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Charging Station Development in the Context of Transport Electrification in Latvia: Systems Thinking Approach

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Abstract **– The EU policy targets require accelerating electrification of the transport sector, which brings both opportunities and challenges for national energy systems. This study aims to identify and prioritize key criteria for accelerating electric vehicle (EV) adoption beyond Innovators and Early Adopters stages of Technology Adoption Life Cycle in Latvian context. The study evaluates the relationship between EV adoption rates, charging infrastructure development, user behaviour, and grid capacity constraints in the form of causal loop diagrams (CLD), defined according to the Systems Thinking approach. The parameters of CLD and their feedbacks are defined based on literature review. The study proposes a set of criteria and their relationship in form of CLD, which further modelling of more effective electric vehicle infrastructure planning and anticipatory investments. As a result, research highlights how decisions in one area (e.g., public subsidies, cost of vehicles or charging infrastructure placement, etc.) can significantly influence others, leading to a nonlinear and delayed feedbacks in expected transport electrification rates. The findings of investigated case within CLDs are crucial to consider for large-scale projects concerning both transport sector and energy sector infrastructure. The Authors conclude that peak electricity demand, especially from fast-charging stations, poses a serious risk to grid stability if not properly managed. The findings of the study contribute to the development of a holistic and forward-looking framework for sustainable transport electrification in Latvia and other emerging EV markets.**

Keywords **– Causal loop diagram; charging stations; electric vehicles; infrastructure resilience; systems thinking.**

1. INTRODUCTION

The transition from internal combustion engine (ICE) vehicles to electric vehicles (EVs) is a central theme in current discussions on transport sector decarbonisation and is widely addressed in the academic literature [1], [2]. One of the primary motivations for promoting electromobility is the transport sector's significant contribution to climate change. In 2023, transport-related emissions made up 21.1 % of total global emissions, with approximately 75 % originating from road transport [3]. According to the Latvian Centre for Environment, Geology and Meteorology, transport was responsible for 30 % of Latvia's total greenhouse gas emissions in 2021, of which 97 % came from road transport [4].

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To address the transport-related emissions, the European Union (EU) has adopted specific regulations targeting emissions from the transport sector as part of Fit for 55 policy package under European Green Deal targets [5]. Light passenger and light commercial vehicles emissions are standardized by the Regulation (EU) 2023/851 [6], which sets out the following objectives:

- CO_2 emissions reduction of 55 % for new cars and 50 % for new vans from 2030 to 2034 compared to 2021 levels;
- 100 % CO_2 emission reduction for both new cars and vans from 2035;
- The 100 % reduction target implies that, from 2035 onward, only zero-emission light passenger and light commercial vehicles such as EVs can be sold within the EU. Heavy-duty vehicle CO_2 emissions are regulated by less stringent Regulation (EU) 2019/1242 [7] with adaptations for 2023–2024, which, in turn, sets the following goals:
- Reduce CO_2 emissions compared to 2019 levels by 45 % by 1 January 2030;
- 65 % by 1 January 2035;
- 90 % by 1 January 2040. In addition, 90 % of new city buses in the EU will have to be zero-emission from 2030, and all by 2035.

The transition to EVs is expected to significantly impact electricity demand, with estimates suggesting a 40 % increase in electricity consumption by the transport sector [8]. To support this shift, infrastructure development is crucial: approximately 300 high-power charging stations are planned along the TEN-T (Trans-European Transport) network, alongside at least 3 000 standard charging points, including facilities for e-bikes, to be installed near apartment buildings and in parking areas [9].

Alternative projections are even more ambitious. The electric car fleet in Latvia is projected to reach between 28 000 and 45 000 units by 2030. The estimates foresee Electricity demand from transport could increase three to four times by 2035, and up to five by 2040, compared to 2024 levels [10]. Thus, large-scale adoption of EV presents complex challenges for energy security and environmental sustainability [11]–[13]. Rapid increase in EV uptake can lead to significant spikes in electricity demand, particularly during peak charging hours, raising concerns about grid stability and the risk of local blackouts [14]. Additional increase in environmental impacts beyond vehicle operation such as land use change, higher material consumption, and embodied emissions related to the development of supporting infrastructure (e.g., charging stations and grid reinforcements to meet rising demand) must be accounted for and addressed in plans for transport electrification to facilitate sustainable transition to EVs [1], [15].

The transition towards widespread EV adoption is crucial for achieving the EU environmental policy goals but has become increasingly complex due to a wide array of interrelated technological, social, and environmental barriers [16]. In addition to the mentioned energy security and environmental sustainability concerns, many challenges are related to performance, safety, energy efficiency, functionality, infrastructure availability, and both capital and operational costs, which vary across stakeholder groups such as private users, companies, logistics operators, and public transport providers. Such multifaceted issues are often analysed by a Systems Thinking approach [17], which focuses on understanding the underlying mental models that shape decision-making [18]. Within the Systems Thinking approach, tool like causal loop diagrams (CLD) [19], helps capturing the dynamic interactions among system components, enabling a holistic perspective rather than an isolated analysis of individual factors.

The aim of this study is to identify key criteria of the driving force that leads transport electrification to wider spread consumer groups beyond the first two Innovators (2.5 % of share) and Early Adopters (13.5 %) in Technology Adoption Life Cycle method, to the next two stages, which take more than 2/3 of the share together, Early Majority (34 %) and Late Majority (34 %) [20]. The study is taking into consideration the impact of adoption on the electrical grid in the context of transport electrification in Latvia, with the objective of supporting the achievement of EU policy goals. Using a Systems Thinking approach, the study takes a holistic perspective on how vehicle adoption trends are shaped by factors such as charging infrastructure development, policy measures, and user behaviour. This approach enables the exploration of feedback loops and system dynamics, supporting more informed and adaptive infrastructure planning and aligns with long-term policy objectives through empirical modelling.

2. LITERATURE REVIEW

2.1. Policy Drivers for Transport Electrification

European Union has set specific targets for the transport sector in terms of carbon emission reductions, focusing on the issue of charging infrastructure in the Alternative Fuels Infrastructure Regulation (AFIR) [21]. From a use case and electricity grid perspective, charging points can be divided into three main parts:

1. Highway/roadside charging use case:
   Category 2 (DC) (Direct Current) –
   Level 2 – Ultra-fast DC recharging point, $P \geq 350$ kW;
   Level 1 – Ultra-fast DC recharging point, 150 kW $\leq P <$ 350 kW;
2. Destination charging use case:
   Fast DC recharging point, 50 kW $\leq P <$ 150 kW;
   Slow DC recharging point, $P <$ 50 kW
3. Home/Office/Street charging user case:
   Category 2 (AC) (Alternating Current) –
   Fast AC recharging point, triple-phase, $P >$ 22 kW;
   Medium-speed AC recharging point, triple-phase, 7.4 kW $\leq P \leq$ 22 kW
   Slow AC recharging point, $P <$ 7.4 kW [22].

The Alternative Fuels Infrastructure Regulation (AFIR) is primarily focused on ensuring the deployment of publicly accessible, high-power charging infrastructure along the Trans-European Transport Network [23]. Nevertheless, it gives the kilometre little consideration when it comes to slow charging alternatives [24]. While TEN-T requirements specify detailed targets for the number and capacity of roadside charging stations, they only marginally address aspects such as public charging outside major corridors, destination charging, or broader user experience considerations, including urban hubs, secure parking facilities, and associated infrastructure.

At the same time, a study by the European Automobile Manufacturers' Association (ACEA) [25] projects that electricity demand for EV charging will increase from 5 TWh in 2025 to 23 TWh by 2030, a rise most of which is expected to be concentrated in densely populated areas.

The current AFIR is the basis for future electricity demand planning and assessment of future network load helps to identify the most effective and timely infrastructure solutions to support transport electrification. Study of [26], found that the extension of EV charging infrastructure, particularly in urban areas, can lead to local overloads and voltage regulation issues, especially during peak hours. The study emphasized that accurate demand forecasting and location planning guide effective investment in charging infrastructure. The study of [27] evaluated grid impact under rapid EV adoption scenarios. The study found that optimised charging controls and strategic infrastructure development can mitigate grid constraints and enhance the effectiveness of electrification efforts.

To understand the development of EV uptake dynamics under the EU policy goals and the related implications for Latvia's energy and transport systems, Table 1 summarises key indicators that should be considered in the planning of transport electrification. This includes vehicle stock, infrastructure development, electricity demand, market incentives, and external trade factors. By comparing the current status of the indicator with the national targets and projections, Table 1 highlights trends, bottlenecks, and leverage points that can be critical for aligning transport electrification in Latvia with EU policy objectives. The context of indicator is described in in form of short comments.

The analysis of information presented in Table 1 shows indicates transport electrification link with broader transformation in the transport and energy sectors. There is a clear trend toward increased reliance on electric vehicles, which brings opportunities for reducing emissions and enhancing energy efficiency but also presents challenges related to infrastructure development, energy demand management, and system integration. The success of transport electrification depends on how well different elements, such as charging infrastructure, user incentives, energy systems, and regulatory frameworks, are aligned.

TABLE 1. CURRENT TRANSPORT ELECTRIFICATION STATUS AND RELATED POLICY GOALS

Category	**Current Status (2025)**	**Targets / Projections**	**Comment**	**Reference**
EV Stock	9 234 passenger EVs (+291 freight); ~1 % of total fleet	28 000 (base) to 45 000 (target) by 2030	Indicates exponential growth trend; key for load forecasting	[28], [10]
New Registrations	7.3 % of new car sales in 2024 are EVs (ACEA)	Targeting 20 000 units of new EV sales by 2030 (passenger), 15 % for commercial vehicles	Signals policy-driven market transformation; sensitive to incentives	[29], [9]
Electricity Demand from Transport	0.73 % in 2019	+700 % increase by 2040 (vs 2025), depending on scenario	Load pressure on grid; timing and charging patterns critical	[8], [10]
Charging Infrastructure (Planned)	340 fast public EV charging stations	300 high-power points (TEN-T); 3000 slow chargers including e-bikes	Infrastructure availability is a major enabling or limiting factor	[9], [63]–[64]
Subsidy Dynamics	Altum offers loans; 2024 subsidies improved (e.g., for families with 3+ kids)	Risk from EU-level or national policy reversal, as seen in Germany	Strong leverage point; changes can trigger reinforcing or balancing loops	[30]–[31]
Battery Price Trends	$ 149/kWh in 2023 and projected $ 111 in 2025, $ 80 by 2026	$ 80/kWh expected to enable TCO (Total Cost of Ownership) parity without subsidies	Falling prices reduce EV CAPEX (Capital Expenditure), boosting adoption – key reinforcing factor	[33]
Import Competition (China)	Chinese EVs still inaccessible due to 10 % tariff + 7.8–35.3 % anti-dumping duties	Ongoing EU–China trade tensions may delay price parity for EU consumers	Highlights external geopolitical constraints affecting local adoption rates	[34]

2.2. The Case of Latvia

While the regulatory targets clearly set the course towards full decarbonisation of transport sector in EU, the actual pace of electric vehicle adoption in Latvia presents a particular case. As of January 1, 2025, there were 9234 passengers and 291 freight electric cars registered in Latvia, which is an increase of 45 % from the beginning of 2024 [28]. At the same time, the proportion of EVs in the car fleet is still only around 1 %. According to data from the European Automobile Manufacturers Association (ACEA) [29], 7.3 % of new car registrations in Latvia in 2024 were electric cars, approaching the EU average 2023 EV share of 7.7 %. To achieve the EU targets, the "National Energy and Climate Plan 2021–2030" [9] for Latvia sets the goal to achieve 20 000 units of passenger EVs by 2030. In the commercial segment, the goals are more modest: 15 % of the entire fleet of taxis and vehicles involved in commercial transport must be zero-emission vehicles.

In a theoretical scenario where neither fast nor slow public charging infrastructure expands, but EV ownership grows due to policy-driven incentives, user charging behaviour would be shaped by necessity rather than preference. Without adequate infrastructure, EV users would be compelled to rely on any available fast charging station throughout the day, rather than charging according to their habitual or off-peak routines. Since the charging capacity would remain limited, the system would not experience a significant increase in peak load purely due to lack of grid access points during high-demand periods. This is consistent with prior charging profile analyses [35].

However, current state shows that the landscape is shifting with the number of fast charging points expanding rapidly and the development of slow charging infrastructure, particularly for overnight residential use falling behind. Such a trend can be explained by market viability concerns. As a result, charging behaviour risks explained as legacy patterns inherited from ICE vehicle use, which users are used to quick top-ups at convenient locations rather than aligning charging with grid efficiency or cost considerations. The inherited consumption pattern has direct effect on electricity grid, increasing the likelihood of peak load stress. Evidence from Danish municipal studies comparing peak and off-peak charging scenarios showed that under the assumption of having 55 % of vehicles as EVs by 2040, total peak electricity demand could rise by 55 % in peak-oriented charging conditions compared to only a 5 % increase under managed, off-peak charging strategies [35].

Discussions on mitigating peak load often focus on fast charging technologies and their management, such as peak shaving. This is a relevant solution for distribution system operators (DSOs), but in Latvia, where there is currently little commercial development of slow public AC charging infrastructure in residential settings, a more effective strategy could be shifting demand to off-peak hours through accessible slow charging solutions.

The problem with accessible slow charging solutions is that entrepreneurs currently lack incentives to invest in such infrastructure due to several constraints:

- First, slow chargers deliver less energy per session, reducing revenue potential compared to fast charging services.
- Second, pricing is highly sensitive for public AC charging, as it directly influences the Total Cost of Ownership (TCO) for EV users, which is also a key factor in EV purchasing decisions. This price sensitivity limits the markup businesses can apply.
- Third, in authors' opinion, the customer base remains limited due to the relatively small number of affordable, second-hand EVs currently available in the Latvian market. In many cases, EV users may resort to basic home charging from standard sockets where feasible, bypassing the need for public infrastructure altogether.

Nevertheless, parallels can be drawn between the development of EV infrastructure and urban cycling networks. In both cases, visible and accessible infrastructure significantly influences behavioural shifts over time. The argument that DC charging will dominate solely due to faster development must be re-evaluated in light of cost competitiveness. For instance, as of March 2025, one regional EV charging network in the Baltics charges approximately € 0.39/kWh for AC charging (up to 22 kW) and € 0.47/kWh for DC charging (up to 300 kW) is making AC charging roughly 20 % more affordable [36].

The most extensive and inclusive uptake of EVs will likely come from cost-conscious users purchasing second-hand vehicles, a demographic that represents the majority of Latvia's car owners. According to data from the Road Traffic Safety Directorate (CSDD), the average age of passenger cars in Latvia was 15.6 years at the beginning of 2025 [37].

The analysis presented in Table 2 highlights the complexity and interconnected factors shaping energy systems, including infrastructure capacity, technology implementation, consumer cost awareness, spatial development, and policy roles in Latvia. Particularly, the interaction between electricity grid limitations and EV usage patterns varies depending on factors such as charging infrastructure distribution, pricing strategies, and regional differences in energy accessibility.

TABLE 2. KEY FACTORS AFFECTING EV CHARGING INFRASTRUCTURE AND LOAD DISTRIBUTION IN LATVIA

Category	Key Findings / Descriptions	Implications for Load Analysis	Source Type	Reference
Substation Constraints	Several 110 kV substations (e.g., Salacgrīva, Skulte, Saulkrasti) have only one transformer; limited reserve capacity. Saulkrasti is owned by Latvian Railways.	High vulnerability in electricity supply reliability and limited reserve leads to risk under peak EV load conditions.	Infrastructure status report (ST, policy-level insight)	[38]
Planned Upgrades	New substations planned: Saldus, Launkalne, Saulkrasti, Berģi; capacity upgrades and extra transformers considered.	Reinforcement of grid nodes critical for future EV charging clusters.	Strategic investment planning (ST)	[38]
Public AC Charging Project	The only DSO in Latvia aims to build 2 060 slow (22 kW max) AC charging connection points with € 6.5 M EU Recovery Fund support, ending by May 2026.	EV load demand will grow gradually and is tied to low-voltage distribution grid zones; vital for modelling long-term demand.	Project documentation (EU-funded ST initiative)	[39]
Price Comparison: AC vs. DC	AC public charging: € 0.39/kWh vs DC fast charging: € 0.47/kWh (as of March 2025).	Cost-sensitive EV users likely to choose slower AC charging, affecting evening/night grid load more than peak-hour spikes.	Market pricing (service providers, observational data)	[36]
Vehicle Profile	Average age of passenger cars is 15.6 years; demand driven by used/affordable EVs.	Load distribution influenced by more frequent, lower-power charging, not rapid charging patterns.	CSDD statistical data	[37]
Population Density Hotspots	Riga leads with 610 780 people and 2414/km² density; 47 % of EVs in Latvia are registered in Riga.	Priority area for infrastructure planning; electricity demand models must centre on Riga for 2025–2030 projections.	Demographic maps (Central Statistics, population GIS data)	[40] [28]

Available Grid Capacity (AC)	Areas with high capacity: Bišuciems (29 MW), Purvciems (22 MW), Grīziņkalns (21 MW); low in Šķirotava (0.5 MW), Imanta (4 MW).	Determines where AC infrastructure can scale quickly without grid reinforcement; critical input for geo-based load modelling.	ST interactive map (grid capacity data, March 2025)	[41]
Organizational Role	Latvenergo leads DC fast-charging rollout.	Institutional alignment affects deployment speed and reliability; should be factored into scenario planning.	Policy & governance context (national) utilities)	[42]

The findings presented in Table 2 show a tendency for Latvia's EV infrastructure development, where the current pace and structure of charging network expansion, particularly the dominance of DC fast charging, risks reinforcing unsustainable load profiles on the electrical grid. This tendency is further strengthened by user behaviour patterns emerging as a heritage of ICE refuelling habits, the number of EV users that will rely on second-hand vehicles, and spatial disparities in access to public charging infrastructure. Therefore, the strategic development of AC public charging stations presents significant potential for municipalities and public utilities to lead transport electrification in a more suitable direction for the case of Latvia.

2.3. Role of Smart Charging, Flexibility, and Forecasting

The Global EV Outlook 2023 by the International Energy Agency [43] highlights that in densely populated urban regions, where home charging access is limited, public charging infrastructure becomes essential for electric vehicle (EV) adoption, as the report foresees EVs contributing to increase up to 9–10 % of total electricity demand in several EU countries. The scenarios under the study show peak load increases of 40–70 % in worst-case situations from uncontrolled charging in high-density residential zones with multiple fast chargers. At the same time, controlled (smart) charging could reduce grid stress and required upgrades by approximately 30 %. This shows that charging infrastructure expansion needs can be optimized through demand-side measures.

Using empirical data from more than 59 520 real world measurements from 267 electric vehicles, the study [44] identifies large differences in charging patterns among individual users, charging locations, and times of day. These findings are critical for forecasting demand, planning charging infrastructure, and designing smart grid strategies that can respond dynamically to different user charging needs.

The study of [45] considering the expected growth of charging demand went further into forecasting charging demand with help of artificial intelligence (AI) and developed a transformer-based deep learning model to predict spatio-temporal EV charging demand more accurately than traditional models.

A recent study titled "Slow but Steady: Assessing the Benefits of Slow Public EV Charging Infrastructure in Metropolitan Areas" [46] explores how public slow charging stations (less than 7.4 kW) in metropolitan residential areas can help overcome sudden impacts on the electrical grid. The study presents a comprehensive review of smart charging strategies for electric vehicles, highlighting their role in the efficient integration of EVs into the energy system. The study categorizes use cases based on charging location, speed, and market structure, and systematically evaluates the evolving business models associated with smart charging. These include aggregator-driven services, peer-to-peer energy trading, and even vehicle-to-grid (V2G) monetization. The study foresees the Internet of Things (IoT), and AI will help to pave the foundation for effective smart charging solutions.

The studies highlight how the variability in charging behaviour across users, times, and locations complicates infrastructure planning and energy forecasting. As a result, advanced tools including AI-based models are increasingly used to improve the accuracy of demand predictions at both spatial and temporal scales. This offers new opportunities for grid flexibility, but implementation is challenged by insufficient regulations and a general lack of user awareness. Thus, further understanding the interconnections between technology, policy, and user experience becomes essential to designing effective, scalable, and EV user focused solutions for charging station development to promote transport electrification.

2.4. Applications of Systems Thinking in EV Charging

From systems perspective, the regulatory fragmentation, interoperability issues, and limited user awareness challenges are separate issues but are interdependent elements of energy, mobility, governance, and social behaviour interaction. In this context, the Systems Thinking approach can be applied to analyse the development of EV charging infrastructure in Latvia in the present study, offering a holistic perspective for identification of leverage points for interventions towards smooth transport electrification.

The use of the Systems Thinking approach is already long recognized in other research topics, including renewable energy transitions [47], energy efficiency [48], [49], bioeconomy [50], [51]. These applications highlight the usefulness of system-oriented approaches in tackling complex socio-technical challenges.

Recent research work [52] applying systems thinking approach to study the integration of smart charging into power grid operations showed the EV and grid interaction as a compound, interdependent system of actors, technologies, and feedback mechanisms. The study includes coordination between distribution system operators, transmission system operators, aggregators, EV users, and charging infrastructure providers. The developed model helped to classify control schemes (centralized, decentralized, hierarchical), reflecting different levels of system coordination and autonomy that influence real-time decision-making, load balancing, and grid stability.

A recent study [53] developed a system dynamics framework to explore how Taiwan's 2020 subsidy phase-out affected user purchasing decisions and charging behaviour. Rather than isolating individual drivers, the research examines the dynamic relationships between policy measures, market responses, and user behaviour within multiple scenarios. The model illustrated how changes in regulatory support or market conditions can influence adoption trajectories. The results of this study give insights into strategies for accelerating the shift toward cleaner transport systems.

A study [54] employs a system dynamics model to explore how EV adoption occurs under the influence of multiple interconnected captured by the feedback loops, including technical, financial, and behavioural variables. The model's results indicate that EV uptake tends to grow gradually at first, then accelerates rapidly and eventually reaches a plateau state. In early phases, policy incentives and subsidies are identified as primary drivers, whereas long-term growth depends on technological cost decline and charging reliability. The findings strongly highlight the need for aligning short-term support mechanisms with long-term development strategies to have a stable market growth.

A system dynamics study by Rafew, Hossain, and Kabir [55] investigates the adoption of EVs in the city of Regina, Saskatchewan. The study integrates local vehicle data, energy-price projections, and behavioural parameters derived from survey responses to test how consumers react to different incentive packages. The results show that aggressive early subsidies can offset climate-related hesitancy but only if accompanied by parallel investment in fast-charging infrastructure. The authors argue that such findings can guide municipal planners when prioritizing between fiscal incentives and infrastructure expansion.

A study from South Africa [56] applied a system dynamics model to evaluate how different electrification scenarios would affect transport and power sectors. The model showed the diffusion of electric cars, buses, and freight trucks from 2020 to 2040. Results suggest that a high-penetration scenario in case of South Africa could cut direct transport emissions by 12 %, yet total electricity-related emissions would rise by about 4 % because of increased demand. The authors emphasize that real climate benefits can only be achieved if vehicle electrification is matched by faster grid decarbonization and stronger coordination between energy and mobility planning.

System dynamics modelling is found in a study focused on Iran [57], which examines the relationship between EV deployment, smart charging integration, and grid performance. The model incorporates various feedback loops, including technical, behavioural, and economic aspects to evaluate long-term system impacts. One of the key findings shows that while subsidies can stimulate early-stage adoption, their effectiveness depends heavily on parallel investments in smart charging infrastructure. Without coordination, grid stress may increase over time, and the research suggests that low-cost interventions can yield substantial benefits in terms of both grid resilience and sustainable EV growth.

The SD model application has shown good recognition across academics working with transport electrification. Existing models often lack a focus on urban-level slow charging infrastructure, which is crucial for widespread EV adoption in case of Latvia under EU policy framework scope. The studies often do not include both long-term and short-term temporal variability of grid constraints, which are increasingly relevant in cities with ageing infrastructure and high population density.

The DSOs lacks methodology on assessing the grid development for preparation to wider transport electrification. Their reactive approach has already shown that grid operators are becoming a bottleneck for EV connection point growth. CLD approach used in this study covers the initial stage of creating such a methodology by analysing users' behaviour. Therefore, this study contributes to the growing body of literature by applying Systems Thinking and CLD specifically to the Latvian case, highlighting how infrastructure availability, price sensitivity, and public policy interact dynamically in shaping EV uptake and its impacts on the grid, thus aiding in identifying leverage points and formulating strategies to promote sustainable transport electrification.

3. METHODS

System dynamics is a modelling approach, originally developed by Jay W. Forrester at MIT in the 1950s, is a method used to explore and interpret complex systems and the interdependencies that drive their behaviour. Initially developed to support decision-making in industrial production systems through feedback control principles. Since then, it has been widely applied in domains ranging from public policy and healthcare to ecology and infrastructure planning. It enables both qualitative system mapping and quantitative simulation to test scenarios and inform long-term strategies. System dynamics provides a structured way to examine processes, internal feedbacks among system components, and freely define system boundaries, within which models are developed and analysed to support better system design and governance. One of key strengths of this approach lies in improving the understanding of system-wide interactions and anticipate unintended consequences before implementing large-scale changes, thus, reducing trial-and-error in real-world implementation [58].

A CLD illustrates the structure of a system using three core components: variables, causal links, and feedback loops [59]. Variables depicted as nodes represent elements distinguished within the system that change behaviour over time. The arrows (i.e., links between variables) indicate how one variable influences another. In system dynamics terms, a positive link means that a rise or fall in one variable produces a change of the same sign in another, amplifying the original effect. A negative link indicates that a rise in one variables value causes the connected variable value to change in the opposite direction, thereby counteracting the initial change in the first variable. What distinguishes CLDs from other mapping tools is their emphasis on feedback where changes in one part of the system eventually influence themselves, either reinforcing or balancing overall behaviour. These feedback structures are main focus point for building and interpreting SD models.

To capture the context-specific dynamics of EV adoption and grid interaction in Latvia, findings from non-scientific sources such as infrastructure reports, national policy documents, utility company initiatives, and market pricing were systematically assessed and categorized (Table 1 and Table 2). This allowed identification of several interrelated factors that influence charging infrastructure development and corresponding grid impacts. These findings provide a critical input to the causal loop modelling in this study.

Drawing on the synthesis of reviewed evidence, the study formulates the main dynamic problem in Latvia's transport electrification: How can infrastructure development and EV user behaviour be coordinated to support inclusive, policy-aligned growth in electric mobility, while avoiding unintended impacts such as peak load stress and social disparities in access?

Reinforcing feedback mechanisms, such as increased availability of used electric vehicles lowering entry costs and encouraging further adoption can accelerate changes in the studied system. At the same time, balancing feedbacks emerge, for example, when widespread use of fast charging infrastructure contributes to peak electricity demand, potentially straining grid stability. However, these effects do not occur instantly. Time delays have an important role. Infrastructure expansion, price adjustments, and user habits evolve slowly, creating time lags that link short-term incentives with long-term system behaviour. Additionally, trade-offs must be considered, such as the financial and operational differences between slower public AC charging and faster but more resource-intensive DC alternatives. To better understand these interdependencies and identify leverage points for action, the study applies a Systems Thinking approach to model the structure of the problem and uncover the underlying drivers for EV adoption and infrastructure dynamics in Latvia.

Another method that is used for a justification of CLD system thinking present decisions is Technology Adaption Life Cycle Method (TALC).

The method explains how high-tech marketing enlightenment takes on different consumer groups to accept the new-technology product based on their values.

According to it there are 5 groups of consumers different in share, decision-making approach:

1. Innovators known as The Technology Enthusiasts, or just Techies, adopt the technology for its own sake. They are the smallest share of the people is 2.5 %, but also, they are the easiest to approach, as long as the latest and the greatest technology.
2. Early Adopters known as Visionaries see so much of potential in the technology, they are the least price-sensitive of any segment and have the budget to fund the idea. The size of share is 13.5 %. According to EV sales statistics for 2024 in Latvia, the share of EV in new registrations was 7.3 %, which corresponds to Early Adopters TALC stage, that comes after the Innovators, and form together just 16 % of the consumers. It is clear that they are only the predecessors to wider adoption consumer groups and

have different buying decision-making criteria [29]. The authors set a goal of the research to identify the leading criteria for the wider adoption of transport electrification. By wider authors assume the share which may be adopted by the majority.

3. The next segment of groups consumers is Early Majority known as The Pragmatists which holds 34 % of the share pie. Pragmatists are hard to win over, but they are loyal as once won. Pragmatists care about the company, the quality, the reliability of the product, and the infrastructure of supporting products. For the available charging infrastructure is going to be as one of the main buying criteria. Pragmatists are reasonably price-sensitive and are looking for the best deal.
4. The same size shareholders of another 34 % is the 4th out of 5 Technology Adopters' group Late Majority – The Conservatives. They want the quality of package to be high at a heavily discounted price. As it may be seen, the wider the segment gets, the more price-sensitive it becomes. The wider adoption will happen on the account of Early and Late Majority groups which form more than 2/3 of the customers – 68 %. Late Majority group comes into the market when half of the market is already using the technology. The purchasing power of these wider adoption consumer groups is limited and the price sensitivity is high, meaning that these consumer groups will most likely drive heavily used around average passenger car age cheap cars.
5. The last group of the consumers is Laggers known also as The Skeptics takes 16 % of the total, and isn't a group of interest for high-tech marketplace, because they are not participating in the market but only block the sales with negative influence.

4. RESULTS AND DISCUSSION

The results of the created CLDs show that the adoption of EVs in Latvia is highly dependent on their TCO, which includes both CAPEX (Capital Expenditure) and OPEX (Operational Expenses) as seen in Fig. 1. Currently, EV adoption is limited due to the high CAPEX, which results from the initial purchase cost of EVs, particularly the battery and car size. However, when analysing the adoption of EVs from a system thinking approach perspective, we find a self-reinforcing loop (R) exists, where the increase in the number of used EVs helps reduce CAPEX over time. Reinforcing Loop (R1) – Growth in Used EV Market Lowers CAPEX can be described as follows: As more EVs are adopted in the world, some will eventually be sold in the second-hand market in Latvia for a lower cost than new EV cost. Overseas competition is going to make this process even faster. This will contribute to lowering the TCO, making EVs more attractive to a wider segment of consumers. As a result, more EVs will be adopted, reinforcing this cycle of increasing adoption and price reduction.

One of the barriers to EV adoption is the need for private charging stations, which adds to CAPEX. However, the expansion of Slow Charging public stations helps reduce the need for private stations, thereby decreasing the additional infrastructure cost for individual EV owners. This is acknowledged as Balancing Loop (B1). Subsidies for Slow Charging public stations further encourage the development of public charging infrastructure, which strengthens the effect of this balancing loop (B) by providing a viable alternative to home charging while avoiding the negative effects of including charging station costs in vehicles CAPEX.

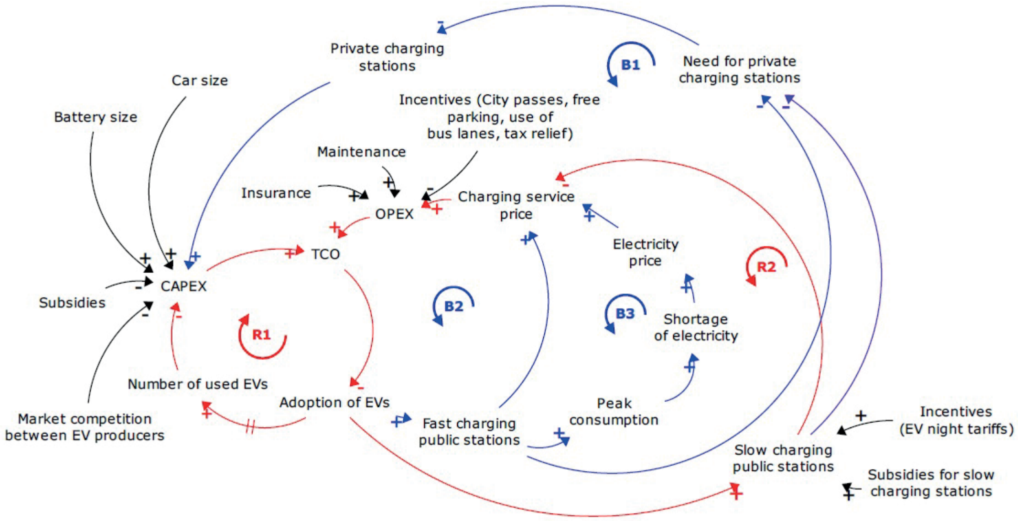

Fig. 1. CLD of EV Adoption in Latvia.

Within the studied system there is potentially also a false solution of implementing Fast Charging, also indicated as another Balancing Loop (B2) for decreasing CAPEX. However, while Fast Charging public stations may seem like a good fix, they introduce an unintended balancing loop (B3) due to their impact on peak electricity consumption, which cancels out the positive effect of loop R1 on EV adoption by increasing OPEX. It is explained that high peak demand can lead to electricity shortages and energy price increases, which are unwanted from the consumer perspective. Thus, this could ultimately slow down rather than encourage EV adoption.

The loop Balancing Loop B3 highlights the risk of relying too much on Fast Charging as a primary solution for EV infrastructure, which can also lead to higher energy prices during peak demand, hence higher OPEX of EVs. Even regardless of usage time, fast Electric Vehicle Charging Infrastructure (EVCI) is naturally more expensive due to higher CAPEX and OPEX. Instead, Slow Charging public stations offer a more sustainable approach, as they provide sufficient charging without causing severe peak electricity demand and also allow the use of electricity during the night, when the energy prices are lower, thus decreasing the OPEX (Reinforcing Loop R2). Therefore, by reducing reliance on Fast Charging, subsidies for slow-charge stations also contribute to maintaining grid stability, making the system more sustainable in the long term and at the same time decreasing TCO.

As per the above-described TALC method perspective, the pricing criteria becomes a major factor of EV adoption as the share of technology users continues to grow. The more the market matures, moving through different consumer groups further, the more price sensitive these groups are.

Types of charging infrastructure described in the paper can also be split into 2 driving user cases: city-cycle and intercity. Fast EV charging infrastructure has a significant positive impact on mitigating users' range anxiety; therefore, it holds an important mission of contributing to EV market development by bringing peace of mind to Early Adopters. However, one should always consider the most common user case for analysing decision-making when it comes to the adoption of the technology. In the case of car drivers, it is commuting to work every day, family-related tasks, and running business errands - the city-cycle user case. Today the existing range of most EVs in the EU market can cover users' needs for a few days, even in the winter, when the range is almost shrinks in double. Fast EVCI is a must-have element to bridge the gap in the 2nd user case – intercity driving, as well as for marketing purposes, but the wider adoption groups have more demands on the price of the technology than the earlier groups.

This is the moment when price parity comes into play. Internal Combustion Engine (ICE) car drivers from the Pragmatists and the Conservatives segments will need a serious argument to switch to another, newer technology. Available public Fast Charging infrastructure is a good point, but not enough, since it is the most expensive one out of these 3 ones: public Fast Charging, public Slow Charging, and private Slow Charging. Authors believe that these 2 groups will likely seek price parity of compared technologies in their decision-making, although for a different kind of it. The Pragmatists are going to be satisfied with parity in TCO (all included capital and monthly expenses related to the ownership of the car), whereas the Conservatives would look for even more: parity to be matched already in CAPEX – an EV alternative of the same price to the ICE car with the same parameters. In that last case TCO of EV should be even more favourable than that of ICE for the Late Majority to make a move.

For both parity scenarios to be achieved in the coming future, the price improvement should come at the account of the main OPEX element - the price of energy per kilometre that moves the vehicle, where the cheapest options are both of Slow Charging – public or private one. This is the grounding for the choice of CLD factors present in the paper. As it is seen in the diagram, all TCO elements are present, with the public Slow Charging infrastructure contributing to the adoption, whereas public Fast Charging doesn't, as it is less favourable in terms of achieving parity in TCO between ICE and EV technologies.

Given this context, one of the most promising solutions could involve public investment in residential-area slow charging infrastructure. DSOs are well-positioned to lead this initiative, especially in areas with high concentrations of apartment buildings. They possess the required administrative capacity, technical infrastructure, and a vested interest in minimizing peak load. Moreover, such an initiative aligns with climate targets and helps address market gaps caused by a lack of private-sector developers. The only Latvian DSO is developing grid connections for slow charging under first EU funded project of this kind in Latvia, which does not include chargers supply and operations [39]. However, since according to Electricity Market Directive (Article 33) DSO is not allowed to own charging points if other players are present in the market, it requires Charging Point Operators (CPOs) involvement for such a project to be a public service [60].

Another working solution is retrofitting existing lampposts with slow charging capabilities is a common practice in other European cities, which offers a practical solution, especially in protected historical urban areas where new structures are often restricted. In Lithuania capital, Vilnius city has a municipal public street lighting operator who already operates 350 charging points to date with 120 more to come in 2025 [59]. A standard 3.7 kW socket on one pole could serve multiple users overnight, enabling charging at off-peak times when Nord Pool market electricity prices are most favourable [60].

As a precedent, state-owned energy company in Latvia has already taken responsibility for developing DC charging infrastructure across Latvia & Baltics with more than 1000 charging points installed at the moment [42]. Although, this network contains a lot of AC charging points, they play only secondary role by supporting fast charging at “Destination” sites with more options. Authors believe that extending this responsibility to Street & Commuter district slow charging service, particularly in underserved residential areas, would be both logical and socially beneficial.

5. Conclusions

By analysing the situation in Latvia, the authors concluded that AC EV charging should be developed further to avoid load peaks in the electrical grid.

Although DC EV charging is widely considered a good solution for solving EV owner range anxiety, it puts more pressure on the grid and pulls parity in TCO with ICEV further away due to its higher price.

AC charging infrastructure should play a key role in broader EV adoption, which will more likely happen on account of used and new affordable cars, from overseas competition, or those European cars of small body and battery size.

In this research, it is seen that Riga, the Capital of Latvia, should be the first main location of such implementation, since the targets stated in governmental plans are very ambitious. It has a share of 47 % of EV registrations and around ~1/3 of the population in the country.

Several commuter districts already have required grid capacities for ensuring wide AC overnight charging service at the densest places of residence.

The main stakeholder in achieving EU climate targets through transport electrification, among other options, is the Latvian state and its municipalities. The state-owned and only DSO in the country, which is mainly responsible for ensuring grid stability and the growth of the network, should continue to work on AC EV charging EU-funded projects. The changes and additions it should take are switching from demand-based connections to proactive development of its network in “bedroom” regions and implementing turn-key solutions that include a supply of EV chargers and CPO functionality.

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