

In line with this gap in implementation of CE business models, and to answer the proposed research question, a socio-technical system change model was utilized to classify barriers and explore the interconnections between them. To enhance Leavitt's (1965) model, two dimensions, namely regulatory framework and market environment, were incorporated into the structure, people, technology, and task as four components of a socio-technical system.

Under the regulatory framework, the main barriers identified are the absence of supportive policies, unclear regulations, insufficient financial support, and lack of battery standardization. Within the market environment component, barriers such as limited market size and restricted access to both waste batteries and the sale of reused batteries impede the transition towards CE. In the structure component, the main barriers to CE transition are the lack of accessible data concerning the end-of-life state of batteries, inadequate partnerships among actors in the battery ecosystem, and inefficiencies in the certification process. People-related barriers to CE transition encompass customers' lack of knowledge and interest in electrification or the CE of LIBs, as well as a general societal lack of awareness. Regarding the technical component, notable barriers are the varying shapes, sizes, and chemistries of the batteries, and the requirement for a backend system to access real-time data on battery state of life. Lastly, within the task component, the main barriers to CE transition are the costs associated with implementing CE practices, particularly transportation fees for waste batteries categorized as dangerous goods, and the absence of attractive business models.

The interactions between barriers were found to be complex, with six reinforcing loops that hinder system change and transition to CE. These loops involve the interplay among factors such as customer interest, collaboration, co-investment, data handling, financial viability, and market attractiveness, resulting in self-reinforcing dynamics within the socio-technical system of the battery industry. The findings underscore the significance of taking into account the interconnections among barriers, revealing the dynamic nature of these barriers. This not only provides insights that extend beyond current literature but also introduces a more comprehensive framework for future research and practical applications.

RQ5: How do the financial strength of transportation actors and the financial system's support for them affect the transition of the sector?

To answer this research question, Paper 5 provides a data-driven simulation using a developed agent-based model. The data were taken from the Business Retriever database and cover the financial data of actors in road freight transportation in Sweden. After cleaning the data and removing companies with missing values, 9,590 companies were used for a descriptive analysis of the system and as initial data for the model. Our descriptive analysis showed that the majority of the hauliers (53.55%) were micro companies. About 43.65% of the hauliers were SMEs, and only 280 hauliers, accounting for 2.8% of the population, were large. The analysis of discounted Z" scores revealed that 46.5% of companies were in the safe zone, 35.7% in the distress zone, and 17.8% in the gray zone. Micro companies had the highest average Z" scores (17.18), while large and small-to-medium companies had the lowest averages (2.55 and 3.83). The variability in Z" scores was highest for companies with zero employees due to fluctuations in the equity-to-liability ratio caused by small total liabilities and high equity values, which also reflect access to external financing. The simulation results show a gap between assets ready to be replaced by BEVs and actual replacements. Most companies lack the cash to replace their fleets. For those who replace assets using internal financing, their balance sheet, liquidity, and eligibility for future replacements through internal financing are affected. Many companies with assets to replace are not eligible for debt financing because of their lack of creditworthiness. Financial stability and credit risk change in each run of the simulation. The return on equity ratio of many hauliers would not suffice to recoup their reinvestment in BEVs, and this trend continues over time. Different policies, including subsidizing the purchase price of BEVs, reducing the purchase price, and subsidizing the interest rate, do not significantly affect the results.

RQ6: How does a company's bargaining power impact its access to financing and, more specifically, the supply network's financing at a tactical level?

To answer this research question, a network analysis was conducted in Paper 6 to analyze trade credit as a source of external financing, to test the antecedents for companies' decisions on accessing trade credits, and to see how these decisions would affect the whole supply network. The results showed a positive effect of the suppliers' share of sales and a negative effect of the buyer's share of purchasing on the buyer's trade credit as proxies for the dependency of each part on the other. When it comes to the supply network structure, the suppliers' connectedness, both within the whole network and among first-tier suppliers, would weaken the buyers' bargaining, causing the latter to receive a lower level of trade credit. Regarding the incremental increase in trade credit in the upstream supply network, we found that upper-level suppliers have higher trade credit. This higher trade credit does not necessarily come from downstream buyers, as the upstream suppliers that are well connected had lower trade credit, rather than higher credit resulting from pressure from the many downstream buyers in their network.

7. Conclusions and future research

7.1. Conclusion

The primary goal of this chapter is to interpret the empirical and theoretical findings. The purpose of the thesis is threefold. The aim of the first part is *to identify the costs of sustainability transition for actors within the transport system.* Three research questions were formulated to achieve this: 1) identifying cost factors, 2) modeling these factors, and 3) projecting transition costs. Consequently, the initial research phase enhanced comprehension of the state of research in sustainability transition and cost analysis. Paper 1 paved the way for a deeper dive into cost analysis by empirically testing transition scenarios in the chosen sector and region.

Paper 2 established a framework for these tests and scenario analyses by introducing a cost analysis model that brought to light previously overlooked cost variables. It clarified that costs encompass more than investment in green powertrains or fuel; the transition extends to altering mindsets and work approaches. The paper underscored that truck charging strategies significantly influence costs; a strategic approach to charging can make green powertrain costs competitive with conventional trucks, even today.

Paper 3 extended the cost analysis. It introduced new transition scenarios in Sweden and emphasized a less explored variable: salvage value. This paper initiated a discourse on how the state-of-life of BEVs, a prominent green technology, is influenced by the charging behaviors and the battery chemistry, batteries' charging temperature. While the findings show a limited impact of batteries' state-of-life after their first use on their salvage value, it bridges the gap between the first and third parts of the research purpose, which involves *identifying the potential barriers to systematic change.* Paper 4 tackled this by investigating barriers to the adoption of battery CE within the current linear system.

The second part of the research purpose depicted the financial dynamics of the transition. It explored how the system aligns with sustainability transition based on actors' potential and their access to financing resources. Two research questions were posed: one on strategic financing and investment planning for fleet replacement, and the other on tactical financing and its impact on actors' network dynamics. Paper 5 intertwined with findings from Papers 2 and 3 to discuss green financing. Whereas Papers 2 and 3 highlighted the importance of discounted financing as an incentive for reducing the technology cost, Paper 5 drew a broader picture of the transition by focusing solely on financing. In terms of relying on an actor's internal resources, the financial markets' rechanneling of cash flow toward green technologies, and the use of equity in financing fleet replacement, Paper 5 also showed how the existing system would approach the transition.

Many actors were micro companies with not many trucks to replace. For those who had more trucks, their internal financing did not suffice for replacements, even when the purchase price of the new trucks was close to that of conventional trucks. Additionally, their credit scores did not satisfy the conditions for external financing. Even if they could finance their initial replacements, the dynamics in their balance sheets would influence the availability of financing for future replacements. Similarly, Paper 6 showed the criticality of bargaining power in receiving trade credit, which serves as the main source of tactical financing. This, in turn, puts smaller companies with less bargaining power at a disadvantage.

Throughout this thesis, the aim has been to show that sustainability transition is a product of interactions among different components of a system and is not limited to a change in technology or a business model. When it comes to fleet replacement, this thesis shows that in the context of freight transportation, transition goes beyond simply replacing a conventional powertrain with a green one. The regulatory framework, supportive/prohibitive policies, the actors' ways of operating, the manufacturing system that supports it, the actors' financial structures and well-being, the financial actors that align with such transitions, and so on, collectively shape the transition. All these variables require change in order to facilitate significant change at the system level.

Without changes in policy instruments, both with regard to lowering technology costs and to facilitating financing for smaller actors with lower credit scores (in terms of external bank financing or lower bargaining power for trade credit financing), transition would not occur at the desired pace. Furthermore, transition and its costs depend heavily on the behavior of the actors involved, particularly when it comes to changing strategies and electricity pricing structure. Given a lower green electricity price during off-peak hours at truck owners' terminals, along with a low power effect, the total cost of BEVs could already be competitive with that of ICEs. This competitiveness would incentivize subsequent replacements and expedite the transition process. If a transition from linearity to circularity were to take place in manufacturers' business models, both manufacturers and hauliers would benefit from higher value, which would impact technology costs and accelerate transition.

When it comes to circularity, the same approach applies. For such a shift to take place, all the components of a system require alteration, because the barriers within the components are interconnected, creating a reinforcing loop that hinders transition. For instance, if battery manufacturers encounter financial challenges when investing in data management for assessing batteries' state of life, it might deter them from incorporating data-driven assessments of CE into their business models. It might also hinder their ability to encourage vehicle manufacturers to join CE initiatives, which in turn, impacts their desire for partnership schemes. This can impact the financial stability of the battery manufacturer and the overall CE transition.

7.2. Future research

Paper 2 measured different costs related to fleet replacement, with more sustainable options including BEVs and FCVs. The opportunity cost of lost loading capacity was measured by accounting for the additional weight and volume of these powertrains. While this analysis accounts for the costs associated with reduced loading capacity, it is limited by not considering the potential increase in the number of sustainable trucks needed to compensate for the capacity lost during the replacement process. This unexplored dimension may have implications for the overall sustainability benefits of BEVs and FCVs in the heavy-duty vehicle sector, and is therefore an area for future research. It is worth noting that the opportunity cost associated with lost capacity and time was assessed by quantifying investment expenditures for ICEs. Subsequent research could explore alternative proxies for calculating these costs, such as the company's revenue per truck.

Paper 2 developed a cost analysis model with a fixed energy price. There is, however, a potential cash flow risk linked to fluctuations in fuel prices, and this is an avenue for future research. This issue has been addressed in contracts for fossil fuel vehicles by incorporating an adjustment index. The contracts require companies to determine transportation fees for customers based on adapted fuel costs and shifts in diesel prices, typically on a monthly basis. Since these existing arrangements have been tailored to conventional vehicles reliant on fossil fuels, they have not accounted for BEVs and the dynamic nature of electricity prices. This omission escalates the vulnerability of these contracts to fluctuations in electricity costs, which are known for their pronounced instability, not only across days but even within a single day. This volatility introduces additional cash flow risk for companies aiming to become fossil-free, which indicates that the current system is designed for conventional vehicles and is not suitable for BEVs. This raises several further questions: how much energy prices fluctuate, influencing the transition cost; how much the differences in electricity and diesel prices would have to be to minimize the risk; how current contracts need to be adjusted by setting up a fuel adjustment factor to cover the potential risks regarding electricity prices; and whether subsidies for charging, such as discounted electricity rates at public charging stations, can facilitate transition. Moreover, exploring the influence of elevated purchase prices in BEVs on their insurance costs and, consequently, their TCO is a valuable avenue for future research. This study focuses on purchasing strategy. Future research could explore how leasing schemes, particularly for technologies like batteries and vehicle leasing in BEVs, affect various costs at a technology and system level.

When it comes to end-of-life vehicles, there is a risk associated with the disposal of end-of-life batteries as one of the most expensive components in BEVs. This uncertainty, from a vehicle owner's perspective, regarding the salvage value of used batteries, together with the challenges, from a battery manufacturer's perspective, surrounding the circularity of batteries, raises the question of how the CE of batteries can become profitable. Paper 3 provided an interesting observation of how a CE business model would impact the transition cost. By analyzing the impact of salvage value on total cost, it also opened a discussion on the underexplored topic of integrating CE into transition cost research. The analysis could be taken further, expanding the discussion on better valuation of used batteries by including variables such as the power effect of the chargers that BEVs are using. Integrating the charging strategies with such components would be an interesting area for further research.

Paper 4 discussed the potential barriers that hinder CE transition in the battery ecosystem from a battery manufacturer perspective. However, other actors within the ecosystem, including the government, battery customers, end users, and recycling service providers, also play key roles in such transition. As such, exploring the perspectives of these actors presents a compelling subject for analysis and great potential for future research.

Another possible future research project comes from Paper 5, which looked specifically at the financing challenges of transition at a strategic level. Taking into account the higher price of zero-emission vehicles and, consequently, higher debt financing, the cost of financing is higher for these powertrains. This cost is particularly sensitive to changes in interest rates, making capital more expensive and investment in zero-emission vehicles riskier. Therefore, the question arises as to how this risk changes with changes in the interest rate. Although a fixed interest rate provides additional insurance and potentially reduces the risk, it also increases the cost of capital due to the rate being higher, especially for BEVs, given their higher purchase price. Therefore, research should be conducted to see whether green financing solutions can help reduce this risk; if so, how much investment or interest rate discounting is required to offset the additional risk; and how much lower the TCO would have to be to compensate for the additional risk. Additionally, this study examined purchasing financing through internal, debt, and equity financing. Investigating alternative schemes such as leasing could be valuable for future research. Paper 6 also provides a platform from which to explore the dynamics of a supply network, thereby creating a space for further research on how the dynamics of supply networks would help or hinder network-level transition.

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Appendix. Papers