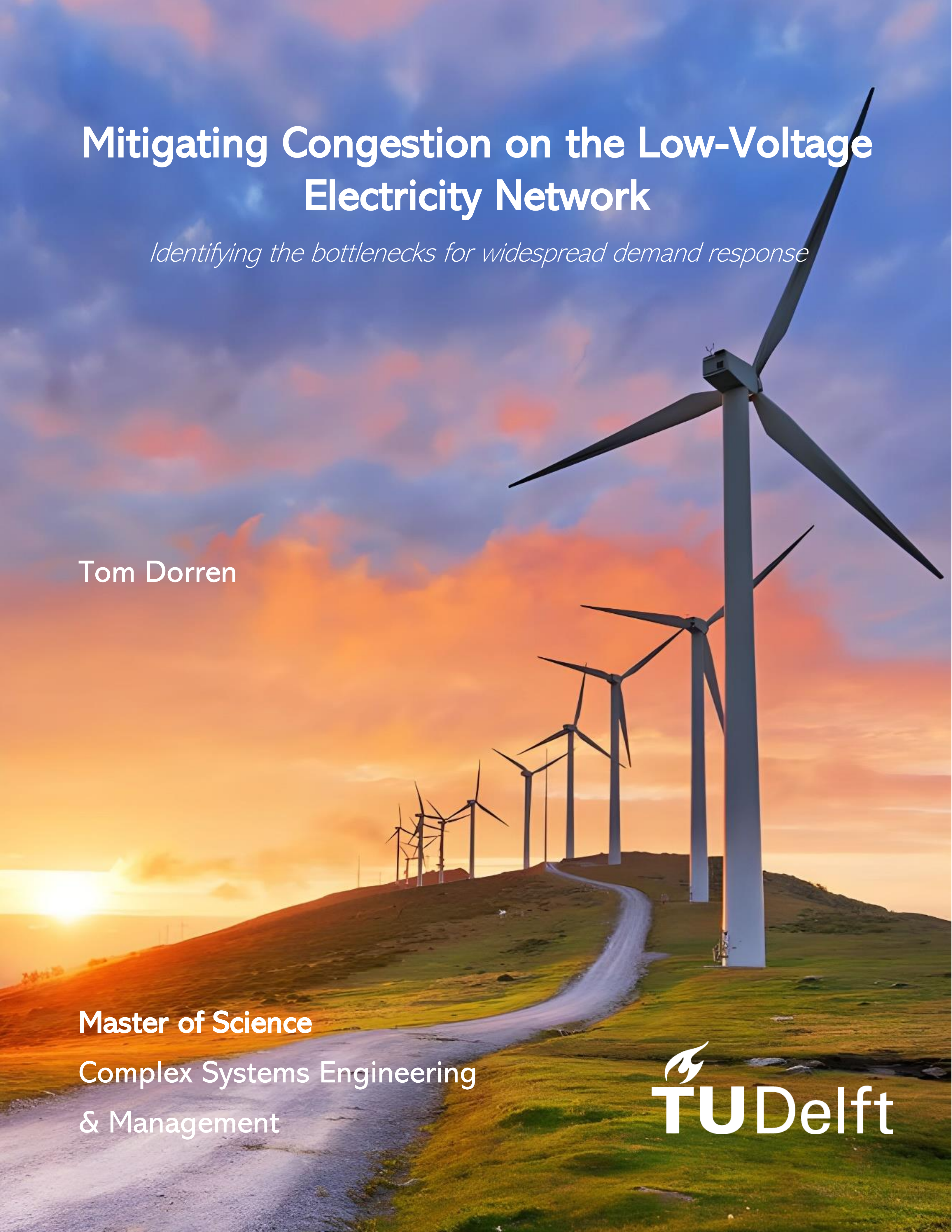


Mitigating Congestion on the Low-Voltage Electricity Network

Identifying the bottlenecks for widespread demand response

Tom Dorren

Master of Science
Complex Systems Engineering
& Management

TU Delft

Mitigating Congestion on the Low-Voltage Electricity Network

Identifying the bottlenecks for widespread demand response

By

Tom Dorren

to obtain the degree of

Master of Science

in Complex Systems Engineering & Management

at the Delft University of Technology,

to be defended publicly on Friday, July 5, 2024, at 10:30 AM.

Supervisor:	Prof. dr. R.A. Hakvoort	
	R.I.J. Dobbe	
External Supervisor:	Henk Wiersma	
	Toon van Holthe tot Echten	
Thesis committee:	Prof. dr R.A. Hakvoort	TU Delft
	R.I.J. Dobbe	TU Delft
	Henk Wiersma	Accenture
	Toon van Holte tot Echten	Accenture

Student number: 5774241

An electronic version of this thesis is available at http://repository.tudelft.nl/.

Preface

This thesis represents five months of dedicated and enjoyable work in a field that I am deeply passionate about. Focusing on the energy transition has been immensely rewarding, and I am grateful for the opportunity to contribute to this vital subject.

This would not have been possible without the invaluable support and guidance of several individuals. I want to thank my first and second supervisors, Rudi Hakvoort and Roel Dobbe, for their time, insightful feedback, and support. Additionally, I am grateful to Henk Wiersma and Toon van Holthe tot Echten, my thesis supervisors at Accenture. Their mentorship, availability for discussions, and constant encouragement were instrumental in overcoming the challenges I faced. I also appreciate the opportunity they provided me to write my thesis within the Utilities team, granting me the freedom to define the topic and objectives within the domain of the low-voltage grid.

I hope this thesis makes a meaningful contribution to the Netherlands' journey towards a resilient and sustainable energy system.

Tom Dorren

Amsterdam, June 2024

Executive Summary

The Dutch electricity network comprises several physical layers: generation, transmission, distribution, and retailing. It is currently transitioning from a centralized, unidirectional system to a more decentralized, bidirectional one. This shift is primarily driven by the integration of renewable energy sources and their characteristics. However, this transition has introduced challenges for the electricity grid, especially at the low-voltage level, due to increased renewable energy production and the electrification of demand.

The main issue addressed in this research is the risks associated with low-voltage grid congestion, which is intensified by the push for decentralized renewable energy sources and electrification initiatives. Smart appliances, which facilitate demand response initiatives, have the potential to address congestion issues. Therefore, this study aims to explore the role of flexible household appliances by diving into widespread demand response.

A comprehensive literature review revealed that while there is significant research on the technical potential of demand response and flexibility initiatives associated with smart appliances, there exists a knowledge gap on the barriers to the widespread adoption of these appliances. This research exposes technical, economic, and regulatory barriers as critical gaps in this adoption process. The research combines qualitative semi-structured interviews with stakeholders and industry experts in the energy sector with critical transactions theory to analyze and understand the bottlenecks identified. Interviews with system operators, retail providers, service providers, and end-users were conducted to capture a comprehensive overview of the various perspectives.

The key findings of this research include four critical bottlenecks for the widespread adoption of smart appliances to enable demand response. The first barrier, uncertainty in the regulatory landscape, involves unclear future market designs and divisions of roles and responsibilities, delaying strategic planning and investments in flexible solutions. The second bottleneck involves an economic barrier, indicating that the financial incentives for households to participate in demand response programs prove inadequate. The third bottleneck includes the technical barrier of lack of standardized communication protocols among smart appliances, which hinders interoperability and effective integration into the grid.

Critical Transactions Theory is employed in the analysis to highlight the misalignment between technical requirements, organizational transactions, and their modes of organization. The current market designs fail to adequately support the critical functions of capacity management, system control, and interoperability, leading to inefficiencies in the energy system and, eventually, the possibility of blackouts.

To address these issues, each bottleneck has been provided with a recommendation for their alleviation. For the first bottleneck, the division of roles in the future energy system requires directive intervention to define the roles and responsibilities to foster investment in development and allow for strategic decision-making. In doing so, decision variables have been identified on which short-term clarity is required. For the second bottleneck, the inadequate financial incentives for participating in demand response initiatives, a control-based approach is suggested in the form of Direct Load Control (DLC). DLC can enhance grid stability by allowing utilities to manage household demand directly. This approach can reduce the peak load and prevent low-voltage congestion by actively controlling the load in the hands of the Distribution System

Operator (DSO). The third bottleneck, the fragmented landscape of standards and protocols, involves establishing a unified and mandatory communication standard for smart appliances to ensure interoperability and seamless integration into the grid.

In conclusion, this research underscores the need for regulatory intervention and a structured approach to address the identified bottlenecks related to adopting smart appliances on the low-voltage electricity grid. Through regulatory clarity regarding the future roles and responsibilities, a unified communication standard, and a control-based congestion management approach, the Dutch low-voltage electricity distribution network can become more resilient and adaptive by integrating increasing levels of renewable energy and flexibility. This executive summary provides a concise overview of the research's main points, objectives, methodology, results, and recommendations for addressing the Netherlands' low-voltage grid congestion. Future research should focus on incorporating social factors into theoretical frameworks to address data sharing in the energy system context. In addition, future studies should assess the best standards for smart appliances in the Dutch energy system. Moreover, the trade-offs involved in regulatory intervention on the low-voltage grid should be further mapped and considered for policy design.

Contents

Preface 4
Executive Summary 5
The Dutch Energy System 13
1.1. Layers of the Electricity Network 13
1.2. Roles and responsibilities 16
1.2. Liberalization of the Dutch electricity sector 17
Introduction 19
2.1. Targets & Electrification 19
2.2. Grid characteristics 20
2.3. Low-voltage congestion 21
2.4. Flexibility 22
Literature Review 24
3.1. Definition of core concepts 24
3.1.1. Renewable energy sources 24
3.1.2. Congestion 25
3.1.3. Demand response 25
3.1.4. Smart appliances 25
3.2. Search strategy 26
3.3. Literature review 28
3.4. Knowledge gap 29
Methodology 32
4.1. Sub-Question 1: *Exploratory approach* 32
4.1.1. Participant selection 33
4.1.2. Data collection method 34
4.1.3. Data analysis & bottleneck selection 34
4.1.4. Ethical considerations 35
4.1.5. Limitations of the methodology 35
4.2. Sub-Question 2*: Analysis of the results* 36
4.3. Sub-Question 3*: Recommendations* 36
Results 38
5.1. Participant selection 38
5.2. Interview results 40

    - 5.2.1. Bottleneck 1: The roles in the future energy system are not defined 40
    - 5.2.2. Bottleneck 2: There margins for households are too thin 42
    - 5.2.3. Bottleneck 3: Appliances can't communicate. 43
    - 5.2.4. Bottleneck 4: Data sharing 43
    - 5.2.5. Bottleneck 5: Novelty of the problem 44
    - 5.2.6. Bottleneck 6: Communication 44
    - 5.2.7. Bottleneck 7: Ease 45
    - 5.2.8. Bottleneck 8: Education 45

Theory 47

  - 6.1. Technical criticality in infrastructures 47
  - 6.2. Critical transactions 48
  - 6.3. Modes of organization 49
  - 6.4. Differences Across infrastructures and Over Time 50

Analysis 51

  - 7.1. Electricity sector analysis 51
    - 7.1.1. Identifying Critical Technical Functions 51
    - 7.1.2. Critical Transactions 52
    - 7.1.3. Changes in the electricity sector over time 53
  - 7.2. Bottleneck analysis 55
    - 7.2.1. Defining Criticality 55
    - 7.2.2. Bottlenecks and Critical Transactions Theory 56
  - 7.3. Evaluation of Theory's Comprehensiveness 59
    - 7.3.1. Scope of Control and the Speed of Adjustment 59
    - 7.3.2. Modes of organization 60
    - 7.3.3. Data Sharing 61

Recommendations 63

  - 8.1. Mechanisms for integrating flexibility 63
  - 8.2. Roles in the future energy system are unclear 65
  - 8.3. The Margins for Households 66
    - 8.3.1 Control-Based Congestion Management Framework 68
  - 8.4. Appliances can't communicate. 70

Discussion 72

  - 9.1. Findings and interpretation 72
    - 9.1.1. Findings 72
    - 9.1.2. Interpretation of findings 73

9.2. Potential Limitations 74
  9.2.1. Scope of interview participants 74
  9.2.3. Interpretation of interviews 75
  9.2.4. Validity of the research 76
Conclusion 78
10.1. Main research question 78
10.2. Reflection 81
  10.2.1 Academic relevance 81
  10.2.2. Societal relevance 81
  10.2.3. Future work 82
  10.2.4. CoSEM alignment 82
  10.2.5. Personal reflection 83
  10.2.6. Final thoughts 83
References 85
Appendix 94
Interview Summaries 94
List of all Bottlenecks 100
Merged Bottlenecks 104
Process of selecting the bottlenecks 105

List of figures

Figure 1: operating regions for DSOs in the Netherlands..

Figure 2: physical layers of the electricity grid 15

Figure 3: roles of key stakeholders 16

Figure 4: vertically-integrated monopoly (left) and liberalized power sector (right) (Battle & Ocana, 2013) 18

Figure 5: Electricity production by source (CBS, 2024) 19

Figure 6: Electrification in the Netherlands for road transport, space heating and hot water (CBS, 2022)... 20

Figure 7: Number of households at risk due to low-voltage congestion (Probleemanalyse congestie in het laagspanningsnet; Ministerie van Economische Zaken en Klimaat, 2024b)......21

Figure 8: range of solutions for incentivizing demand response (Ministerie van Economische Zaken en Klimaat, 2023b) 23

Figure 9: Organizational requirements in parenthesis (Kunneke et al., 2010)........................... 49

Figure 10: Identified bottlenecks and corresponding scope of control and speed of adjustment. 56

Figure 11: Congestion Management mechanisms (Hennig et al., 2023)..................................... 64

Figure 12: Modified Congestion Management mechanisms framework.................................... 69

Figure 13: Control-based mechanisms enlarged. 69

List of tables

Table 1: keywords used 27

Table 2: inclusion and exclusion criteria 28

Table 3: Literature Overview 31

Table 4: Interviews conducted 39

Table 5: Overview of bottlenecks 46

Table 6: Critical Transactions in the electricity sector 53

List of Abbreviations

RES	Renewable energy sources
PV	Photovoltaic
EV	Electric vehicles
TSO	Transmission System Operator
DSO	Distribution System Operator
DR	Demand Response
CM	Congestion Management
DLC	Direct-Load-Control

1

The Dutch energy system

This section will give a general overview of the Dutch electricity system to serve as background information for the rest of the research. Section 1.1 will elaborate on how the physical layers of the electricity are segmented. Section 1.2 will elaborate on the roles and responsibilities of the key players operating at these levels. Lastly, section 1.3 will discuss the history of the Dutch electricity grid as well as its unbundling.

1.1. Layers of the electricity network

The electricity grid is a complex network that encompasses the generation, transmission, distribution, and retailing of electricity, ultimately serving the demands of the end users (Tanrisever et al., 2015). Each segment in this chain plays a crucial role in ensuring a reliable and efficient supply of electricity from production to consumption.

Generation

Generation refers to the production of electricity from various energy sources. Power plants, which may use fossil fuels (coal, natural gas, oil), nuclear energy, or renewable sources (solar, wind, biomass, hydro), are the primary sources of electricity generation. In conventional power plants, fuel is burned to produce steam that drives turbines connected to generators. It is relatively easy to ramp power plants up or down and adjust their generation to the current demand. When producing energy through renewable sources, natural forces such as wind, sunlight, or water flow drive turbines or photovoltaic cells to generate electricity directly (Kosmadakis et al., 2013). Energy generation through renewable sources is dependent on external factors such as the weather or seasonal fluctuations, meaning its production cannot be adjusted to match demand. Electricity cannot be stored. When converted to energy it can be stored, however, but not in large quantities. This would also require a conversion. Therefore, a critical aspect of electricity generation is the need to balance the load. This requires continuous adjustment of the generation output to match the demand, ensuring the stability of the grid. As soon as the electricity is produced, it must be transported to the end-users through transmission and or distribution.

Transmission

Transmission involves the high-voltage transport of electricity from power plants to substations located near populated areas. High-voltage power lines are used to transmit large quantities of electricity. Substations play a crucial role in this process, as step-up substations increase the voltage for efficient transmission, while step-down substations decrease the voltage for safe distribution (Tanrisever et al., 2015). Transmission System Operators (TSOs) manage the high-voltage grid to ensure stability, reliability, and facilitate cross-border electricity flows. High-voltage levels are voltage levels of 25,000 Volt or higher. Stepping down the voltage level, medium voltage is used and is classified at Voltage levels between 1,000 Volt and 25,000 Volt. For safe distribution, low voltage is used. Low-voltage are the voltage levels of 1,000 or lower.

Distribution

Distribution entails the process of transportation of electricity from substations to end-users. This distribution segment utilizes medium- and low-voltage lines which distribute electricity to end-users, like households, businesses, and industries. Distribution networks cover smaller geographic areas compared to transmission networks, and include infrastructure such as poles, transformers, and wiring systems (Tanrisever et al., 2015) . Distribution System Operators (DSOs) are responsible for operating and maintaining the distribution network, ensuring the reliable electricity supply to consumers. DSOs in the Netherlands are divided per region, where each DSO operates in its own region (Figure 1).

Figure 1: operating regions for DSOs in the Netherlands

Retail

Retailing involves selling electricity to consumers through the provision of customer services. Energy retail suppliers purchase electricity on the wholesale market and sell it to end-users. In doing so, they handle billing, customer service, and additional services like sustainability- and energy efficiency advice. In markets with liberalized energy systems, like the Netherlands, consumers have the freedom to choose their energy supplier based on factors such as price, service quality, and options regarding renewables (Hennig et al., 2023).

Demand

The segment of demand refers to the consumption of electricity by end-users. This includes residential households, commercial businesses, and industrial complexes. The usage patterns vary per consumer type, with industrial end-users typically having more consistent and higher usage, while residential demand peaks in the morning and the evening (Tanrisever et al., 2015). End-users are encouraged and sometimes incentivized by the DSO to shift their load to reduce their electricity consumption during peak hours. Mechanisms in doing so are elaborated on in section 2.4.

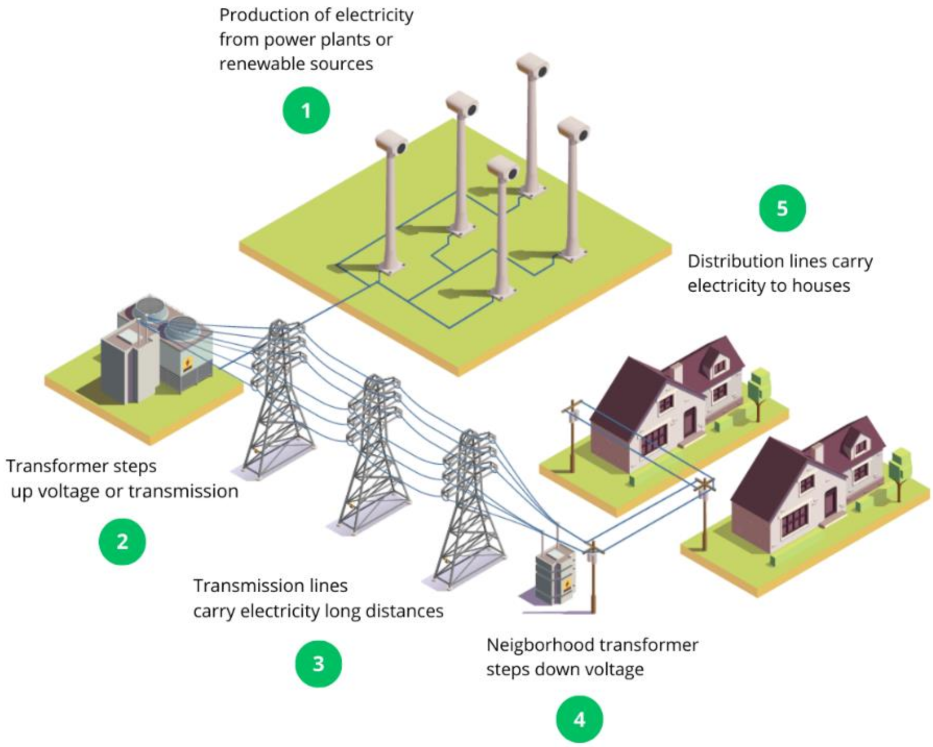


Figure 2: physical layers of the electricity grid

1.2. Roles and responsibilities

Across these layers, different roles and responsibilities of the relevant stakeholders apply. Below, the roles and responsibilities of the most important players within this domain will be described briefly.

Network operators: or system operators, are key players and responsible for maintaining the reliable and secure operators of the electricity grid. In doing so, they monitor the system's performance, ensuring the grid meets the demand from end-users (Hennig et al., 2023). In the Netherlands, there exists one grid operator on the transmission network, the TSO, and multiple grid operators on the distribution network, the DSOs.

Consumers: or end-users, are active in the distribution grid, at the end of the low-voltage network. These end-users are obligated to pay network tariffs to the network operator and retail prices for electricity to their retail provider, in line with their consumption. In addition, the network operator may have other contractual mechanisms to mitigate congestion. These can involve agreements with individual end-users to adapt and shift their consumption to reduce peak demand. These agreements can also be with aggregators or retail providers, who may contain mechanisms to control end-user loads in accordance with the desires of the network operator (Hennig et al., 2023).

Retail providers: purchase and sell electricity on the markets. This can be either the day-ahead market, the intraday market, or through long-term bilateral agreements with large end-users (Hennig et al., 2023). Retail providers can offer retail rates through fixed prices or a dynamic retail contract, which can take multiple forms, which have been introduced in the Dutch electricity market in 2023 (Proctor, 2023)

National regulators: are responsible for regulating the network operators. Among this responsibility, the regulator must assess the investments and revenues from tariffs and determine if these are adequate (Hennig et al., 2023).

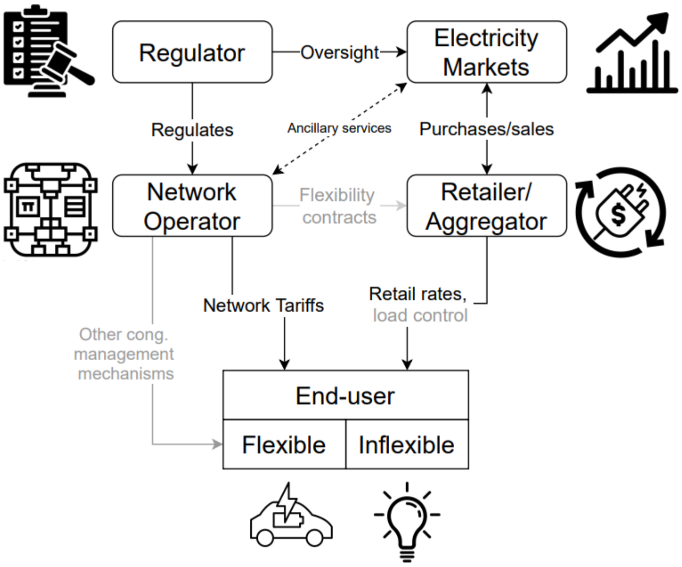


Figure 3: roles of key stakeholders (Hennig et al., 2023)

1.2. Liberalization of the Dutch electricity sector

The unbundling of the Dutch electricity sector has been a process influenced significantly by both national policy and directives from the European Union. This transformation has shaped the sector with the goal to foster competition, enhance grid reliability, and pave the way for a more sustainable energy future (Damme, 2005). This section provides an overview of the Dutch liberalization process to provide context to its continuous development but path dependency.

Pre-unbundling

Before the 1900s, the Dutch energy sector was dominated by vertically integrated monopolies. Utilities that were state-owned controlled the generation, transmission, distribution, and supply of electricity. This monopolistic structure meant there was no competition, and consumers had no choice in their energy supplier. Since the sector was heavily regulated, prices were controlled, and planning was performed centrally (Damme, 2005).

Initial steps towards unbundling

In the 1900s, driven by the European's efforts to create a single, competitive energy market, the push for unbundling began. The EU issued directives that were aimed at liberalizing the energy market across its member states. In response, the Dutch government introduced the Electricity Act (1998), which marked the first steps towards liberalization. This Act mandated the separation of generation and supply activities from network operations, although full ownership unbundling was not yet implemented. In 1999, the market began to open up gradually, allowing large industrial consumers to actively choose their suppliers. This choice was extended to all consumers by 2004 (Damme, 2005).

Full-unbundling

The EU's Second Energy package in 2003 underscored the need for further unbundling to eliminate conflict of interest and enhance competition. In response to this, the Dutch government enacted the Independent Network Operation Act (Wet Onafhankelijk Netbeheer, WON) in 2006. This law required the full ownership unbundling of energy companies. This mandated the separation of network operations from commercial activities (Damme, 2005).

Implementation of ownership unbundling

From 2008 to 2010, the energy companies faced a deadline to comply with the new unbundling requirements, necessitating significant restructuring within the industry. Companies like Essent and Nuon resisted their requirement, which led to legal disputes. However, eventually the Dutch Supreme Court upheld the unbundling legislation (Damme, 2005).

Post-unbundling

By 2011, most of the Dutch major energy companies had completed the process of unbundling. Essent and Nuon, for example, had separated their network operations into independent entities (Enexis and Alliander, respectively). This period experienced continued efforts to liberalize the energy market, promote renewable energy, and improve grid efficiency. The introduction of smart grids and advanced metering infrastructure further enhanced competition and consumer choice (Damme, 2005).

Initial steps towards unbundling

The unbundling of the Dutch energy sector has led to increased competition, where multiple suppliers contend for customers. Customers now also have the freedom to choose their energy provider, which was implemented with the goal of better service and more competitive pricing. This separation of network operations from commercial activities has ensured non-discriminatory access to the grid for all market participants, which fosters innovation and investments in renewables. Currently, the Netherlands is one of the few countries that has fully opened up its electricity market to competition (Tanrisever et al., 2015).

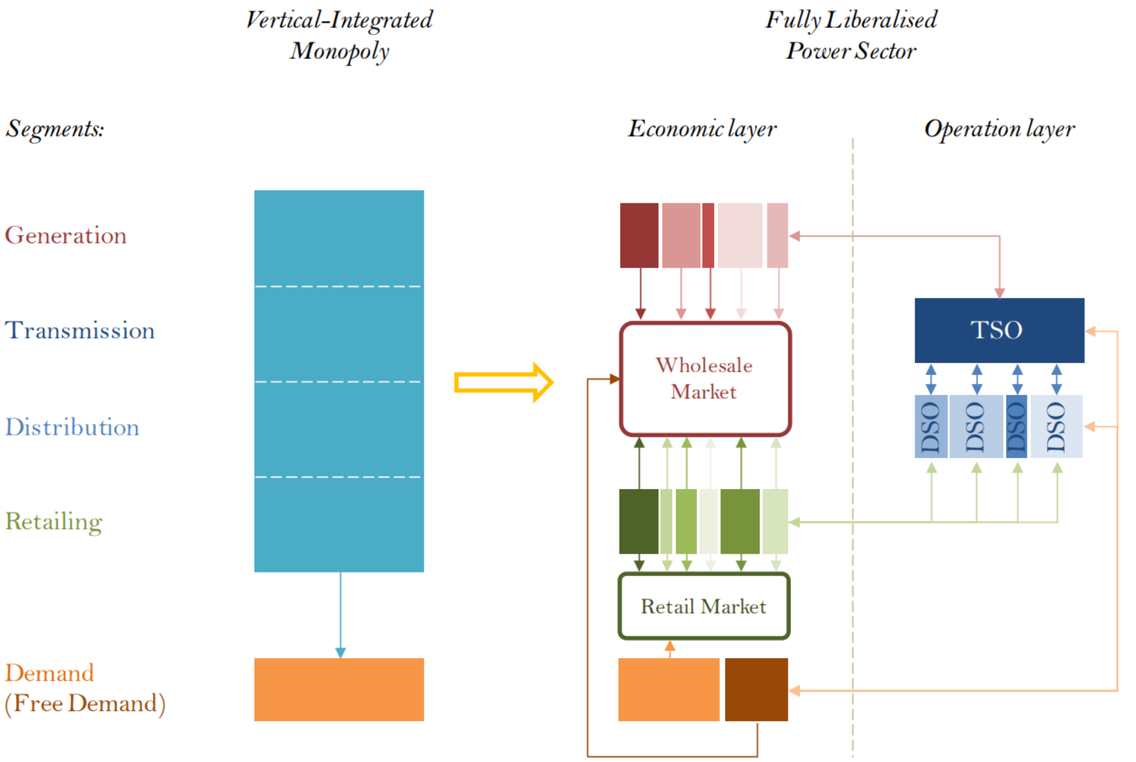


Figure 4: vertically-integrated monopoly (left) and liberalized power sector (right) (Battle & Ocana, 2013)

2

Introduction

2.1. Targets & electrification

The Netherlands, among many nations around the world, has recognized the urgent need to combat climate change and transition towards a more sustainable and resilient energy system. According to the Intergovernmental Panel on Climate Change (IPCC), high risks of severe damage to the climate exist when not limiting global warming to 2 degrees Celsius or below by 2050, resulting in severe weather effects, biodiversity loss, food and water security risks, health risks and significant impact on the economy (Climate Change 2022, Impact, adaption, and vulnerability, z.d.). In response to growing concerns over greenhouse gas emissions, the Dutch government has set ambitious climate targets of a 55% reduction in greenhouse gas emissions in 2030 compared to 1990 levels while simultaneously targeting to increase the share of renewable energy production to 70% of the total electricity mix by 2030 (Ministerie van Economische Zaken en Klimaat, 2022). The goals of the Netherlands are also in line with the European Union's climate targets and the global commitments under the Paris Agreement (2030 Climate targets, z.d.)

To achieve these goals, legislation in the Netherlands has increasingly favored the development of renewable and decentralized energy projects (Salet, 2021). This has resulted in that in 2023, nearly half the electricity produced in the Netherlands was renewable (CBS, 2024; Figure 2). The production of electricity from renewable sources increased to 57 billion kWh in 2023, going up with 35% compared to 2022 (Figure 2).

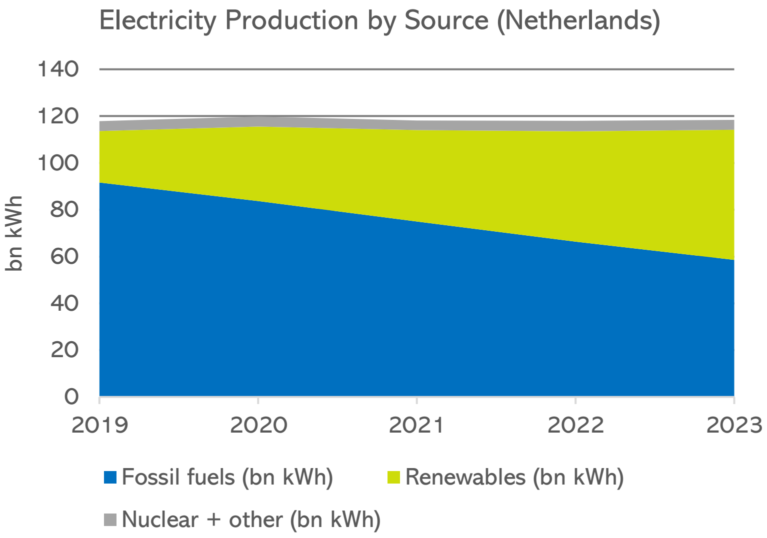


Figure 5: Electricity production by source (CBS, 2024)

In addition to increasing the share of renewable energy production, the Netherlands also focuses on the electrification of demand as a critical component of its climate strategy (Moraga-Gonzalez & Mulder, 2018). This electrification involves shifting the energy consumption from fossil-based sources to electricity particularly from renewables. This electrification of demand has led to a significant electrification in the major sectors of transportation and heating (Figure 3 ; CBS, 2022).

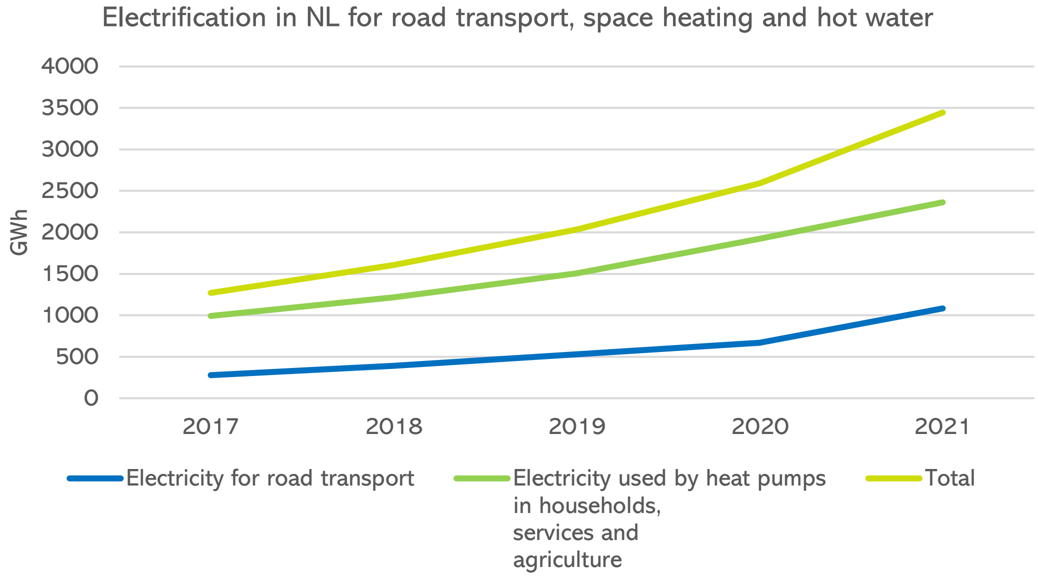


Figure 6: Electrification in the Netherlands for road transport, space heating and hot water (CBS, 2022)

Since electrification facilitates the shift away from fossil fuels towards cleaner energy sources, this transition is essential for reducing carbon emissions and combatting climate change. However, the fast pace of this transition has also introduced significant challenges for the electricity grid, notably congestion, which occurs when particular areas of the grid are overloaded with power due to disproportionate feed-in or take-off of electricity (Van Westering & Hellendoorn, 2020).

2.2. Grid characteristics

As explained in section 1, the electricity grid was designed for centralized, unidirectional flows from large power plants to consumers. Increasing penetration of decentralized energy technologies such as Solar PV, vehicle-to-grid technology, and storage systems introduces bidirectional flows, where electricity also flows from decentral technologies back into the grid.

Next to this, renewable energy like solar power and wind power is often produced in remote and rural areas. While the availability of resources like wind and sunlight is abundant in these places, the grid is often designed for merely transporting electricity to a few connected end-users. Therefore, the grid is most of the time not suitable for transporting large amounts of electricity production within these areas (Thomaidis, 2016).

These characteristics of the electricity grid design, combined with the decentralized and intermittent nature of renewable energy generation, make it increasingly difficult to balance and coordinate demand and supply. This results in congestion, where electricity demand exceeds the capacity of the power grid to supply it, which already exists on the medium- and high-voltage levels (Van Blijswijk & De Vries, 2012).

2.3. Low-voltage congestion

Traditionally, congestion has been a challenge associated with high-voltage and medium-voltage levels, where large-scale transmission of power occurs (Van Blijswijk & De Vries, 2012). However, this landscape is expanding as low-voltage grids, which are the final link in supplying electricity to households, are now facing significant congestion issues.

While congestion at all levels poses challenges, addressing the low-voltage congestion is often considered the most critical in the short-term, due to the quality-of-life impacts on end-users (Ministerie van Economische Zaken en Klimaat, 2024b). If low voltage congestion is not addressed in the short-term, 1.5 million small-scale consumers are at risk of being affected by too low- (Undervoltage) or too high voltage levels (Overvoltage), and even outages by as soon as 2026 (Figure 4; Ministerie van Economische Zaken en Klimaat, 2024b).

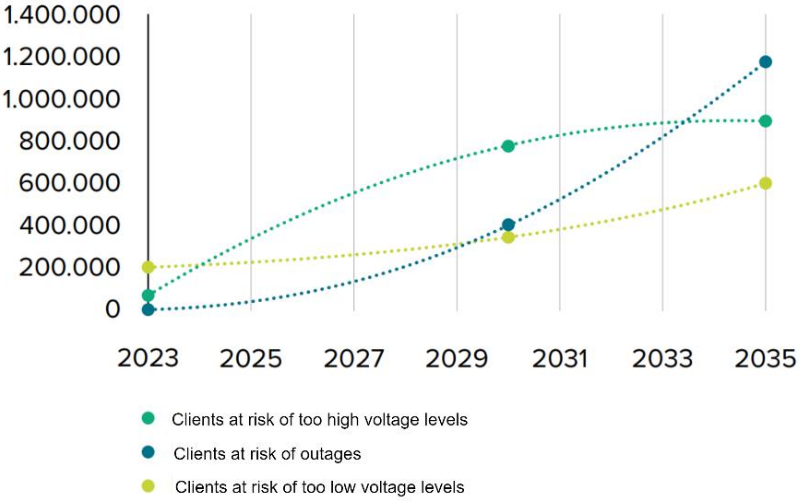


Figure 7: Number of households at risk due to low-voltage congestion (Probleemanalyse congestie in het laagspanningsnet; Ministerie van Economische Zaken en Klimaat, 2024b)

Undervoltage occurs when the electricity demand exceeds the system’s ability to supply it, resulting in insufficient voltage being delivered to the end-users. Complications of undervoltage could include flickering lights, malfunctioning appliances, or even damage to sensitive equipment. Overvoltage exists when there is an excess supply of electricity, which is often due to the high feed-in from decentralized renewable sources like solar panels. Overvoltage can result in damage to electrical devices or reduce their lifespan. Overloading the distribution network can cause cables and transformers to overheat, which potentially leads to equipment failure and even power outages. As the distribution network is increasingly integrated by high-consumption devices, like heat pumps and electric vehicles, the risk of overloading becomes more pronounced.

Low-voltage congestion in the Netherlands is a relatively new challenge compared to congestion at high-voltage and medium-voltage levels or compared in other countries like the United Kingdom, where low-voltage congestion has been an issue for a longer amount of time (Petrou et al., 2015).

Compared to the low-voltage grid, the high-voltage grid is equipped with advanced monitoring systems that provide real-time data on voltage levels, the current flow, and system performance (Moldoveneanu et al., 2010). In addition, the high-voltage grid has fewer but larger connections compared to the low-voltage grid. It typically connects major power plants, substations, and large industrial consumers (Pawar et al., 2021). Moreover, the high-voltage grid contains more substantial technical reserves, such as spinning reserves and standby generation capacity, which can quickly be mobilized to maintain grid stability during fluctuations in supply and demand. The advanced monitoring equipment, small number of connections, and technical reserve reduce the complexity of managing the high-voltage grid compared to the low-voltage grid (Pawar et al., 2021).

In contrast to the high-voltage grid, each low-voltage grid is unique and, therefore, more complex to manage. In addition, the low-voltage grid now must handle bidirectional flows, decentralized production, and the intermittent nature of renewable energy production. This complicates grid management and requires new approaches to ensure stability and reliability.

2.4. Flexibility

Mitigating congestion on the low-voltage grid can be addressed in two ways: grid reinforcements – increasing the physical amount of distribution lines – or utilizing the existing grid more efficiently, enabling better coordination between supply and demand. However, the required grid reinforcements are too large to be realized in a timely manner, considering the short-term risk for low-voltage congestion, according to current practices. This is mostly due to insufficient availability of labor, materials, and capital (Ministerie van Economische Zaken en Klimaat, 2024b). Therefore, the Dutch government mainly aims to tackle congestion through the second option, which is stimulating more efficient use of the grid.

Household flexibility can play a significant role in mitigating congestion issues on the low-voltage grid. It refers to the system's ability to adjust and respond to energy supply, demand, or grid congestion changes. This includes generation flexibility (ramping up and down power plants), storage solutions (e.g., batteries, pumped hydrogen), and demand-side management (e.g., demand response).

Demand response, a subcategory of flexibility, specifically refers to the strategies and programs managed to alter the consumption patterns of end-users, the consumers, to match the grid's supply. This involves adjusting consumers' electricity usage in response to signals or incentives from the system operators. The DSO can incentivize consumers to adjust their load in several ways, ranging from mild and preventive measures like communication strategies, connection conditions, or dynamic retail rates to more drastic and reactive measures such as market-based solutions or direct curtailment.

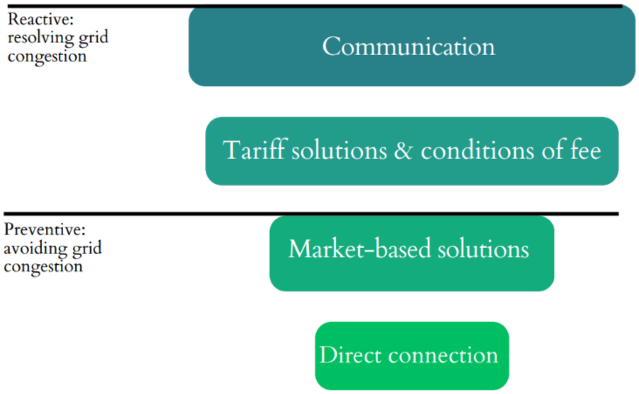


Figure 8: range of solutions for incentivizing demand response (Ministerie van Economische Zaken en Klimaat, 2023b)

Household demand response can play a significant role in mitigating congestion issues on low voltage. Demand response can be enabled through smart appliances, which are household devices or appliances equipped with advanced features and functionalities that allow them to communicate with other devices and be controlled remotely (Ministerie van Economische Zaken en Klimaat, 2023).

Utilizing smart and controllable devices, households can adjust their electricity consumption patterns to align with grid needs, enhancing overall grid stability. Key appliances include smart thermostats and heat pumps, which can adjust heating and cooling settings based on real-time grid conditions (Zhou et al., 2016). In addition, electric vehicles are equipped with batteries that can be charged during off-peak hours. Advanced vehicle-to-grid (V2G) technology even allows the EVs to discharge some of the electricity back into the grid during peak demand, functioning as a distributed energy source. Moreover, smart household appliances such as washing machines, dryers, and dishwashers can be programmed to run during off-peak times, or can even be controlled remotely or scheduled to operate when the electricity demand is low (Zhou et al., 2016).

To effectively address congestion on the low-voltage grid and with the timeline of the associated risks involved, it is important to explore further the role of smart, flexible assets in households. The capabilities of smart appliances to facilitate demand response strategies make it particularly interesting to look further into the widespread adoption of smart appliances (Kolster et al., 2020). Exploring this topic should give insight into the role of shifting flexible demand in households in tackling congestion on the low-voltage grid and mitigating the associated risks described above.

3

Literature Review

Extensive literature research was conducted to ensure a comprehensive understanding of the available literature on low-voltage grid congestion and the role of flexible appliances within this energy domain.

3.1. Definition of core concepts

The fundamental concepts of the chosen academic field have to be defined and explained to identify the main topics and guide the discovery of a possible academic knowledge gap.

3.1.1. Renewable energy sources

Renewable energy sources are sustainable natural flows of energy that can be replenished over short periods of time. Unlike finite fossil fuels, which emit greenhouse gases that contribute to climate change, renewable energy sources are considered environmentally friendly and inexhaustible. Several types of renewable energy exist (Revel, 2011).

Solar energy is harnessed from the sun's radiation using photovoltaic cells that convert sunlight directly into electricity or through solar thermal systems, which use sunlight to heat fluids to produce steam for electricity generation. Solar energy is one of the most accessible and abundant forms of renewable energy, capable of being deployed on residential rooftops, commercial buildings, and even solar farms (Revel, 2011).

Wind energy is generated by converting kinetic energy from wind current into electrical power using wind turbines. Wind farms can be onshore or offshore, with offshore installations benefiting from stronger and more consistent winds. Due to its scalability and declining costs, wind energy is a rapidly growing energy source (Revel, 2011).

Hydropower, or hydroelectric power, is derived from the energy of moving water, typically harnessed by dams on rivers. The gravitational force of falling or flowing water spins the turbines, which generate electricity. Hydropower is one of the oldest and most established renewable energy sources, providing a stable and significant portion of global electricity (Revel, 2011).

Biomass energy originates from organic materials, such as plant and animal waste, which can be converted into biofuels like ethanol and biodiesel or burned directly for heat and power. Biomass can also be sourced from agricultural residues, forestry by-products, and dedicated energy crops. It is a versatile energy source that can contribute to reducing waste and managing carbon emissions (Revel, 2011).

Geothermal energy harnesses heat from beneath the Earth's surface to generate electricity or provide direct heating. Geothermal power plants use steam from hot water reservoirs found a few miles below the Earth's surface (Revel, 2011).

Ocean energy includes tidal energy, which exploits the rise and fall of sea levels; wave energy, which harnesses the energy from surface waves; and ocean thermal energy conversion, which utilizes the temperature difference between warmer surface water and colder deep water (Revel, 2011).

3.1.2. Congestion

Congestion, in the context of energy system systems, refers to the overloading of electrical grids when the electricity demand exceeds the transmission or distribution capacity. This can occur in peak demand periods or when there are constraints on the grid's infrastructure, preventing the smooth flow of electricity from generation sources to consumers. Congestion can lead to higher electricity prices, inefficiencies in the energy markets, and, in extreme cases, blackouts or brownouts (Hussin et al., 2006). Congestion in the electricity system is a complex challenge that arises from high demand periods, insufficient infrastructure, the integration of renewable and distributed energy sources, and market dynamics. It increases electricity prices, causes reliability issues, and results in inefficient energy distribution. Effective mitigation strategies include upgrading grid infrastructure, implementing demand response programs, integrating renewable energy with storage solutions, pursuing regulatory and market reforms, and leveraging smart grid technologies. Addressing congestion is critical for ensuring a reliable, efficient, and sustainable electricity system that meets future energy demands (Hussin et al., 2006).

3.1.3. Demand response

Demand response (DR) refers to programs and strategies designed to adjust consumer demand for power instead of adjusting the supply. It aims to incentivize or compel consumers to reduce or shift their electricity usage during peak periods or when the grid is under stress. Demand response, as a sub-group of flexibility, can be classified into incentive-based programs (ICP) and price-based programs (PBP). These two programs have been used as a standard when discussing demand response (Yang et al., 2008). Incentive-based programs use rewards or compensations to encourage specific behaviors or actions. Price-based programs adjust prices to influence consumers' behavior.

3.1.4. Smart appliances

Smart appliances play a pivotal role in enhancing the effectiveness of demand response programs within the energy system. Demand response refers to strategies and programs designed to adjust the demand for power instead of adjusting the supply, encouraging consumers to reduce or shift their electricity usage during peak periods or when the grid is under stress (Nagesh et al., 2010).

Smart appliances are equipped with advanced sensors, connectivity, and control systems, which allow them to respond dynamically to external signals, like from the grid. These appliances can automatically adjust their operation based on real-time information about electricity prices, grid conditions, or even DR initiatives. This ability to modulate energy consumption significantly helps to balance supply and demand and reduce grid congestion to enhance overall system reliability. Some examples of smart appliances are mentioned below.

Smart thermostats can adjust their heating and cooling settings in response to DR signals. For example, during periods of peak demand, a smart thermostat can pre-cool or pre-heat a home and then reduce the power usage during the peak period itself. This helps to flatten the demand curve and reduce the straining on the grid (Nagesh et al., 2010).

Smart water heaters can shift their heating cycles to off-peak times without impacting the availability of hot water. By heating water during times of low demand, they can store the thermal energy which can be used later, and so reduce the load during peak periods.

Smart washing machines and dishwashers can be programmed to operate during off-peak hours, either manually by the user or automatically in response to DR signals. This flexibility helps to distribute energy usage more evenly throughout the day.

While maintaining their primary function of preserving food, smart refrigerators can reduce their power usage during peak demand times by adjusting cooling cycles or temporarily increasing temperatures within safe limits.

Electric vehicle (EV) chargers can be scheduled to charge vehicles during off-peak hours or dynamically adjust charging rates based on grid conditions. This significantly helps manage the additional load EVs place on the grid and supports overall grid stability.

3.2. Search strategy

This research has identified relevant studies and gathered insights into the topic of the widespread adoption of smart appliances to mitigate short-term congestion on the low-voltage grid. A multi-step approach was adopted to ensure a thorough and comprehensive review of existing literature. Figure 9 visualizes the overall search strategy adopted.

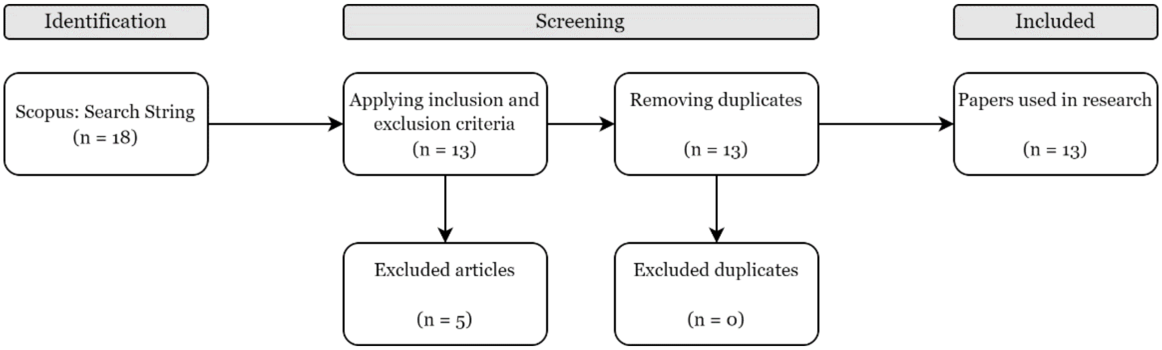


Figure 9: Search strategy used.

The initial step involved an extensive search of the Scopus database, chosen for its user-friendly interface and reputation as an effective, comprehensive, and trustworthy source. Scopus provides access to a vast array of academic journals, conference proceedings, and other academic sources, making it an ideal starting point for literature reviews.

After the initial broad search, a more focused and comprehensive search was conducted to delve deeper into specific aspects, such as congestion on the low-voltage network and data-sharing mechanisms. This step aimed to narrow down the scope to the most relevant and specific studies addressing the subject.

A set of keywords has been proposed to refine the search and identify relevant papers. These keywords were categorized to ensure a structured and comprehensive search. Table 1 provides an overview of the keywords used, organized by categories such as stakeholders, electricity, data, and the regulatory domain.

Stakeholders	**Electricity**	**Data**	**Regulatory**
Households OR household	Decentralized OR decentral	Data	Regulatory OR regulation
DSO OR Distribution System Operator OR Distribution Grid Operator	Low Voltage OR Low-Voltage Congestion Flexibility OR Flexible OR Demand-Response OR Demand Response OR DR	Smart-meters OR smart meters OR smart-meter OR smart meter OR smart appliances	Policy OR policies

Table 1: keywords used

The search string was constructed by combining all cells from this with the AND operator. Within the cells, OR operators have been used to indicate similar concepts. This resulted in the following search string:

Scopus

- DSO OR distribution system operator AND households OR household AND low-voltage OR low voltage AND congestion AND flexibility OR flexible AND demand-response OR demand response OR DR AND decentralized OR decentral AND smart meters OR smart-meters OR smart-meter OR smart meters OR smart appliances AND data AND regulation OR regulatory AND policies OR policy

After applying the search string to the Scopus database, exclusion and inclusion criteria have been applied to filter the results for relevance to the research. The selection criteria aim to ensure the inclusion of relevant papers on the subject. Table 2 provides an overview of inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Discuss low voltage electricity congestion and data sharing	No open online access
Findings are applicable to research	Not in the English language

Table 2: inclusion and exclusion criteria

The literature search aimed to encompass a wide range of relevant studies, following a systematic approach. This provided a comprehensive foundation for the subsequent analysis and findings. Table 3 provides an overview of the articles resulting from the search strategy and, therefore, selected for the literature review.

3.3. Literature review

This literature review focuses on the flexible potential of household appliances in mitigating congestion on the low-voltage network. Due to the urgency of addressing low-voltage congestion in the short term and the risks associated with it, this subject has been a hot topic for research. Preliminary studies have been carried out within this domain, and thirteen papers have been selected for further analysis.

Existing literature often discusses the integration of renewables from a computational point of view. Tushar et al. (2022) discuss the interaction of cyber-physical systems using game theory. Zaini et al. (2023) discuss Particle Swarm Optimization (PSO) based methods and explore their usage within demand side management. Both papers discuss the integration of renewable energy but merely in the context of algorithm optimization. Thasnimol et al. (2020) discuss the role of multi-agent systems in the connection of smarter distribution grids, after explaining the history of the development of smart distribution grids. While this research provides context to the development of smart grids and the interaction between agents, it still only touches upon the subject from a computational view.

Sharda et al. (2021) further dives into the integration of renewables and even elaborates on load shifting and the concept of Demand Response Management (DRM). In doing so, the paper discusses the challenges and opportunities in implementing DSM, but mainly in the context of the Internet of Things (IoT). Assad et al. (2022) also dives into Demand Response Optimization and reviews computational methods for optimizing Demand Response Programs. While most of these papers described above relate to the electricity grid and load-shifting methods, they also aim to give more insight into this subject by providing algorithms or computational-based methods like the Internet of Things, which falls out of the scope of this research.

Other existing literature focuses more on regulatory, technological, and behavioral aspects of load shifting within electricity distribution. Alpizar-Castillo (2022) and Gulotta et al. (2023) focus on the ancillary markets within the electricity grid, like providing balancing and redispatching. Gulotta et al. (2023) provide an in-depth analysis of the integration of distributed energy resources into Ancillary Services Markets (ASMs), but in doing so, focus merely on ancillary services. Carreiro et al. (2017) also focus on the ancillary services market and mainly on how end-users can contribute to providing ancillary services through Energy Management System Aggregators. Alpizar-Castillo et al. (2022) also focus on the ancillary services market by introducing storage facilities and their potential role in these markets.

Other existing literature focuses more on demand response and flexibility within the electricity distribution network and its effects on low-voltage congestion. Davarzani et al. (2021) and Grzanic et al. (2022) both give comprehensive overviews of DR programs and categorize several DR strategies in doing so. Grzanic et al. (2022) provide a systematic review of demand-side management models and highlight the roles of consumers as market participants. Davarzani et al. (2021) also overview DR mechanisms and categorize DR programs into incentive-based and price-based schemes. In doing so, Davarzani et al. (2021) also highlight the role of local communities and consumers in providing flexible demand. While Davarzani et al. (2021) and Grzanic et al. (2022) dive deeper into DR to address congestion, they merely provide an overview of DR programs, which they also classify.

Honarmand et al. (2021) give more insight into DR by elaborating on the potential for economic, grid-oriented, and socio-environmental aspects. In doing so, the research highlights the barriers and enablers for realizing the potential of DR. Plaum et al. (2022) focus on flexibility in the residential energy domain, mainly on the aggregators' role. Next to the value of aggregators providing flexibility, the paper focuses on quantification methods of energy flexibility, forecasting techniques, market opportunities, and challenges faced by aggregators entering the market. Ghaili et al. (2023) provide the most insight on the topic of DR and its potential. The paper offers a thorough examination of the current state of research on DR in smart grids, focusing on connected buildings. In doing so, the papers identify knowledge gaps in the literature, guiding future research efforts toward policy decisions.

3.4. Knowledge gap

As the analysis above has revealed, most research papers identify the technical potential of demand-response programs to mitigate congestion. Analyzing computational applications within the energy domain addresses the role of demand-side management in mitigating congestion on the low-voltage network. In this context, technical potential refers to the contribution that flexible technologies and appliances can make to mitigate congestion based purely on their technical capabilities (Alpizar-Castillo et al., 2023). While these papers indicate that demand-response management, enabled by smart and flexible appliances, often has significant potential to mitigate congestion effectively, widespread adoption is still lacking due to other factors within the socio-technical system, like financial or regulatory barriers (Al-Ghaili et al., 2023).

Al-Ghaili et al. (2023) suggest that future research should explore the impact of regulatory frameworks governing smart appliances and demand response programs, assess the effectiveness of existing regulations in incentivizing consumer participation, and identify regulatory barriers to integrating demand-side resources in the energy market. Honarmand et al. (2021) suggest future research directions should focus on evaluating the alignment between regulatory policies and technological advancements, examining the role of regulators in promoting grid modernization and energy efficiency and supporting the transition towards a more sustainable and resilient energy system. Honarmand et al. (2021) and Al-Ghaili et al. (2023) also emphasize the need for further research on integrating smart appliances and demand response in the context of sustainable energy practice. They indicate that successful implementation is currently limited and underscore that further research should investigate the barriers hindering the widespread adoption of smart appliances to enable demand response initiatives.

To address this knowledge gap, this research will aim to identify additional barriers to the widespread adoption of smart appliances to enable demand response. In doing so, the research addresses demand response to mitigate the low-voltage congestion issues described in section 2. To identify the essential challenges involved and how these should be addressed, an appropriate research question should be answered. Therefore, the following research question has been formulated:

How can demand response be enabled to mitigate congestion on the low-voltage network?

To address this question, the first part of the research question aims to identify the barriers limiting the adoption of smart appliances. Second, the research will aim to address these barriers and alleviate the bottlenecks.

Table 3: Literature Overview

Title	**Author**	**Year**	**Found**
A Systematic Review on Demand Response Role Toward Sustainable Energy in the Smart Grids-Adopted Buildings Sector	Al-Ghaili et al.	2023	Search string
Assessing the Role of Energy Storage in Multiple Energy Carriers toward Providing Ancilarry Services: A Review	Alpizar-Castillo et al.	2023	Search string
Smart Grid, Demand Response and Optimization: A Critical Review of Computational Methods	Assad et al.	2023	Search string
Energy management systems aggregators: a literature survey	Carreiro et al.	2017	Search string
Residential Demand Response Strategies and Applications in Active Distribution Network Management	Davarzani et al.	2021	Search string
Renewable and Sustainable Energy Reviews	Grzanic et al.	2022	Search string
Opening of Ancillary Service Markets to Distributed Energy Resources: A Review	Gulotta et al.	2023	Search string
An Overview of Demand Response: From Its Origins to the Smart Energy Community	Honarmand et al.	2021	Search string
Aggregated demand-side energy flexibility: A comprehensive review on characterization, forecast and marketing prospects	Plaum et al.	2022	Search string
Demand side management through load shifting in IoT based HEMS: Overview, challenges and opportunities	Sharda et al.	2021	Search string
The Paradigm Revolution in the Distribution Grid: The Cutting-Edge and Enabling Technologies	Thasnimon et al.	2020	Search string
A Survey of Cyber-Physical Systems From a Game-Theoretic Perspective	Tushar et al.	2022	Search string
A Review on the Applications of PSO-Based Algorithm in Demand Side Management: Challenges and Opportunities	Zaini et al.	2023	Search string

4

Methodology

This section aims to formulate an approach to answering the research question. The methodology developed, should be appropriate to answer the research question in a comprehensive manner. When dissecting the research question, three main components can be identified. First, the critical bottlenecks related to implementing smart appliances on low-voltage grids will be identified. Second, these bottlenecks will be analyzed through academic theory to logically explain them from a scientific point of view. Third, recommendations for alleviating these bottlenecks with respect to scientific theory will be provided.

To define a research design, what should be known and done to answer the research question should be considered. To answer the research question in a comprehensive manner, three sub-questions, each linked to a research component, have been developed:

1. *What critical bottlenecks exist for adopting flexible appliances on the low-voltage network?*
2. *How can these bottlenecks be explained?*
3. *How can these bottlenecks be alleviated?*

Based on the three main components and sub-questions identified, this research can be viewed as exploratory, followed by a thorough analysis of the results and eventually recommendations.

Section 4.1 will explain the explorative part of the research. Section 4.2 will elaborate on using abductive reasoning to analyze the results from the first part, as well as evaluating the theory for its ability to explain the results. Section 4.3 will discuss how the recommendations will follow from the identified results and analysis.

4.1. Sub-Question 1: *Exploratory approach*

The first part of the research entails a qualitative explorative approach aimed at identifying bottlenecks related to the widespread adoption of flexibility on the low-voltage grid (Hunter, 2018). Semi-structured interviews with stakeholders and industry experts within the Dutch energy domain have been conducted to explore these bottlenecks. First, the selection methods for participants will be elaborated on. After this, the interview questions, data collection methods, and data analysis methods, and limitations of this approach will be discussed.

4.1.1. Participant selection

The participants should be selected accordingly to ensure a comprehensive overview of perspectives on the scope in question, the low-voltage congestion network. As discussed in Section 1, the low-voltage grid entails the distribution network, which involves system operators, retail parties, end-users, and additional service providers, which could be system operators but often exist other parties. Therefore, the participants should consist of:

- *System operators*
- *Retail providers*
- *End-users*
- *Service providers*

In addition, to ensure a comprehensive overview of perspectives, the TIP framework (Bots, 2012) has been used to complement the participant selection process. The TIP framework is a common research methodology within the TU Delft Faculty of Technology, Policy, and Management and aims to approach complex socio-technical problems through multiple lenses. The TIP framework stands for:

- *Technical systems*
- *Institutions*
- *Decision-making processes*

These lenses are used to comprehensively structure design activities related to socio-technical systems (STS). The framework emphasizes the relationship between technical components, institutional rules that govern human behavior, and decision-making processes within STS design. By ensuring the comprehensiveness of perspectives in complex systems, this framework adds value to the participant selection process.

To complement the TIP framework, two additions have been made to the framework to strengthen its comprehensiveness in the specific context of the low-voltage distribution grid. First, the category of 'costs' has been added as a lens to the framework. This decision has been made based on the scientific literature on motives and barriers for end-users to integrate flexibility, which stated financial savings and incentives as one of the main drivers (Li et al., 2012). Second, in the context of the TIP framework, the Institutional category encompasses 'soft' and 'hard' institutions. Soft institutions in this framework relate to rules of behavior, norms, and shared strategies among stakeholders. Hard institutions refer to regulations like agreements and contracts. To better isolate the identified results, the institutional category has been split up into a social category, relating to soft institutions, and a regulatory category, relating to hard institutions.

To summarize the participant selection methodology, stakeholders from each category should be involved, while they collectively should satisfy all lenses identified relevant for doing research in the specific socio-technical system of the low-voltage grid.

Stakeholders:

- *System operators*
- *Retail providers*
- *End-users*
- *Service providers*

Lenses:

- *Technical systems*
- *Regulatory*
- *Social*
- *Decision-making processes*
- *Financial*

This section elaborates on the factors considered for selecting the interview participants. The participants selected are showcased and discussed in section 5.1.

4.1.2. Data collection method

Semi-structured interviews have been conducted to analyze the perspectives of the interview candidates on the situation on the low-voltage grids. Interviews are a fundamental qualitative research method that is highly effective in exploring complex behavior, perceptions, and experiences of stakeholders and industry experts within the energy sector (Adeoye-Olatunde & Olenik, 2021).

In this research, semi-structured interviews are utilized to allow for both a guided discussion and the flexibility to explore ideas and themes that emerge during the conversation. This approach is particularly suitable for this study because it provides the necessary structure to address specific research questions while also permitting an in-depth exploration of participant perspectives and experiences (Adeoye-Olatunde & Olenik, 2021).

The same questions were involved in every interview to structure the interviews and compare responses per party. This also gave room to discuss the answers in detail. The questions asked are the following:

1. Is congestion on the low-voltage grid a problem for you, and why or why not?

2. According to you, is the current situation optimal to allow for the widespread adoption of flexible appliances? If so, why or why not?

3. If not, what needs to happen to remove the limitations to allow for this widespread adoption?

4.1.3. Data analysis & bottleneck selection

To analyze the interviews' findings, the use of NVivo was integral to efficiently managing the complexity and volume of data. NVivo's capabilities in handling detailed coding and thematic categorization provided the necessary support for a comprehensive analysis, ensuring that the findings were grounded in the collected data (Welsh, 2002).

Once the interviews were conducted and transcribed, they were uploaded to NVivo. In Nvivo, citations that referred to possible bottlenecks were marked and categorized under the specified bottleneck. The themes were identified in accordance with the objective of the research question. Eventually, this provided a cross-interview overview of all the relevant bottlenecks regarding the widespread adoption of flexibility on the low-voltage network.

Furthermore, the selection of bottlenecks in the adoption of smart appliances is a critical component of this research. This selection involves analyzing the interview data to expose the significant themes. Once the major themes are defined, they will be analyzed to understand the common bottlenecks that are experienced and shared by all stakeholders or most of them. After this, the bottlenecks will be selected based on their frequency and impact on stakeholders. Given the potential for diverging views among stakeholders, it is crucial to consider the most relevant bottlenecks for the DSO, the problem owner, as defined in section 1.

4.1.4. Ethical considerations

The ethical considerations in this research ensure the integrity and credibility of the findings while protecting the rights of the interviewed participants. First and foremost, informed consent has been obtained from all interview participants, which clearly explains the purpose of the research and the findings, the voluntary nature of their participation, and their right to withdraw at any time without consequences. In doing so, the confidentiality and anonymity of the interview participants have been strictly maintained, with personal identifiers removed from the transcripts and documentation to protect their privacy. Also, the data has been stored securely and is only accessible to the research team. In addition, care has been taken to present the findings in an accurate and objective manner where misinterpretation or biases are avoided. Potential conflicts of interest are disclosed, and the research has been conducted in compliance with all relevant guidelines. By adhering to these ethical principles, the research aims to uphold the highest standards of academic integrity and respect for the interviewed participants and other involved parties.

4.1.5. Limitations of the methodology

The limitations of this research are discussed in the discussion section. This subsection will discuss the limitations of using interviews as a data-gathering method and how these have been taken into account. Conducting interviews is a powerful tool for gathering in-depth insight and understanding the perspectives of multiple stakeholders (Nunkoosing, 2005). However, it also comes with limitations that must be acknowledged. Firstly, interviews are inherently subjective, as they rely on personal experiences and perceptions which can introduce biases, affecting the interpretation and reliability of the data (Adeoye-Olatunde & Olenik, 2021). The skills of the interviewer, like asking the right questions and becoming acquainted with the participant, can also affect the quality of the data. To address this subjectivity and potential biases, a semi-structured interview guide has been developed and used, which is showcased in section 4.1.2. This guide included standardized questions, which ensured consistency across all interviews while allowing flexibility for follow-up questions to explore the responses in greater detail.

Secondly, interviews are resource-intensive and time-consuming, limiting the number of participants who can be included in the story (Griffee, 2005). This, in turn, can result in a smaller sample size, which could affect the generalizability of the findings. Additionally, the interpretation of the quality data from the interviews is often complex and, therefore, can be influenced by the biases and perspectives of the researcher, potentially leading to subjective interpretation (Adeoye-Olatunde & Olenik, 2021). To address this, efforts were made to include a diverse and sufficiently large sample of stakeholders throughout the whole energy domain. This involved system operators, stakeholder groups, policymakers, market parties, and experts to capture a wide range of perspectives. This sample aims to ensure a representative sample, where the findings are more likely to reflect the broader context of smart appliance adoption on the low-voltage grid.

Moreover, the responses to the interview questions can be influenced by social desirability bias, where the participants may answer according to what they believe is expected or acceptable rather than sharing their true feelings about the subject (Adeoye-Olatunde & Olenik, 2021). This can be particularly challenging when discussing controversial or sensitive topics. To address and minimize this social desirability bias, participants were assured of the anonymity of their responses. This was communicated clearly during the informed consent process, where participants were encouraged to share their authentic experiences and opinions. Additionally, interviews were conducted in a neutral manner, creating a comfortable environment for participants.

4.2. Sub-Question 2*: Analysis of the results*

The initial phase of the research focuses on identifying bottlenecks related to the widespread adoption of smart appliances on the low-voltage grid. Through semi-structured interviews with various stakeholders, this has been achieved. The data collected from these interviews has been systematically analyzed to expose significant themes and bottlenecks that give insight into the adoption process. The analysis of the results first provides insights into the results from the participant selection process by elaborating on the selected participants and their perspectives on the research. Next, the results from the interviews will be analyzed.

This phase utilizes abductive reasoning to analyze the bottleneck identified. Abductive reasoning is a powerful tool in academic research for generating hypotheses and developing explanatory theories, especially in a field characterized by complex, multifaceted phenomena. Its strength lies in its ability to navigate through incomplete data and propose plausible explanations, thereby advancing knowledge and guiding future research directions (Lipscomb, 2012).

By integrating abductive reasoning into this research methodology, this research aims to explore the interview results through the lens of Critical Transactions Theory. In doing so, the research also evaluates the ability of this theory to explain the results and grasp the concepts discussed fully. Abductive reasoning facilitated a deeper understanding of the complexities involved in adopting smart appliances on the low-voltage grid.

4.3. Sub-Question 3*: Recommendations*

The combined insights from the exploratory interviews and abductive reasoning approach provide a comprehensive approach to the bottlenecks involved. This dual approach ensures that the third part, the recommendations, are both empirically grounded and theoretically robust. The integration of empirical data with theoretical analysis provides a solid foundation for developing targeted recommendations to address the identified bottlenecks. This structured approach enables addressing the root causes of the issues identified in adopting smart appliances on the low-voltage grid.

5

Results

This section is dedicated to the research results. The main results are the bottlenecks identified from the interviews. However, the participants selected are also important for the quality and validity of the research. Section 5.1 provides the results from the participant selection process, as described in section 4.1.1. Section 5.2 lists and discusses the bottlenecks arising from the interviews.

5.1. Participant selection

As presented in section 4.1.1, the participant selection process aimed to ensure a comprehensive representation of stakeholders within the low-voltage electricity network and their perspectives. By involving a diverse range of stakeholders, including system operators, retail providers, end-users, and service providers, this research provides a holistic view of the challenges and bottlenecks for adopting smart appliances. The participant selection aimed to interview at least one stakeholder per stakeholder category; system operator, service provider, retail provider, consumer. In addition, perspectives from all five lenses – technical, regulatory, process, financial, and social – have been incorporated, as this was formulated as a requirement. This requirement was based on the TIP framework (Bots, 2012) and modified to the extent of the low-voltage grid.

This selection process resulted in 11 interviews with various stakeholders and industry experts from private, public, large, and small institutions. Table 4 below provides an overview of the results.

Stakeholder category	***Name of organisation***	***Contributed perspectives***
System operator	Stedin	Technical, regulatory, and process
	Liander	Technical, regulatory, and process
	Enexis	Technical, regulatory, and process
Services	EDSN	Technical, regulatory, and process
	Withthegrid	Technical, financial, social
	Equans	Technical, financial, social
	Shell Recharge Solutions	Technical, financial
Research institution	ELaadNL	Technical, regulatory
Retail	ANWB Energie	Technical, financial, social
Policy institution	Mffbas	Technical, regulatory

Table 4: Interviews conducted

Representatives from these organizations were interviewed who were perceived as experts on flexibility and demand response-related activities within their organization. The organizations of which representatives have been interviewed have been briefly described below.

Liander: is one of the largest distribution network companies in the Netherlands. It is responsible for distributing electricity and gas to millions of households and businesses. Liander is active and operates in six regions in the Netherlands; Friesland, Flevoland, Gelderland, Noord-Holland, Zuid-Holland, and Amsterdam (Liander, 2024). Liander operates and maintains the energy infrastructure, ensuring a reliable and safe energy supply. In doing so, Liander is at the forefront of of integrating renewable energy sources and smart grid technology.

Stedin: is, like Liander, a major Dutch DSO that manages the electricity and gas networks in the Randstad area, including in cities like Rotterdam and the Hague. Stedin also operates in the regions of Utrecht and Zeeland and smaller regions like Kennemerland, Amstelland, and Noordoost-Friesland (Stedin, 2024). Stedin also focuses on providing stable and reliable energy supply, promoting the energy transition, and ensuring that the electricity grid can accommodate increasing amounts of renewable energy.

Enexis: is, like the other system operators, a key DSO in the Netherlands, serving the regions of Groningen, Drenthe, Overijssel, Noord-Brabant, and Limburg. Like the other system operators, Enecis is dedicated to maintaining and innovating the electricity and gas infrastructure, playing a significant role in the energy transition facilitating the integration of renewable energy sources and promoting energy efficiency.

EDSN (Energie Data Services Nederland): is a central data services organization in the Dutch energy market. EDSN manages data flows between various market parties, ensuring the secure and efficient data exchange between these parties. EDSN plays a significant role in the energy transition by facilitating the integration of renewable energy sources through data exchange.

Withthegrid: is a technology company focusing on the Internet of Things (IoT) solutions regarding the energy and utilities sector. The company provides a platform for real-time monitoring and management of energy assets, supporting grid operators, end-users, and energy organizations in optimizing their operations and maintenance. In doing so, Withthegrid's solutions enhance grid reliability and efficiency.

Equans, formerly known as ENGIE Services, is a global leader in technical services, including energy. In the Netherlands, Equans provides a wide range of services like energy management, sustainable building solutions, and infrastructure projects. The company focuses on improving energy efficiency and supporting the energy transition.

Shell Rechange Solutions is Shell's division focusing on electric vehicle (EV) charging infrastructure, such as charging stations. Shell Recharge Solutions provides charging solutions, including home, workplace, and public charging stations. The company aims to facilitate the transition to electric mobility by ensuring convenient and reliable access to EV charging.

ElaadNL: is a knowledge and innovation center focused on smart charging infrastructure for electric vehicles. ElaadNL is an initiative by Dutch grid operators to support the development and implementations of smart charging solutions. In doing so, ElaadNL conducts research, develops standards, and also tests new technologies to enable scalable and efficient EV charging.

ANWB Energie is part of the Royal Dutch Touring Club (ANWB), which offers energy services with a focus on sustainability. The organization provides green electricity and dynamic contracts to consumers, emphasizing consumer-centric services. By promoting renewable energy use, it aims to contribute to the energy transition.

Mffbas (Marktfaciliteringsforum & Beheerder Afsprakenstelstel): is facilitates the exchange of data among market participants. Mffbas ensures efficient, transparent, and secure data sharing to support the development of the electricity grid. It brings together various stakeholders, including grid operators, energy suppliers, and consumer groups, to establish and regulate data usage agreements, enhancing energy system flexibility, efficiency, and innovation.

5.2. Interview results

During the interviews, 23 bottlenecks were identified to influence the widespread adoption of smart appliances. Zooming in on these 23 bottlenecks, it has been concluded that some of the bottlenecks experience overlap. Therefore, these bottlenecks have been merged and classified into eight broader and more comprehensive bottlenecks. In sections X and X of the appendix, all 23 bottlenecks have been listed, as well as their classification process into 8 more comprehensive bottlenecks.

In this section, the eight more comprehensive bottlenecks have been described elaborately.

During this analysis, three main themes or bottlenecks recurred, which existed for a significant share of the shareholders and were perceived as most relevant and challenging. The other six bottlenecks were mentioned less frequently but remain barriers to widespread adoption and will, therefore, be presented in this section. Table 5 provides a systematic overview of the bottlenecks and includes their frequency of occurrence in the interviews.

5.2.1. Bottleneck 1: The roles in the future energy system are not defined

The first significant bottleneck to the adoption of flexible appliances in the low-voltage electricity grid is the uncertainty surrounding the future market design, including the roles and responsibilities of the future energy system. This lack of regulatory clarity results in hesitation among market parties and system operators, as they are unsure about their rules, roles, and the regulatory environment in the future. This ambiguity limits strategic planning and, therefore, the integration of flexibility in solutions, propositions, and mechanisms. This bottleneck seemed to exist mainly at system operators.

There is a need for consensus on how to structure the future energy system. As a representative from Stedin pointed out, "*I think it is mostly that we have to collectively agree how you arrange it [the roles in the energy system], so that you together will have an idea about that. And then you can start thinking about measures; are you going to find the solution in the tariffs, or the connection conditions? Then, will you get a discount if we can steer your devices? Or are we going to offer you remuneration each time we steer the load of your devices?"*. This citation highlights the necessity for unified visions and clear policies to guide the development of flexibility mechanisms. Due to this uncertainty, it is also hard to establish technical or regulatory mechanisms to facilitate this integration of flexible appliances. As the representative from Stedin also pointed out, "*At this moment, we do not have the mechanisms yet. We have not arranged the technical or regulatory mechanisms with which we can do this*".

Liander also shared this view and expressed their concerns by stating, "*But it is just very hard to see how this will look like in the future. Are they all going to have a different congestion service provider? I am not sure, and even if, how are you going to arrange this? Will the market act on street level? And would there then be like 7 market parties? This would be unrealistic. It is just very hard to picture right now*." This uncertainty adds to the complexity of long-term planning and strategic decision-making.

To add to the perspectives of both system operators, the respondent from ElaadNL mentioned, "*In which proposition are the system operators going to ask for flexibility or a reduction of the load? There has not been decided regarding that subject. If there isn't a decision on that, we are left behind with all of us. What is lacking in the Netherlands, is just a decision on this [the market design].'* This indicates that without a defined market, the stakeholders are left without direction, further stalling the process.

In addition, there is also some uncertainty about the extent of flexibility that is desirable. A representative from Mffbas stated, "*So there is also a limitation in how much flexibility is actually desirable. And this again has to do with which proposition exists in the future. There could be a chance that if this is not implemented right you will just get some sort of netting rule 2.0 [salderingsregeling]."* This statement indicates that poorly defined roles and market rules could lead to, on top of uncertainty and delay, ineffective solutions that do not address the core issues.

Moreover, to compare the Dutch electricity system with other countries, a representative from Elaad mentioned: "*If you look at other countries in Europe, they have made decisions already on which mechanisms to implement. They first chose which technical mechanisms to use and then developed the regulatory frameworks around it. In the Netherlands, this is vice versa*".

The citations from the interviews above indicate that the lack of a clear and agreed-upon framework for the future energy system creates significant barriers for system operators and market participants. According to the interviewed parties, without clear rules and a well-defined market structure, it is challenging to design and implement effective demand response programs and integrate flexible appliances at a large scale.

5.2.2. Bottleneck 2: The margins for households are too thin

Another significant barrier to adopting flexible appliances on the low-voltage grid is the inadequate or barely existing financial returns for households. The potential earnings from load shifting and flexibility services are currently too little and minimal to motivate small end-users, such as households, to invest in the necessary technology or change their consumption behavior. This results in a low participation rate among households, affecting the overall effectiveness and scalability of flexibility and demand response programs.

Many households do not see sufficient financial benefits to justify the investment in appliances facilitating demand response, like home energy management systems (HEMS) and smart meters. According to a representative from ElaadNL, "*The customer must earn something from this. There is no trigger for the consumer to purchase such a system*." This lack of financial benefit and the ability to monetize their flexibility is the major disincentive.

The existing market structure is not helpful or useful to small consumers participating in demand response initiatives. An interviewee from Alliander pointed out, "*The market isn't organized adequately to allow small consumers to make money from flexibility. In origin, this was, of course, only a possibility for large consumers or producers*." This citation highlights the structural issue where the market currently leaves little room for household-level engagement. This representative further elaborated, "*I don't necessarily believe consumers will actively consider buying a Home Energy Management System and ensure all their appliances are smart and steerable to see if they can make their money back with changing energy prices. I don't believe in this because you will make a lot of costs with a low margin*." The cost of purchasing and installing the necessary technology often outweighs the potential savings or earnings from participating in demand response and flexibility.

To elaborate on the business case for households, an interviewee from Withthegrid explained: "*The business case is just really thin, like, how many euros you can make with a flexible household, which is much less than for a large consumer. Moneywise, there has to come an installer to your house for 60 euros, and then you will have to buy the hardware for 100 euros, which is 160 euros. How much can you make from flexibility? They have to return that money, making it extremely challenging*." This breakdown of costs versus the potential earnings illustrates the economic disincentive for households. As was jokingly mentioned during this interview: "*A year's long of demand response will currently retrieve you a cup of coffee.*"

Two representatives of Equans elaborated on the role of the government in providing incentives: "*There is no incentive from the government to households. Then why would they, throughout the day, turn on their washing machine in a flexible way? They just want to have their laundry done. The same holds for solar panels, where everyone is criticizing the netting rule [salderingsregeling] , talking about how you can't change the game's rules during the game. So, I think they first have to start with this incentive.*"

To reflect on the situation from a consumer perspective, retail party ANWB stated the following: "*Time and time again, from our research, the costs are at the top of the list of what consumers find important.*" This indicates that consumers are likely to be interested unless the financial benefits are clear and substantial. This representative also mentioned: "*Through our dynamic contracts approach, consumers can earn money for their flexibility. However, they really only pays for consumers with EVs, as only then there exists a possibility to earn back a realistic amount of money.*"

5.2.3. Bottleneck 3: Appliances can’t communicate.

The integration of flexible appliances into the low-voltage grid is hindered by a technical and fundamental issue: the lack of standardized communication protocols. Regarding solar panels and bidirectional charging, flexible appliances adjust their operation times, power consumption, and production based on grid demand. This requires effective communication with energy management systems to optimize their function and contribute to grid stability. Underlying this technical issue is a market-driven lack of incentives for manufacturers to use the same protocols in their products.

One interviewee from Liander highlighted this fundamental issue: “*One of the problems is that appliances are not steerable. Also, they can’t communicate with each other*”. This citation mentions that not only are most appliances not steerable, they are running on different protocols. The complexity of integrating the same protocols was elaborated on by Equans: “*The question is how are we going to let these flexible assets talk to each other, which measuring instruments do we need, and which software? You have this problem with, for example, old and new washing machines, or with different types of cars. I think this makes the adoption difficult. Also, sometimes you are dealing with a different controller, which again reacts differently to something. Then you will have the same protocol, but it is still different.*” This statement discusses the technical hurdles of integration and the variability in control systems. Even when a common protocol is in place, this can complicate integration efforts.

Next to the technical issues of appliances being unable to control or communicate, the interviews exposed that there is also no incentive for market parties or manufacturers to use the same protocols. As a spokesperson for Mffbas pointed out during the interview: “*It is a technical component at play here, but there is also no market for it”. There is no incentive for market parties to offer this. You can just attach a technical component which makes it controllable, but there is no proposition for this which currently makes it non-feasible*”. This citation underscores the absence of market-driven incentives for manufacturers to adopt standardized protocols. Discussing the incentives, specifically for heat pumps, an interviewee from Alliander stated: “*What is the incentive to make heat pumps controllable on the protocol we are choosing? That is the difficulty.*” This also reflects the reluctance of manufacturers to standardize protocols without clear incentives. A representative from Shell Rechard Solutions presented a related challenge that exists even when appliances use the same standards: “*Their chargers are on the same protocols, but still, you have 20 different manufacturers, who all work in a different way. That is the hardest challenge to large-scale adoption. You can also maintain the same protocol, but when you interpret it differently, it still doesn’t work.*” This citation highlights the difficulties in implementing standards and the different interpretations of the same protocols by various manufacturers, leading to inconsistencies in functionality.

5.2.4. Bottleneck 4: Data sharing

Data sharing is required to effectively utilize the available capacity on the distribution grid. Data sharing enables real-time monitoring and management of the low-voltage grid. By collecting and analyzing data from various sources, such as smart meters, distributed energy resources, and smart appliances, grid operators can gain a comprehensive overview of grid conditions. However, effective data sharing encounters significant barriers.

Sharing data should be performed with consent from involved consumers. However, as a representative from EDSN stated: “*A lot of people have smart meters. In a digitalizing energy landscape, it becomes time we use this data. Therefore, the Energy Law [Energiewet] should be* *implemented. This is a large bottleneck currently. The smart meters at your home are the property of the system operators, but they are not allowed to retrieve this data yourself; this has to go through retail parties since the law still prescribes this. Retail parties can share this data with the system operator. However, what currently happens is that this only happens if you explicitly state that you allow it. What happens when you ask this somewhere in a portal at the end of the agreement? Then it doesn't happen, of course*". This citation implies two things. First, there exists a blind spot for system operators for data regarding the low-voltage network, which was confirmed by the Stedin representative: "*We are now coming to the conclusion that our low-voltage projections are quite good on a large scale, but we have little methods to validate or confirm if these calculations are correct, we are relatively blind in what really happens*". Second, it implies that the ease of sharing data for consumers is lacking.

In addition to the regulatory framework's inability to enable data sharing, data security in sharing was also mentioned. A representative from Equans mentioned their customers' fear of data breaches: "*Someone from outside could intrude the systems and manipulate the assets. That is where all our customers are afraid of. Therefore, cybersecurity should also adhere to certain requirements. This could also result in their competitors seeing their consumption profile, and this is just really privacy sensitive."* This citation exposes that, in addition to regulatory frameworks hindering data sharing, other factors like security and privacy are also involved.

5.2.5. Bottleneck 5: Novelty of the problem

Congestion on the low-voltage grid is a relatively new problem, unlike the medium-voltage and high-voltage grids that have established congestion management mechanisms and frameworks. The novelty of this problem, which has arisen in a relatively short amount of time, results in the mechanisms for congestion management and the market being underdeveloped. As a representative from Liander pointed out: '" *We as system operators have been working for hundreds of years on putting copper and aluminum into the ground, and that is where we're good at. Then, about twenty years ago, we were asked to use our transmission lines very efficiently. Currently, we are asked to deal with the energy transition. We as system operators realize we need flexibility; however, this is just a new concept for use, which makes it very hard to find a way to include this flexibility.*"

5.2.6. Bottleneck 6: Communication

In the past, system operators primarily had to focus on the physical arrangement and maintenance of the electricity grid in the Netherlands without needing to explicitly communicate their design choices and their implications to grid users. However, as the energy grid approaches its capacity limits, (distribution) system operators now must inform end-users about these constraints and guide them on the effective operation of the grid and their consumption patterns. This need for smart and effective communication is a relatively new challenge for system operators with little experience in such communication practices. In addition, communication is a new practice for system operators, As mentioned by a representative from EDSN: *"Communication is, for example, something they do at water utility companies. So, when there is a dry period, utility companies want people to use less drinking water. Then, by starting a campaign on a regional level, they ask people to use less water, for example, saying not to spray the garden. Afterwards, you will see that this communication directly affects households' water consumption. But these practices for communication are totally new for system operators."*

5.2.7. Bottleneck 7: Ease

The ease of use affects the adoption of consumers. The need for significant changes in consumption patterns discourages the consumer from adapting to this change. Consumers prefer straightforward solutions that fit seamlessly into their everyday lives and patterns; adapting their energy consumption to their everyday activities instead of vice versa. As a representative from ABWB Energy pointed out: *"We speak to customers saying I think a dynamic contract is interesting. However, I also have a family of six, so I will not delay my laundry to the moment it becomes interesting for me regarding costs. It's just like, I have laundry to do, which needs to happen right now."* This sentiment highlights the reluctance of consumers to adjust their daily activities around energy-saving schedules, indicating that smart appliances must integrate effortlessly into existing habits and routines to be widely adopted.

5.2.8. Bottleneck 8: Education

There exists a knowledge gap among users regarding the benefits and usage of smart appliances. Consumers are undereducated on the subject of flexibility and are, therefore, unaware of the value and functionality of demand response. As a representative from retailer ANWB Energy pointed out: "*I think it mainly comes down to three things: education, costs, and the ease of use. With education indicating that you have the knowledge of knowing what you are doing."* This indicates that for consumers to embrace smart appliances, they must first understand how these devices can enhance their energy management and overall household efficiency.

Table 5: Overview of bottlenecks

Bottleneck	Description	Mentioned in the number of interviews
1. *Unclear roles in future energy system.*	Unclear roles and responsibilities of stakeholders in the future energy system result in uncertainty – stakeholders hold back the development of mechanisms for incorporating flexibility.	6
2. *Inadequate financial incentives for households.*	The financial incentives for households to participate in flexibility initiatives is significantly inadequate.	6
3. *Appliances can't communicate*.	Various appliances suited for flexible management run on different protocols and standards and are, therefore, not interoperable. There is also no incentive for manufacturers to align standards.	6
4. *Data sharing.*	Current regulations and market structures hinder the data-sharing process and, therefore, the optimization of the allocation of electricity.	4
5. *Novelty of the problem.*	Congestion on the low-voltage grid is a relatively new problem, resulting in underdeveloped mechanisms and the market.	4
6. *Communication.*	Until now, system operators primarily had to focus on physically arranging the grid. With possible scarcity of electricity, communication to customers arises as a new practice for system operators.	1
7. *Ease.*	Consumers prefer straightforward solutions that fit seamlessly into their everyday lives and patterns.	1
8. *Education.*	A knowledge gap exists among users regarding the benefits and usage of smart appliances. Consumers are undereducated on the subject of flexibility and are, therefore, unaware of the value and functionality of demand response.	1

6

Theory

Scientific theory as a framework is required to analyze the results presented in section 5 academically. Through scientific theory, how and why the bottlenecks have arisen can be explained. A theory that aligns with the context and the results is essential to really understand the characteristics of the identified results and get to the root of their existence.

Critical transactions theory (Kunneke, 2010) provides an analytical framework to understand the interplay between technology and organizational structures, particularly in the context of infrastructure reforms. The theory is rooted in the idea that infrastructures are complex socio-technical systems requiring coherent alignment between technological functionalities and organizational arrangements to ensure reliability and efficiency. Below, this theory will be further elaborated on to fully grasp the concepts - critical functions, critical transactions, and modes of organization - before applying it to the energy sector and the results from the research in section 7.

Over the last decades, infrastructure reform has been a hot topic for economists and policymakers (Kunneke, 2010). These reforms often focus on introducing new market mechanisms to increase efficiency, drive innovation, and meet investment needs. However, it is often assumed that the technological underpinnings of infrastructure adjust automatically to new market conditions. Critical transactions theory challenges this assumption by highlighting the technical complexities and interdependencies that must be managed through supporting organizational structures.

6.1. Technical criticality in infrastructures

Large infrastructures are characterized by strong technical complementarities, which means that various technical components and functions are interdependent. Critical Transactions Theory explains that certain technical functions are essential to maintain the system’s overall performance, termed the ‘critical technical functions. Examples of these include capacity management, system management, interconnection, and interoperability. Failure to support these functions can lead to significant disruptions in the system, as evidenced by historical blackouts in electricity systems and accidents in rail transport.

Defining criticality

Criticality, and the concept of it, involved identifying the aspects of technical operation and management that are vital for the system's performance. These expectations of performance include reliability, safety, and security of supply. Critical functions, in this sense, are those that, if not adequately supported, can lead to system-wide failures.

Control engineering perspective

From a control engineering perspective, these infrastructures can be modeled as closed control systems, where feedback loops ensure that the actual performance aligns with the desired performance. The key components for such a system are comparators, compensators, actuators, and the technical process itself. This approach helps identify critical technical functions by examining the necessary control mechanisms to maintain system integrity and reliability.

Control mechanisms can be labeled critical if:

(1) They imply a sufficient technical scope of control and they are unique in the sense that there are no alternative control mechanisms that perform similar tasks. A failure will have system wide consequences.

(2) They involve strong time constraints, since critical control mechanisms need to be activated in a specific and often very short period of time.

6.2. Critical transactions

Next to critical functions, Critical Transactions Theory further elaborates that certain transactions are essential to support the critical technical functions of infrastructures. These 'critical transactions' are characterized by their necessity for maintaining technical performance and their requirements for specific organizational arrangements to support them.

Technical-Control Dimension

The technical-control dimension of critical transactions involves two aspects:

1. **Scope of Control**: The extent of technical complementarity required across the system. This ranges from the highest level, the system level (e.g., national electricity grid), to subsystems (e.g., low-voltage grid) and components (e.g., dishwashers).

2. **Speed of Adjustment**: The time frame within which control mechanisms must respond to disturbances, ranging from immediate operational adjustments to capacity utilization to capacity allocation and eventually to long-term system innovation.

Scope of Control **Speed of Adjustment**	**System** *(requires directive intervention)*	**Subsystem** *(requires coordination)*	**Component** *(requires corroboration)*
T_0 Operational Balancing (requires supervision)	Authoritative supervision *[‘system operator’]*	Collaborative Supervision *[‘system regulator]*	General framework conditions *[‘system norms and standards’]*
T_5 Capacity utilization *(requires monitoring)*	Compulsory monitoring and enforced adjustment	Mutual monitoring and stimulated adjustment	Self monitoring and voluntary adjustment
T_{15} Capacity allocation *(requires facilitation)*	Controlled allocation mechanism	Guided allocation mechanism	Competitive allocation mechanism
T_{50} System transformation and innovation *(requires planning)*	Directive planning	Indicative planning	Decentralized planning

Figure 9: Organizational requirements in parenthesis (Kunneke et al., 2010)

Critical transactions also have organization-specific dimensions, including *asset specificity* and *uncertainty, and strategic behavior*. In asset specificity, investments in critical assets are often highly specific to their intended use, necessitating secure organizational arrangements to mitigate risks. In uncertainty and strategic behavior, technical systems' complexity and unpredictability could lead to significant uncertainty, which requires robust organizational structures to manage potential strategic behavior and ensure technical reliability.

6.3. Modes of organization

Aligning technical functions with organizational structures is crucial for managing critical transactions. Critical Transactions Theory identifies various organizational modes, ranging from hierarchical integration to more decentralized and market-based approaches. The choice of organizational mode depends on the characteristics of the critical transactions involved.

Categories of Critical Transactions

Critical transactions can be categorized based on their control dimensions and required speed of adjustment. Below, some modes of organization will be explained.

1. System Level and Immediate Adjustment: Requires centralized, authoritative supervision due to the high degree of technical interdependence and the need for a quick response (e.g., load balancing in electricity systems)
2. Subsystem Level and Medium-Term Adjustment: May involve hybrid arrangements, which can include some decentralized decision rights but coordinated through a strategic center (e.g., the allocation of rail slots)
3. Component Level and Long-Term Planning: Allows for more decentralized and competitive arrangements due to lower asset specificity and longer adjustment periods (e.g., development of new trains and locomotive models).

6.4. Differences Across Infrastructures and Over Time

Critical Transactions Theory also emphasizes that different infrastructures have distinct technical and organizational requirements, which can also vary significantly over time. Technological advances and evolving societal needs and dynamics can significantly alter the critical transactions required within infrastructures and their corresponding organizational requirements. Over time, new technologies can change the nature of critical functions and the way they should be supported and managed.

Factors such as technological change, infrastructure modernization, regulatory and market reforms, and environmental and social considerations can significantly impact infrastructure development and management. Section 7.1 will analyze these factors in the context of the Dutch energy system. This research aims to provide a nuanced analysis of bottlenecks to offer tailored recommendations that account for the dynamic nature of the electricity system.

7

Analysis

This section analyses the electricity sector in the context of critical transactions theory and the bottlenecks identified from the interviews. First, section 7.1 analyses the electricity sector and defines its critical functions and corresponding transactions. Second, section 7.2 analyses the bottlenecks identified and positions them within critical transactions theory, aiming to explain them logically. Third, section 7.3 analyses the theory in light of the results and provides insight into the theory's ability to explain the bottlenecks comprehensively.

7.1. Electricity sector analysis

The electricity sector is undergoing significant changes, driven by technological advancements and the need to switch to sustainable energy solutions. To ensure a reliable supply of electricity, it is essential to align technological requirements with the appropriate organizational structures. This analysis will use the framework of critical transactions to evaluate the alignment of technology and institutions in the electricity sector. To do so, this research follows a structured approach that incorporates defining critical technical functions and transactions and aligning those through modes of organization.

7.1.1. Identifying Critical Technical Functions

The electricity sector relies on several critical technical functions to maintain the system's reliability, safety, and efficiency. These functions are critical to proper operation and include system control, capacity management, interconnection, and operability. The critical functions will be described in depth below.

System Control: involves the real-time monitoring and adjustment of the electricity required to maintain stable voltage and frequency levels. This is essential to preventing outages and ensuring a reliable and continuous supply of electricity.

Capacity Management involves ensuring that the electricity supply always meets demand. It includes both short-term capacity adjustment and long-term planning to balance generation and consumption.

Interconnection refers to linking the physical layers and operational parts of the electricity grid, including generation, transmission, and distribution networks. If these layers are effectively interconnected, this enhances the grid's reliability and flexibility.

Interoperability ensures that all components of the electricity grid, from power plants to consumer devices, can work together seamlessly. This is also critical to maintaining efficiency and reliability.

7.1.2. Critical Transactions

Critical transactions in the electricity sector refer to the transactions and exchanges essential to support the critical functions explained in the last section; system control, capacity management, interconnection, and interoperability. Therefore, critical transactions are essential for maintaining the grid's reliability, efficiency, and stability. This sector will further elaborate on the critical transaction, by defining the criteria relating to the electricity grid.

Speed of adjustment

The speed of adjustment in critical transactions theory refers to the time frame within which a transaction needs to occur to maintain the overall system performance and stability. This ranges from immediate, real-time actions to long-term operational planning and investments.

Real-time (T_0): This requires immediate adjustments that must be made within seconds to a few minutes to prevent system failure. This includes real-time load balancing and frequency control, which often need to happen within milliseconds. These transactions typically require automated systems to facilitate instant communication between the grid's components.

Short-term (T_5): these actions require operational adjustments and can be planned and executed ranging from hours to days. In the energy system context, this involves scheduling power generation and demand response activation and signaling.

Medium-term (T_{10}): These tactical actions need to be performed within days to months and include seasonal adjustments in generation or the scheduling of maintenance activities. They require detailed planning and coordination among the involved stakeholders.

Long-term (T_{15}): this strategic planning involves long-term investments and infrastructure development, such as building new power plants or upgrading transmission lines. In addition, these transactions relate to significant policy decisions and capital investments.

Scope of control

The scope of control refers to the extent or level within the electricity grid which is impacted by the transaction. This ranges from the system-wide control to specified components or local areas.

System Level: on the system level, grid-wide impact includes transactions which affect the entire electricity grid or a significant portion of it. This includes load balancing on the national electricity grid. These transactions are managed by centralized entities, like national grid operators such as TenneT, and typically entail the high-voltage network.

Subsystem Level: in these regional or local networks, transactions are included that impact regional distribution networks or specific areas locally. This includes regional and local load balancing, performed on the medium- and low-distribution network. Focusing on specific parts of the grid, this is typically managed by regional operators, like the DSO.

Component Level: these are transactions which involve specific components, like power plants or substations, or individual decentralized resources connected to the grid, such as heat pumps or electric vehicles. The transactions related to this level are therefore managed locally, often by the operators themselves.

The figure below provides the matrix of the speed of adjustment with the scope of control for the context of the Dutch energy system,

	SYSTEM-LEVEL	**SUBSYSTEM**	**COMPONENT**
REAL-TIME (SECONDS)	Immediate load balancing and frequency control	Regional load balancing	Individual unit control
SHORT-TERM (HOURS TO DAYS)	Generation scheduling	Demand response activation and signaling	Local generation scheduling
MEDIUM-TERM (MONTHS)	Seasonal adjustments	Maintenance planning	Tactical upgrades
LONG-TERM (YEARS)	Strategic planning	Infrastructure investment	Long-term component investments

Table 6: Critical Transactions in the Electricity sector

7.1.3. Changes in the electricity sector over time

The electricity sector has undergone profound changes through various phases which have shaped its current structure, layers, and operational dynamic. This progression provided the context for understanding how current emerging trends – such as the integration of renewable energy – will impact the future of the electricity system.

As described in section 1, initially, the electricity sector was characterized by vertically integrated monopolies, which controlled all aspects of generation, transmission, and distribution. Therefore, the technological infrastructure was relatively simple, focusing on large, centralized power plants. In the late 20th century, the Netherlands began liberalizing their electricity market, which resulted in separate entities responsible for generation, transmission, and distribution. Regulatory bodies were established to maintain fair access to the grid and to prevent monopolistic practices and strategic behavior on the transmission and distribution grid.

The push for renewable energy production began gaining momentum in the late 20th and early 21th century, which was driven by environmental concerns and technological advancements. Currently, the integration of wind, solar, and other renewable energy sources into the grid introduce new challenges due to their intermittent nature. Their dependence on weather conditions makes electricity production less predictable and more difficult to balance with demand.

Below, the emerging trends within the electricity are discussed as well as their effect on the critical functions and transactions elaborated on in section 7.1.

Decentralization: integration of renewables

The shift towards decentralized energy generation, which is primarily driven by the integration of renewables, fundamentally alters the critical function of capacity management to the intermittent nature of renewable energy production. Unlike traditional power plants, renewable energy sources produce power variably, depending on weather conditions and seasonal effects.

Regarding critical transactions, generational scheduling becomes more complex, having to include data from numerous decentralized energy sources. Transactions must adapt to include flexible and responsive mechanisms that can efficiently match supply and demand in order to leverage real-time data and predictive analytics.

As the focus of energy generation shifts from centralized production to decentralized production, the focus of critical transactions also shifts from centralized control to distributed control systems that can handle localized generation and consumption. This decentralization requires a reevaluation of the traditional modes of organization, pushing towards more hybrid arrangements which allow the facilitation of mutual monitoring and coordination among various decentralized entities.

Digitalization: Enhancing System Operability

The increasing digitalization of the energy system is driven by smart ICT solutions which enhance the interoperability of the grid. However, this digital transformation also adds to the complexity of the integration, requiring sophisticated systems to manage the integration of diverse technologies to enable seamless communication between various grid components.

Digital tools enable more efficient real-time monitoring and control. Critical transactions in this context involve the seamless integration of data from smart meters and appliances, sensors, and devices connected to the Internet of Things. Automated systems can quickly respond to fluctuations in supply and demand.

Digitalization has the potential to bridge the gap between various technologies and the systems within the grid, which could enable them to work together seamlessly. The interoperability of components is crucial for managing the increasing complexity of decentralized systems. However, the reliance on these ICT solutions also necessitates robust cybersecurity measures and standardized protocols to prevent vulnerabilities and weakened system performance.

Emergence of New Service Providers

The emergence of new service providers, like flexibility providers such as local aggregators, introduce new dynamics in the electricity sector. These kinds of entities aggregate demand and supply at the local level to provide grid stability and efficiency.

This introduction of new roles and service providers requires a shift in traditional organizational models to accommodate them, such as hybrid organizational structures that allow for decentralized decision-making and coordination.

7.2. Bottleneck analysis

In section 5.2, 8 bottlenecks for the widespread adoption of smart appliances on the low-voltage grid have been identified. While all these bottlenecks negatively influence the adoption, the alleviation of all bottlenecks is not required to maintain the system's performance. Therefore, critical bottlenecks should be identified. As explained in section 6, the Critical Transactions Theory aims to align technical critical functions with the required critical transactions. In doing so, the theory equips a framework for defining criticality.

Criticality, and the concept of it, involved identifying the aspects of technical operation and management that are vital for the system's performance. These expectations of performance include reliability, safety, and security of supply (Kunneke, 2010). Critical functions, in this sense, are those that, if not adequately supported, can lead to system-wide failures. In section 7, the critical functions in the context of the energy system have been identified, and are the functions that relate to *system control, capacity management, interconnection, and interoperability*. By comparing the critical functions related to the bottleneck, their criticality can be determined.

7.2.1. Defining Criticality

This section identified four bottlenecks related to one or more of the critical functions described above. First, these four bottlenecks and their criticality will be discussed.

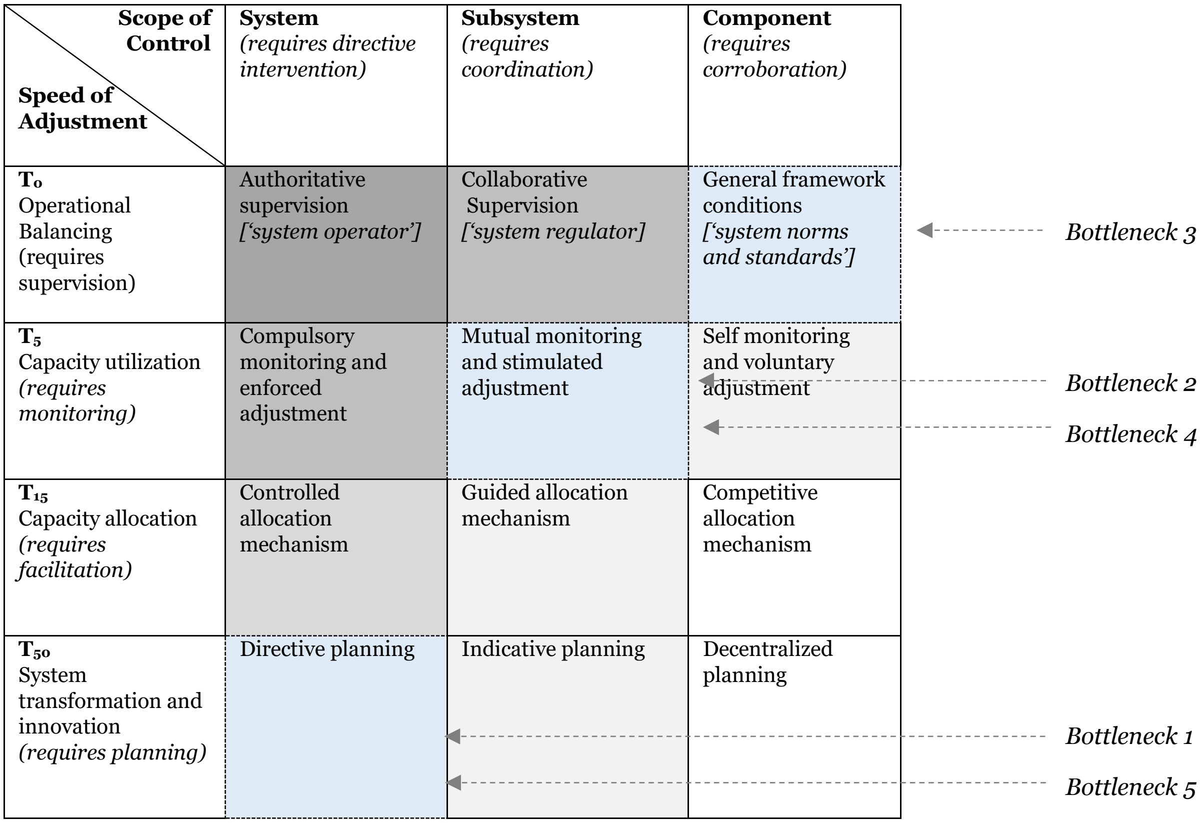
1) Lack of regulatory guidance and uncertainty in comprehending the overall direction of the system. By indicating that there is a lack of regulatory guidance on roles and responsibilities, this bottleneck directly affects all four critical functions. 2) *The margings for households being too thin* relate to capacity allocation and effectively matching the supply of energy with the demand, and the most incentives are involved in doing so. Therefore, they relate to the critical function of capacity management. 3) *The lack of standardized protocols directly affects the system's interoperability*. In doing so, the indirect effects of interoperable systems limit the ability to match supply and demand effectively, therefore affecting the critical function of capacity management. In addition to standardized protocols, 4) *data sharing* by smart appliances affects the *interoperability* of devices, in the sense that they can communicate and share information on the utilization of electricity. Next to this, sharing data affects *capacity management*, as it became clear during the interviews that data sharing facilitates optimal and efficient allocation of supply and demand.

The other bottlenecks – 5) *the novelty of the problem*, 6) *communication*, 7) *ease*, and 8) *education* – do not directly relate to the four critical functions and are therefore not categorized as critical for the energy system's performance. Due to the criticality of their nature, only the first four bottlenecks will be further addressed in the bottleneck analysis of section 7.2.2, where the bottlenecks will be positioned within critical transactions theory.

7.2.2. Bottlenecks and Critical Transactions Theory

This section will analyze these critical bottlenecks through the lens of Critical Transactions Theory. Here, each bottleneck will be analyzed in relation to the critical functions and transactions they aim to support, giving theoretical explanations for how these issues have arisen. In section 8, a recommendation for alleviating these bottlenecks will follow.

To analyze the bottlenecks accordingly, they should be positioned on the critical transactions matrix (Figure 11). The positioning of these bottlenecks on the matrix will be elaborated further below.



Scope of Control / **Speed of Adjustment**	**System** *(requires directive intervention)*	**Subsystem** *(requires coordination)*	**Component** *(requires corroboration)*
T_0 Operational Balancing (requires supervision)	Authoritative supervision *['system operator']*	Collaborative Supervision *['system regulator]*	General framework conditions *['system norms and standards']*
T_5 Capacity utilization *(requires monitoring)*	Compulsory monitoring and enforced adjustment	Mutual monitoring and stimulated adjustment	Self monitoring and voluntary adjustment
T_{15} Capacity allocation *(requires facilitation)*	Controlled allocation mechanism	Guided allocation mechanism	Competitive allocation mechanism
T_{50} System transformation and innovation *(requires planning)*	Directive planning	Indicative planning	Decentralized planning

Figure 10: Identified bottlenecks and corresponding scope of control and speed of adjustment.

Bottleneck 1: undefined roles in the future energy system

The first significant bottleneck to the adoption of flexible appliances in the low-voltage electricity grid is the uncertainty surrounding the future market design, including the roles and responsibilities of the future energy system. This lack of regulatory clarity results in hesitation among market parties and system operators, as they are unsure about their rules, roles, and the regulatory environment in the future. This ambiguity limits strategic planning and, therefore, the integration of flexibility in solutions, propositions, and mechanisms. The first bottleneck is of a different nature than the other bottlenecks. While other bottlenecks indicate findings within the technical and economic domain, this bottleneck is of a more organizational nature. In addition, the Netherlands is perceived as slow in decision-making within this domain by the interview respondents, as they claimed surrounding countries first arranged the technical requirements before the adequate regulatory frameworks. They perceived the Netherlands to approach this the other way around.

The underlying uncertainty relates specifically to low-voltage congestion management methods and frameworks imposed top-down by regulation. The uncertainty within this domain limits the development of flexibility mechanisms by, for example, system operators and agreements, including flexibility from retail and service providers. This uncertainty makes it difficult to establish the necessary technical and regulatory mechanisms.

When positioning this bottleneck on the critical transactions matrix, it intersects at the overall *system level*, and the *long-term system transformation and innovation*. The mode of organization supporting this intersection is *directive planning*. However, currently, this guidance and planning is lacking – making it logical that this bottleneck has surfaced from the findings and analysis. Furthermore, it should be noted that this bottleneck indirectly influences the other bottlenecks. As the lack of regulatory guidance extends throughout the whole low-voltage system, suitable agreements and mechanisms are lacking.

Bottleneck 2: the margins for households are too thin

The second bottleneck is of a financial nature and exists within the socio-economic dimension. As the interview results indicate, the financial returns for households participating in flexibility is currently inadequate. Dynamic contracts allow for the possibility to monetize flexibility, but from the interviews, it became clear that the money to be made is perceived as too little to actively participate in demand response. In addition, these dynamic contracts only made sense for consumers with EVs, as total shifting demand is higher for vehicle charging than, for example, in doing laundry. It was mentioned during the interviews, that the perceived monetization of flexibility would only result in a few tens of euros. Therefore, the financial returns for households in contrast to the effort of participating in flexibility are currently perceived as inadequate. This disincentivizes small end-users from two things: 1) investing in the hardware required to integrate controllable smart appliances and 2) changing their consumption patterns based on the electricity supply.

When positioning the incentives for households to participate in demand response on the critical transactions matrix (figure), it can be noted that this bottleneck intersects at the *capacity utilization* (medium-term) at the *sub-system level.* According to the critical transactions framework, this combination of *scope of control* and *speed of adjustment* should be facilitated through *mutual monitoring and stimulated adjustment*. However, the findings from the interviews exposed that this stimulated adjustment, the financial incentives, are inadequate in supporting the critical function of capacity management. Looking at the alignment of the functions this incentive supports, and the suggested mode of organization, it is logical that this bottleneck exists. This revelation indicates that the existing incentives and market structure are failing to engage households in participating in demand response initiatives.

Bottleneck 3: applications can't communicate.

Within appliance communication, standards and protocols are required. Protocols are sets of rules which define how data is transmitted and received over a network. These protocols have the goal of ensuring that devices from different manufacturers can communicate effectively. One example is Bluetooth, which services short-range wireless connections. In the context of smart appliances, protocols determine how devices exchange data with each other and energy management systems. Standards are agreed-upon guidelines that ensure the compatibility and interoperability among products like smart appliances. These are established by standardization bodies like ISO, IEEE, or the IEC. Standards ensure that products from different manufacturers can communicate seamlessly. For smart appliances, standards define how these devices should behave, communicate, and integrate into larger systems, such as the smart grid.

The third bottleneck relates to these standards and exists within the technical dimension. The critical functions, which have been explained in section 7.1, affected by this bottleneck are *interoperability* and *capacity management* since this bottleneck appeals for interoperability to match supply and demand in the short term, as explained in section 7.2.1.This integration of flexible appliances into the low-voltage grid is hindered by the lack of standardized communication protocols for smart appliances. Flexible smart appliances must adjust their operation and consumption based on the grid demand, which requires effective communication with energy management systems and each other to optimize their functionality.

Looking at the critical transactions related to this bottleneck, this bottleneck affects *operational balancing* at the *component* level, where appliances must communicate instantly to adjust their operation and maintain system stability. Therefore, the framework suggests *system norms and standards* through a general framework as the supporting mode of organization. However, the lack of standardized protocols resulting from the fragmented landscape regarding protocols and standards disrupts this process, exposing the misalignment. Effective interoperability requires aligned norms and standards, but the absence of these standards currently leads to difficulties in integrating diverse appliances – affecting the system's performance. Therefore, it is logical that this bottleneck has surfaced from the interviews.

It can be technically challenging to integrate appliances that run on different protocols. Even with common protocols, variations in implementation by different manufacturers causes inconsistencies. As indicated in the interview results, there is no market-driven incentive for manufacturers to adopt standardized protocols. Without clear financial gains and benefits, manufacturers have little incentive to invest in aligning their products with common standards.

Bottleneck 4: Data sharing

As explained in section 7.2.1, the fourth bottleneck of data sharing relates to the ability to share data among smart appliances and facilitate effective communication and optimal allocation of electricity supply and demand. Therefore, this bottleneck relates to the critical functions of interoperability and capacity management.

This bottleneck should not be confused with the third bottleneck, the lack of standards in smart appliance communication. While both bottlenecks involve data sharing, they differ significantly in their nature and implications. This bottleneck focuses on regulatory, privacy, and security challenges associated with accessing and sharing data from smart meters. This bottleneck directly affects consumer willingness to share data and the system operator's ability to use this data for grid management. On the other hand, the third bottleneck, the lack of standards, deals with the technical and market-driven challenges of integrating appliances through standardized.

To position this bottleneck on the critical transactions matrix, the purpose of data sharing should be taken into account. Data sharing is a broad concept that, in this context, relates to the ability of smart appliances to effectively share production and consumption information to allocate electricity in the short term and, in doing so, mitigate congestion. Therefore, sharing data in this context affects the low-voltage grid and the *subsystem* and intersects with *capacity allocation*. This *scope* and *speed of adjustment* intersect at the following suggested mode of organization: *mutual monitoring and stimulated adjustment*. When looking at the statements from the interviews, allowing for data sharing by consumers is a grey area for regulatory frameworks. In addition, consumers can allow for their data to be shared with appliances and the DSO, but this possibility should be agreed upon in online portals and at the end of large descriptions and pieces of text. Analyzing the mode of organization and stimulated adjustment, it can be concluded that not only the sharing of data is not stimulated, but it is even stimulated.

What further stands out, is that the suggested mode of mutual monitoring and stimulating falls short to describe the extensive bottleneck of data sharing. Where stimulated adjustment could be used to address the incentives for sharing data, this does not quite incorporate the more social factors of this bottleneck, such as privacy and security-related issues. The following section will further explore the comprehensiveness of the theory in explaining data sharing in section 7.3.3.

Lastly, while this bottleneck is classified as critical for the widespread adoption of smart appliances on the low-voltage grid, it will not be considered for the recommendations for the following reasons. This research directs the short-term issues on the low-voltage grid and examines the role of smart appliances in alleviating congestion-related burdens. Although enhancing data-sharing capabilities for smart appliances could improve the allocation of electricity, interviews with Stedin revealed that system operators already possess accurate projections of electricity dynamics on the low-voltage grid. These projections are sufficient for the short term, suggesting that the benefits of data sharing and smart metering in addressing congestion will primarily manifest in the long term.

7.3. Evaluation of theory's Comprehensiveness

This section will evaluate the comprehensiveness of the Critical Transactions theory and describe the research results. In doing so, it will analyze to which extent this theory can justify the bottlenecks and explain their existence. First, the section will evaluate both dimensions of the Critical Transactions framework, scope of control, and speed of adjustment, and evaluate their comprehensiveness based on the interview discussion topics. Second, the suggested mode of organization which exists at the intersection of both dimensions will be analyzed. Third, the inability of the theory to comprehensively address the bottleneck of sharing data, as identified in section 7.2.2., will be discussed.

7.3.1. Scope of Control and the Speed of Adjustment

First, this section will identify which parts of the theory are represented by the results. Second, it will discuss which parts might have been unrepresented and the potential reasons behind this, reflecting on the results and the interview participants. As section 7.2.2. positions the bottlenecks on the matrix, the relevant discussion topics, and points of focus have been indirectly mapped. This positioning and the points of emphasis can be identified for the scope of control and the speed of adjustment.

When looking at the positioning of the bottlenecks, from the perspective of *the speed of adjustment*, it can be noted that the operational balancing, capacity utilization, and system transformation are represented and have been extensive subjects for discussion. When looking at the positioning of the bottlenecks from the perspective of the *scope of contro*l, it can be noted that all three scopes of control, the *system* level, *subsystem* level, and *component* level, are equally represented. Given this, it can be noted that, regarding the scope of control, three dimensions have been discussed and arise as a result of the interviews. Looking at the required speed of adjustment, however, it can be noted that the capacity utilization is not only underrepresented but not represented at all. This indicates capacity utilization was not a point of discussion during the interviews. Capacity utilization, as defined in section 6, refers to matching the supply and demand in the medium term, which consists of days to even months. In doing so, capacity utilization encompasses, for example, seasonal adjustments to the change in consumption and production patterns. When trying to logically explain the absence of this segment of the theory in the interview results, three possible reasons are provided below.

Absence of capacity utilization

First, a reason could be that capacity utilization and seasonal adjustments on the low-voltage grid do not experience bottlenecks. The interviews function to identify bottlenecks to the widespread adoption and are therefore centered around possible issues arising within this domain. A reason for the absence could be that there are no bottlenecks on the capacity utilization dimension. In addition, the focal point of this research is demand-response, which exists in the short-term, as a subcategory of flexibility. Flexibility, on the other hand, also includes storage. Storage, often associated with seasonal adjustments, can be included in this domain.

Second, the interviewees could not involved or engaged in medium-term planning in the form of capacity utilization. However, to provide a comprehensive overview, a range of diverse stakeholders, ranging from retail parties to system operators, have been interviewed. While it could be true that some parties are not represented in this set, it can be argued that system operators would be most involved in the medium-term planning of capacity utilization. Therefore, this reason provides little argument.

Third, there could exist a blind spot among interview participants regarding the importance of medium-term capacity utilization. Critical Transactions Theory considers capacity utilization an important theme for the scope of control. The fact that it was not mentioned during the interviews could indicate that there exists a blind spot for the medium-term planning of supply and demand. Short-term planning could be a focal point of development, whereas medium-term planning is neglected by the stakeholders. As the stakeholders in this research include key players in the low-voltage energy system, it is essential a potential blind spot is addressed.

7.3.2. Modes of organization

At the intersection of the scope of control and speed of adjustment, the theory suggests modes of organization to support these transactions. In this section the suggested modes of organization will be further analyzed. In doing so, their ability to comprehensively cover and alleviate the bottlenecks will be evaluated.

For the first bottleneck, the lack of clear regulatory guidance is in line with the need for directive planning. Clear regulatory guidance resulted in uncertainty for stakeholders, hindering further development of flexibility mechanisms and contractual agreements. According to the theory, directive planning as a mode of organization could relieve these bottlenecks. This also aligns with the discussions during the interview, where stakeholders like system operators stated to prefer directive guidance.

For the second bottleneck, stimulated adjustment is in line with the absence of incentives for households to shift their loads. This mode of organization suggests that there should be an incentive for subsystems and households to participate in demand response. Stimulated adjustments like financial remuneration are considered to incentivize households to participate in demand response, therefore aligning the theory with the results from the interviews. The results from the interviews, however, exposed that stimulated adjustment for households in this context is inadequate. Therefore, it can be argued that the suggested mode of organization, which exists at the intersection of the subsystem and capacity allocation, fails to comprehensively prescribe recommendations in the context of this research.

For the third bottleneck, a need for standards and norms is suggested. This is exactly in line with the fragmented landscape of standards resulting from the interview results, as well as with the collective agreement on need for the unification of these standards. Therefore, it can be stated that the theory aligns with the characteristics of this bottleneck.

7.3.3. Data Sharing

The fourth bottleneck addresses the sharing of data, which entails the current regulations that hinder the sharing of data among consumers and system operators to allow for efficient allocation of supply and demand on the low-voltage grid. This bottleneck has been positioned on the matrix at the intersection of the subsystem and the capacity utilization as the required speed of adjustment. This intersection suggests mutual monitoring and stimulated adjustment as the mode of organization. However, stimulated adjustment falls short of prescribing modes of organization for arranging data sharing management. While this “stimulated adjustment” approach could identify economic or regulatory incentives for sharing data, it fails to grasp the identified key factors of privacy and security in this research. Therefore, it falls short in addressing the broader social challenges that accompany data sharing in an increasingly digitalized landscape. In this low-voltage landscape, data sharing requires a more comprehensive approach that extends beyond technical and economic considerations to include critical social dimensions. Two primary social considerations identified in this research are privacy and security.

Privacy emerges as a critical concern in the context of data sharing (Maidment et al., 2020). Consumers are increasingly wary of sharing detailed consumption and production data due to fears of data misuse and breaches. The theory’s current approach does not sufficiently integrate privacy considerations in the modes of organization, which are essential for gaining consumer trust and compliance. Ensuring robust privacy protections is crucial for the successful implementation of data-sharing initiatives. Policies that guarantee the anonymity and security of shared data must be developed to address consumer concerns and foster a willingness to participate in data-sharing programs. Data sharing mechanisms must also consider issues of data security. Data security relates to the critical aspects of rensuring the reliability, safety, and efficiency of moden grid energy infrastructure. As the energy sector continues to evolve with advancements like smart grids and renewable energy integration, maintaining robust data security will remain critical (Qio et al., 2011)

To summarize this, while critical transactions theory provides valuable insights in the economic and technical aspects of the first three bottlenecks, it does not fully capture the complexities of a digitalizing energy landscape, and therefore falls short in explaining the fourth bottleneck, data sharing. A more holistic approach that includes social dimensions is necessary to effectively address the bottlenecks in data sharing.

8

Recommendations

This section aims to provide recommendations to alleviate the three critical bottlenecks with the potential to mitigate the short-term congestion issue. Section 8.1 will elaborate on the possibilities of integrating flexibility. Sections 8.2, 8.3, and 8.4 address the specific mechanisms of integrating flexibility with respect to these possibilities.

8.1. Mechanisms for integrating flexibility

Hennig et al. (2023) provide a comprehensive framework for understanding the various congestion management (CM) mechanisms used in electric distribution networks (Figure 11). This framework will serve as a starting point for developing the recommendations in this section.This diagram categorizes these mechanisms into distinct types and illustrates their relationships and trade-offs. The key elements and categories of the diagram are the categories of congestion management mechanisms and the decision variables involved, as explained by Hennig et al. (2023), and will be explained below briefly.

Categories of Congestion Management mechanisms

Static tariffs are fixed charges for network access that do not change over time. They are simple to implement but do not adapt to the changing network conditions. This makes them less effective in managing congestion that varies over time. Dynamic tariffs prices vary based on real-time or near-term network conditions. Dynamic tariffs provide more effective incentives for reducing peak loads and managing congestion but are more complex and introduce potential risks for users.

Local Flexibility Markets allow for the trading of flexibility services between consumers, aggregators, and network operators. These markets can efficiently allocate resources to manage congestion enabling the purchase of flexibility from those willing to adjust their consumption patterns. They are effective but susceptible to strategic behavior by market participants.

Direct Load Control (DLC) mechanisms involve the network operator directly controlling the power consumption of specific high-power devices, such as EVs and heat pumps. This approach provides immediate and reliable load adjustments but requires the installation of control infrastructure and may face regulatory challenges.

Design choices

The diagram also maps the influence of various design choices on the performance and risks associated with each CM mechanism.

The load-controlling party can either be the DSO or the user. When the DSO controls loads, the end-user or aggregator faces a curtailment risk. If the end-user or aggregator controls leads, the DSO faces a risk of network overload. The DSO position includes the offering of network access or the buy-back of network access. Offering network access includes control incentives directly in network access conditions, and buy-back network access is offered without tight limitations, and control is achieved through buy-back mechanisms. In addition, the timeframe is specified, ranging from static to near-term and real-time.

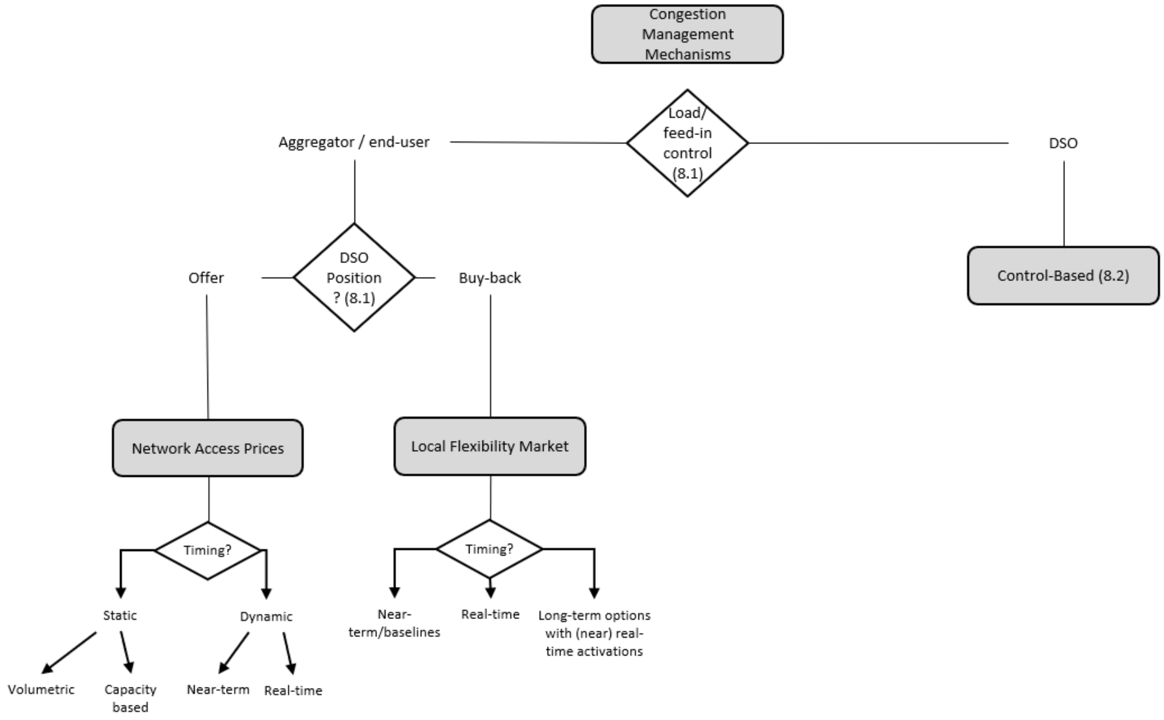


Figure 11: Congestion Management mechanisms (Hennig et al., 2023)

In the following sections, the recommendations for alleviating the bottlenecks will be provided. These recommendations have been developed with respect to the framework from Hennig et al. (2023) and the results from the interviews with stakeholders in this research.

8.2. Roles in the future energy system are unclear

To address this bottleneck, regulatory guidance, and directive intervention are required to define the division of roles and responsibilities within the future electricity market. Such regulatory clarity will provide a structured framework that enables all parties involved to develop and implement appropriate congestion management mechanisms into their portfolios and business models. By establishing clear guidelines, regulatory bodies can ensure that all stakeholders are aligned in their efforts to develop and modernize the distribution grid to enhance its efficiency and reliability.

From the interviews, the issue is not necessarily that the roles or responsibilities should be filled in a specific way but that they should be filled in the short term. Decision-making in the Netherlands within this domain was perceived as lagging behind other European countries, stalling development. Therefore, this research recommends providing clarity on the roles and responsibilities on the decision variables formulated in the framework.

The framework proposed at the beginning of section 8 proposes main decision variables where directive guidance and decisions should be made. These decision variables are as follows:

- Who is responsible for controlling the load and feed-in of electricity into the grid?
    1. *The DSO? The end-user? The aggregator?*
- If the DSO should be responsible for congestion management, what will its position be?
    1. *Offer or buy-back?*
- *What is the timing of the proposed mechanisms?*
    1. *Near-time or day-ahead?*
- What is the scope of control-based mechanisms?
    1. Should mechanisms be asset-based or connectivity based?

Trade-offs

When designing the roles and responsibilities, trade-offs should be taken into account. Some of these frameworks have been produced below.

- *Autonomy* or *Control*; certainty for DSOs through DLC could invade the privacy for end-users.
- *Complexity* or *User Engagement*; advanced demand response schemes can be complex for consumers to interpret.

- *Data Privacy* or *Grid Optimization*; aggregators might need access to detailed consumption data to optimize demand response.

- *Economic Incentives* or *Reliability*; over-reliance on financial incentives may lead to inconsistent participation, jeopardizing grid reliability during peak times.

Addressing this comprehensive bottleneck will not only support in alleviating the other two bottlenecks but will also pave the way for decision-making within stakeholders regarding which mechanisms and processes to implement. When stakeholders clearly understand their roles, they are more likely to collaborate effectively and contribute to a cohesive energy system.

8.3. The Margins for households

One of the primary bottlenecks identified from the research is the inadequate financial incentives for households to participate in demand response programs. Households and end-users currently lack the ability to monetize their flexibility, which results in little to no motivation to participate in demand response programs.

This recommendation suggests a control-based approach by the DSO as a CM mechanism and incentive for flexibility for two reasons. First, since this research has identified financial incentives to be inadequate, the recommendations look beyond voluntary measures to obligatory measures. Second, even if a better and more effective financial incentive is implemented, this does not directly create a market since it takes time for a new market to develop, which clashes with the short-term urgency of the low-voltage congestion issues.

Direct-load-control

DLC refers to a mechanism where the utility or grid operator, the DSO, directly controls certain electrical appliances within a household to manage the demand and ensure the stability of the grid. This approach can be particularly effective in reducing household peak demand and managing the congestion existing on the low-voltage grid. It is important to understand that while DLC is not based on financial incentives, remuneration for (mandatory) participation could involve financial measures. DLC measures differ between connection-based approaches, where the maximum consumption is constrained, and asset-based approaches, where certain types of assets like EVs are excluded from using the grid during peak hours.

This approach offers a structured and potentially more effective approach to managing load distribution on the low-voltage level. To provide a real-life example: as of January 1st, Germany has implemented new legislation enabling DSOs to control the power usage of electric vehicle chargers and other high-power devices to manage grid congestion (ElaadNL, 2024). This includes remote adjustment of power consumption for devices over 4.2 kW. This law ensures that consumers receive compensation combined with incentivized off-peak usage through dynamic retail rates. This technical solution involves smart meters and home energy systems, which facilitate communication between grid operators and devices.

DLC can be implemented in several ways. There is no one-size-fits-all solution. A comprehensive approach should consist of a combination of the following methods, the specific conditions of which should be further specified during development:

Automated control of appliances: In DLC programs, the DSO can remotely control specific heavy-consumption appliances, such as air conditioners, water heaters, and electric vehicle chargers. During peak hours, the DSO can temporarily turn off these appliances or reduce their power consumption.

Contractual agreements: Households participating in DLC programs typically enter into agreements with their utility provider regarding electricity consumption. These agreements outline the conditions under which the DSO is allowed to control their connected appliances. In return for this agreement, the households may receive incentives such as reduced energy bills or fixed payments.

Regulatory and market integration: The DLC can be integrated into existing regulatory frameworks and market structures around the DSO. For example, the utility provider can be mandated to offer these programs as part of their ancillary services offerings to ensure a wider adoption across different household types.

Technological infrastructure: To implement DLC programs, advanced metering infrastructure and smart devices that are capable of receiving and executing control signals are required. This infrastructure allows for real-time monitoring and controls, ensuring that the mechanisms are effective while minimally disrupting household patterns.

Benefits and drawbacks of DLC

Benefits

The largest significant benefit of Direct Load Control is the enhancement of grid stability. Providing utilities with the ability to actively manage peak demand helps prevent congestion and potential system failures. This proactive grid management ensures a more reliable and resilient electrical grid capable of accommodating the increasing energy demand from modern households. In addition, this approach provides a significant amount of certainty for the DSO since it can control the demand itself.

Another advantage is the cost efficiency of grid upgrades compared to the current situation. DLC is able to reduce the need for costly grid upgrades by optimizing the use of the existing grid infrastructure. This efficient management can lead to substantial cost savings for utility providers, which can eventually be passed on to consumers through lower energy bills. Moreover, by flattening the peak demand, the DLC can decrease the necessity for expensive peak power plants, further reducing the costs of operating the grid.

DLC also positively impacts the environment compared to mechanisms that aren’t control-based. Effective demand management can reduce the need for additional power generation, particularly from fossil-fuel-based sources like coal. This reduction in power generation leads to lower emissions, therefore contributing to national and global sustainability targets. By minimizing the sustainable footprint of energy consumption, DLC supports a cleaner energy system.

Drawbacks

Despite the benefits, DLC also has some drawbacks. One of the primary challenges associated with the drawbacks is consumer acceptance. Many consumers and end-users might be reluctant to relinquish control over their appliances to utilities, fearing the loss of autonomy and discomfort. Overcoming this resistance would require effective communication strategies and attractive incentives that showcase the benefits and ensure consumer participation.

Another significant issue is privacy concerns. DLC involves real-time monitoring and the control of household appliances, raising concerns about data privacy and security. To build up consumer trust, utilities must implement robust data protection measures and transparency policies.

Technological challenges also pose barriers to this widespread adoption and implementation. The deployment of DLC requires significant investment in smart technologies in IT infrastructure, including advanced metering and smart appliances capable of receiving and executing control signals. This investment could prove to be substantial, particularly for smaller utilities.

8.3.1 Control-Based Congestion Management Framework

In addition, the insights from this research have been used to further elaborate on the possibilities existing in the control-based domain, further developing the framework of Hennig et al (2023). Where Hennig et al. (2023) discuss decision variables and factors to take into consideration for control-based mechanisms, this research uses the results and insights from the interviews to extend the control-based approaches further.

To validate this framework, Stedin has been consulted to justify the main focus points of the framework. Following DSOs, this research emphasizes two main decision variables as focus points for decision-making in control-based approaches: *asset-based* and *connection-based*. Connection-based approaches relate to limited grid connection in teams of peak consumption, where a maximum limit of energy consumption per household will be implemented. Asset-based mechanisms relate to the exclusion of high energy-intensive appliances during peak hours, for example, electric vehicles.

A connection-based approach could be similar to the approach in Germany, where during peak hours, the DSO has the power to reduce the maximum capacity to 4,2 kW for all controllable appliances (ElaadNL, 2024). Asset-based approaches could include the exclusion of certain types of assets during peak hours. These assets will likely involve appliances with high consumption of electricity, like EVs. During the interviews, DSOs tended to favor an asset-based approach in the short term due to its simplicity and short-term influence. In the long term, DSOs favored connection-based approaches, as these are estimated to be more efficient as congestion management mechanisms.

The modified and extended framework, which further highlights control-based mechanisms, is displayed on the next page.

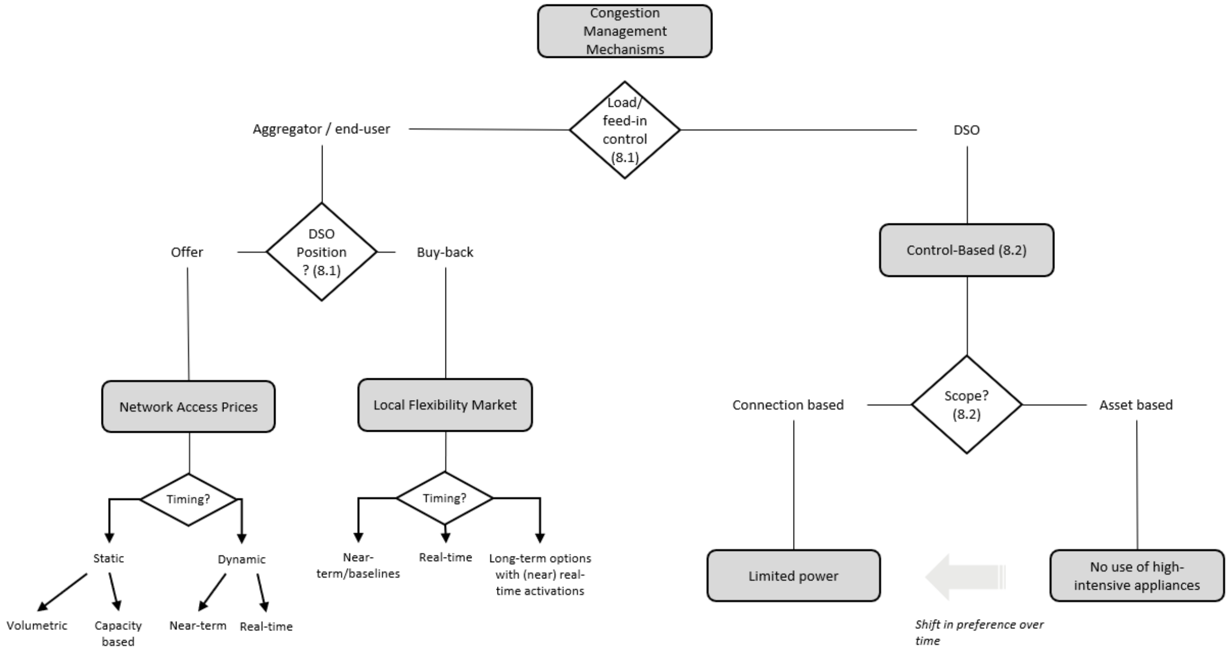


Figure 12: Modified Congestion Management mechanisms framework.

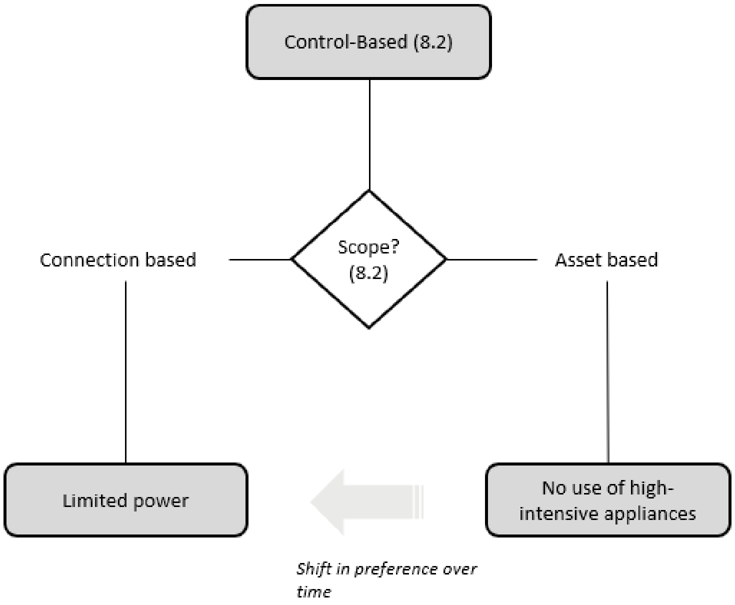


Figure 13: Control-based mechanisms enlarged.

8.4. The lack of standardized communication protocols

A critical bottleneck identified in this research is the lack of one unified standard among smart appliances. This issue significantly limits the widespread adoption of smart appliances, as they operate on different protocols and standards. This makes effective communication and interoperability among appliances challenging. Without a common language, appliances cannot effectively coordinate with each other or with the distribution grid. Currently, there is no incentive for appliance manufacturers and other market parties to align their smart appliance products with a single standard. This fragmentation of protocols and standards persists because individual companies prioritize systems that are applicable to their own products, providing them with a competitive advantage. However, this approach is detrimental to the broader goal of creating an integrated and cohesive smart grid.

Given the lack of market-driven solutions and the urgency of the short-term congestion risks on the low-voltage grid, it is crucial to consider other directions, such as direct intervention. Establishing a single, mandatory communication protocol among all smart appliances could solve this bottleneck while safeguarding the critical function of *interoperability* and *capacity management*. In addition, mandating one shared protocol respects the modes of organization provided by the critical transactions framework, *systems, and norms*.

The bottleneck here is the lack of one unified standard. While this research does not further explore the criteria for selecting an adequate standard, it should be noted various stakeholders mentioned the S2 protocol during the interviews as suitable within the Dutch energy ecosystem. The S2 protocol is a critical communication standard that facilitates the control and coordination of smart appliances (S2standaard, 2024). It enables the integration of smart meters and home energy management systems with grid operators, allowing for real-time adjustments in power usage to effectively manage grid congestion (S2standaard, 2024).

The recommendation, therefore, suggests directive intervention, where one single standard is mandated among smart appliances. Which standard would be the most suitable is not discussed within this research.

Benefits and drawbacks of standardized communication protocols

Benefits

One of the primary benefits of mandating a single communication protocol is the enhancement for interoperability of smart appliances. With all smart appliances operating at the same standard, they can communicate seamlessly with each other and with the grid. This interoperability is essential for flexibility and demand response and optimizing electricity allocation across the grid. This ensures all connected devices can participate in energy-saving measures. In addition, this allows for real-time data sharing with grid operators, enabling more accurate and dynamic grid management.

Furthermore, standardized communication protocols can further drive innovation. When all devices adhere to one common standard, developers can create new services and applications which could leverage the full capabilities of the connected grid. This environment could stimulate technological advancements and innovation in new business models, driving economic growth and improving end-user experiences.

Drawbacks

Implementing a standard communication protocol could also bring along several drawbacks. One significant challenge is the resistance from manufacturers, who have invested heavily in exclusive and personal systems. These companies could be reluctant to shift to a new standard, which could result in substantial financial losses and operational disruptions for them. Overcoming this resistance will require careful regulatory design and intervention. In addition, manufactured internationally could be particularly resistant to implement a Dutch standard.

Another drawback could result from the regulatory and bureaucratic delays. Establishing a new standard involves extensive coordination among the various stakeholders, including manufacturers, utilities, regulating parties, and end-users. This process can be time-consuming and could face opposition from multiple market parties, delaying the implementation of a standard.

In addition, there is a risk of technological stagnation, where mandating a single standard could limit the pace of innovation if the chosen protocol becomes outdated or fails to keep up with technological advancements. Ensuring that the standard remains flexible and adaptable to future development is crucial to avoid locking in the energy industry.

Challenges with the S2 Protocol

The S2 protocol is a Dutch standard. Mandating a single standard like the S2 introduces various difficulties. Products are manufactured internationally, making it challenging to impose Dutch standards universally. Implementing Dutch standards could lead to fragmented standard in the long-term at a higher level, particularly within the European market. This fragmentation would mirror current issues but on a broader scale, further complicating the integration and coordination across different regions and manufacturers.

9

Discussion

In this section,, the findings of this research project will be summarized and discussed. They are based on the bottlenecks identified from the interviews and the recommendations provided for alleviating them. Following those findings, the limitations of the research, mainly based on the methodology and the results from the interviews, will be discussed.

9.1. Findings and interpretation

In this section, the key findings of the research will be discussed. These key findings will be supplemented with their interpretation within this research.

9.1.1. Findings

The findings from this research highlight critical factors and bottlenecks that influence the widespread adoption of smart appliances into the Dutch low-voltage electricity network. These factors, which have been identified through extensive literature review and stakeholder and industry expert interviews, include the lack of regulatory guidance, the margins for households to monetize their flexibility, and the lack of standards. Each of these bottlenecks presents unique challenges and opportunities that must be addressed in order to achieve a more resilient and reliable energy system that allows for optimal integration of flexibility.

Regulatory uncertainty emerged as a major impediment to the adoption of smart appliances and flexible mechanisms. Stakeholders and market participants are hesitant to invest in long-term solutions and propositions since their future roles and responsibilities within the future energy system are unclear. This lack of clarity limits strategic decision-making and the development of the necessary mechanisms and IT infrastructures. Providing regulatory clarity and guidance is critical for enabling stakeholders to align their strategies with long-term objectives to drive innovation and accommodate coordinated development.

The findings in this research gave insight into incentives for households to participate in flexibility initiatives. This research revealed that the current economic incentives for households to invest in flexible appliances are insufficient. This financial barrier limits the participation of end-users in demand-response programs and load shifting, which are essential for the management of peak demand and short-term allocation of electricity to mitigate congestion on the low-voltage grid.

The implementation of Direct Load Control (DLC) programs was identified as a potential direction that could safeguard the critical function of capacity management, providing structured incentives and real-time control capabilities. These programs can enhance grid stability while offering financial incentives and benefits to end-users. This enhances the economic viability of smart appliances.

The lack of standardized communication protocols among smart appliances emerged from the interviews as a significant barrier to effective integration into the electricity grid. This finding underscores the importance of interoperability for enabling seamless communication between appliances. Standardization is crucial for optimizing energy management systems and enhancing the effectiveness of flexibility and demand response programs. Without shared communication standards, the potential for flexible appliances to contribute to the stability of the grid is severely limited. The findings from this research suggest that regulatory intervention is essential in this case and that mandating universal communication protocols should foster a cohesive ecosystem where all devices can interact effectively.

Effective data sharing is vital for enabling real-time allocation of supply and demand and optimizing the use of smart appliances. However, current regulations and market structures hinder this process. The absence of clear policy frameworks and guidelines for data sharing creates significant barriers.

9.1.2. Interpretation of findings

In the Netherlands, characterized by its liberalized energy market, there has been a prevalent belief in the power of market forces and parties to efficiently contribute to efficiency and innovation within the energy domain (Marktwerking elektriciteit & gas – Energie Nederland, z.d.). This approach, which is grounded in economic theory, suggests that competition and consumer choice together drive innovation and the optimal allocation of resources. Where these forces might drive costs for consumers down, the results from this research raise several questions about the market's ability to address the short-term congestion issues on the low-voltage grid. First, *can these market forces ensure the security of supply on the low-voltage grid*? As the Netherlands plans to tackle low-voltage congestion, it aims for smart metering and demand response to become the new standard of the future energy system for households. However, this research exposed several bottlenecks for the widespread adoption of these mart appliances on the low-voltage grid. As smart appliances prove crucial for maintaining the future security of supply, this questions the market's ability to drive innovation in this direction effectively, therefore ensuring the future security of supply. Second, *should market forces ensure the security of supply*? As this research indicates in section 7, market forces drive the transactions to support the electricity system's four critical functions (system control, capacity management, interoperability, and interconnection). In doing so, market forces are trusted to maintain the performance of the electricity system and, therefore, guarantee the security of supply. However, it could be argued such essential aspects of critical infrastructures for the Netherlands as a whole should be liberalized. Third, while markets may be formed efficiently on a large scale, *can this approach be applied to the low-voltage grid*? Every low-voltage grid has unique characteristics and constraints. According to a representative from Liander during the interviews, it would be unrealistic to translate this large-scale approach to low-voltage grids. This would mean that each street of are has multiple market parties offering congestion mechanisms, which is unfeasible. Fourth, even if market forces would prove to produce efficient incentives aimed at indirectly addressing congestion and flexibility, the question arises *if they can within the relevant* *timeframe*? Providing a market for, for example, dynamic tariffs does not equal an instant market. Market development and optimal allocation of supply and demand take time. However, the projected congestion risks arise as soon as 2026, with around a million households experiencing risks from low-voltage congestion in 2030. Therefore, the question arises if, taking this timeline into account, market forces can address these issues on time.

Second, the future energy grid, as a broader perspective, should not be overlooked. The rapid uptake of renewable energy and the policy push for electrification of demand resulted in significant additional flows of electricity on the low-voltage grid. Therefore, one could say that these issues should not come as a surprise for stakeholders within this domain. However, congestion on the low-voltage grid has still remained a surprise for system operators and regulatory parties. It is important that in addressing these issues, the bigger picture is not overlooked. While flexibility and smart appliances are expected to be essential components of the future energy system, increasing the transmission and distribution lines to facilitate energy flows and the transition to a sustainable energy system is crucial. In addition to managing congestion and smart metering as a focal point of the future energy system, increasing capacity should remain the main enabler of the transition for the electricity grid.

Third, where the bottlenecks regarding regulatory guidance, the margins for households, and standardization are issues that can be mainly addressed through a techno-economic perspective, this is not the case for data sharing. In an increasingly digitalizing energy landscape, data sharing among stakeholders such as system operators and consumers should be approached with more nuanced, incorporating a social perspective. Social factors such as data sharing and equality should be taken into account and integrated in developing incentives and decision-making.

9.2. Potential Limitations

While this research exposes valuable and interesting insight into the adoption of smart appliances and their integration into the low-voltage grid, several limitations should be considered.

9.2.1. Scope of interview participants

The findings from this research are derived from interviews conducted with a specific group of stakeholders within the Dutch energy sector. While efforts were made to ensure diversity among the participants – ranging from system operators, retail providers, and service providers to regulatory institutions, and including both small and large entities – there are inherent limitations to this approach. The selected participants, though varied, might not fully represent the entire spectrum of perspectives within the energy sector.

One significant limitation is the underrepresentation of end-users, the consumers, in the sample of interviews. While the perspectives of end-users were indirectly addressed through interviews with retail providers, this approach may not fully capture the nuanced views and experiences of the actual consumers of energy services. Retail providers, although they interact with end-users, may present filtered or even a strategic perspective which aligns with their business objectives, potentially overlooking concerns at the center of consumer worries, behaviors, and expectations of individual consumers.

The selection process might have introduced a bias towards stakeholders who are more accessible, willing to participate, or even more vocal about their experiences and perspectives. This could have led to an overrepresentation of certain viewpoints while marginalizing less prominent but equally important perspectives. For instance, smaller or emerging entities, which might face different challenges compared to established players, could have been underrepresented.

Additionally, the focus on stakeholders within the Dutch energy sector means that the findings are context-specific and may not be easily generalizable to other geographical regions or sectors. The regulatory, economic, and cultural context of the Netherlands shapes the energy sector in unique ways, and stakeholders from other countries or regions might face different challenges and opportunities that were not captured in this study.

To address these limitations, future research should incorporate a more representative range of stakeholders. This could include direct interviews with end-users to capture their firsthand experiences and expectations. Moreover, expanding the research to include stakeholders from different regions or countries could provide comparative insights and enhance the generalizability of the findings. Including a diverse range of participants will help achieve a more comprehensive understanding of the complexities within the energy sector and the various perspectives on its challenges and opportunities.

9.2.3. Interpretation of interviews

Another significant limitation of this research is the interpretation of the findings derived from interviews with stakeholders within the Dutch energy sector. Interpreting qualitative data, particularly from interviews, is inherently subjective and can vary widely depending on the researcher's perspectives and biases (Griffee, 2005).

The analysis and interpretation of interview results are influenced by the researcher's own background, beliefs, and experiences. This subjectivity can affect how themes and patterns are identified and emphasized (Griffee, 2005). Although efforts were made to apply rigorous and systematic methods for data analysis, it is possible that other researchers might have drawn different conclusions from the same set of data. For instance, specific responses might be interpreted differently based on the researcher's familiarity with the industry, theoretical inclinations, or even personal experiences within the energy industry.

The context in which the interviews were conducted also plays a critical role in shaping the findings. The timing of the research, the current state of the energy sector, and contemporary issues at the time of the research and interviews could have influenced the responses of participants. Different temporal or situational contexts might lead to different interpretations of the same issues. For instance, regulatory changes or technological advancements occurring after the interviews might alter the relevance or interpretation of the findings (Griffee, 2005).

There is also the potential for confirmation bias, where the researcher might consciously or unconsciously interpret the data in a way that confirms the pre-existing beliefs or hypotheses. This can lead to an overemphasis on certain findings while neglecting or underplaying other that might be equally significant but do not fit the researcher's anticipated narrative (Nunkoosing, 2005).

To mitigate these limitations, future research should consider employing multiple analysts to revie and interpret the data. This approach, known as inter-coder reliability, involves having several researchers independently analyze the same data and then compare their findings to identify and reconcile discrepancies. Additionally, adopting a triangulation method, where multiple data sources, theories, and methods are used, can provide a more balanced and comprehensive interpretation of the findings. Engaging with participants to validate the interpretations, can also enhance the credibility of the results.

9.2.4. Validity of the research

Another critical area of limitation in this research is the validity of the results obtained from interviews with stakeholders and industry experts. Ensuring validity in qualitative research involves accurately capturing and representing the studied phenomena. Several factors discussed above can affect the validity of the interview results (Nunkoosing, 2005).

The process of selecting participants can introduce bias, affecting the validity of the results. Despite efforts to include a diverse range of stakeholders, the sample and the selection size may not fully represent the entire population within the Dutch energy sector. Certain groups, like smaller or less vocal stakeholders, may have been underrepresented, leading to a skewed understanding of the sector's dynamics (Nunkoosing, 2005).

Participants may also provide socially desirable responses or answers that they believe the interviewer wants to hear, rather than their true thoughts and experiences. This can be particularly prevalent in sectors like the energy sector, where political, economic, or regulatory sensitivities may exist. Response bias can compromise the authenticity of the collected data, impacting the findings' validity (Griffee, 2005).

The accuracy of the information participants provide can be influenced by their ability to recall past events and experiences accurately. Recall bias can occur if participants have difficulty remembering details or if their memories have been influenced by subsequent events. This can lead to inconsistencies or even inaccuracies within the data, affecting the overall validity of the research (Nunkoosing, 2005).

The presence and behavior of the interviewer can also impact the validity of the interview results. Interviewers may unintentionally lead participants with their questions or reactions, influencing the responses given. This can be mitigated by using standardized interview protocols and training interviewers to minimize their influence, but it remains a potential source of bias (Nunkoosing, 2005).

The context in which the interviews were conducted, including the timing, location, and environment, can affect the responses of participants. External factors like current events, organizational changes, and recent experiences can influence participants' perspectives and the information they provide. These contextual factors have to be considered when interpreting the validity of the results (Nunkoosing, 2005).

As discussed in this section, the integration of flexible appliances has the potential to enhance the overall efficiency and reliability of the Dutch electricity grid. By addressing these bottlenecks through targeted recommendations and interventions, the Netherlands can pave the way for a sustainable and resilient energy system.

The energy grid in general and the existing challenges in this research are complex and multifaceted, requiring a coordinated approach that involves multiple perspectives, like regulatory intervention technological innovation, and active consumer engagement. The recommendations designed in this research offer a roadmap for overcoming these challenges and achieving a more flexible and efficient energy system.

The successful implementation of these recommendations will depend on collective efforts of the involved stakeholders, which include regulatory bodies, industry participants, and end-users. By working together, these parties can develop an energy system which not only meets the current demand but is also suited to face the challenges of the future.

Ultimately, the transition to a flexible, resilient, and sustainable energy system is not just a technological or economic challenge but also a social one, as discussed in this research. This means it requires a paradigm shift in how we approach energy consumption and management. This research has provided a foundation for understanding key issues and opportunities existing within this transition and offers a path forward for achieving a more sustainable energy future for the Netherlands.

This journey towards a more sustainable energy future is ongoing and dynamic by nature. As new technologies emerge and the behavior of consumers evolves, continuous research and adaptation will be essential. By remaining flexible and responsive to potential changes, the Dutch electricity sector can become a model region for other countries striving to reach similar goals. This research marks a step forward in that journey by contributing to the collective effort to create a more resilient and sustainable energy system.

10

Conclusion

In this section the outcomes of the thesis project will be concluded on. First, the research question will be answered and then a reflection on the project and its relevance will be presented.

10.1. Main research question

At the beginning of this research, multiple research questions were formulated, which motivated the research. The main research question comes from the identified knowledge gap as explained before, grounded both in practicality and academics. From this question, several sub-research questions are derived. In this section, the main research question is first answered, and then the sub-research questions one by one. This main research question is:

How can demand response be enabled to mitigate congestion on the low-voltage network?

Within this research question, the goal of the research can be seen: to identify the bottlenecks of widespread adoption of smart appliances to enable demand response on the low-voltage grid. In addition, the research provides recommendations aimed at alleviating these same bottlenecks. This is what was done in this research to identify critical bottlenecks that hinder the widespread adoption and provide further recommendations. The critical bottlenecks identified in this research are the lack of regulatory guidance, the margins for households to monetize their flexibility being too thin, the fragmented landscape of standards and protocols, and the regulatory barriers for data sharing among end-users and system operators. Of these four main bottlenecks, the first three were classified critical in accordance with critical transactions theory. Therefore, these bottlenecks have been taken into further account in the recommendations. The recommendations to alleviate these bottlenecks shared the main theme of direct regulatory intervention and refraining from solely trusting market forces to address this issue in the short term. Per bottleneck, the recommendation includes short-term decision-making on the decision variables provided, direct-load-control-based mechanisms for the DSO on the distribution grid, and the implementation of one unified standard for smart appliances.

10.1.2. Sub-research questions

The main research can be dissected into a few smaller questions, that together have made it possible to answer the research question comprehensively above. These sub-research questions are answered in detail throughout this thesis, but will be summarized here, as well as referring to the parts where the full answers can be found.

What critical bottlenecks exist for adopting flexible appliances on the low-voltage network?

This question explores the critical bottlenecks the widespread adoption of smart appliances is facing. To do so, interviews with stakeholders and industry interviews have been conducted in order to provide a comprehensive overview of the situation and dynamics of the low-voltage grid. During the interviews, eight bottlenecks arose as limiting the adoption of smart appliances. Of these eight bottlenecks, four bottlenecks were classified as critical lending the critical transactions theory and this theory's definition of criticality in the context of complex infrastructures, which is described in the theory section. Section 5.2 in this research discusses the bottlenecks arising from the interviews, while section 7.2 elaborates on determining their criticality. Below, the key findings of this question, the four critical bottlenecks, have been summarized.

The lack of regulatory guidance

The uncertainty regarding the division of roles and responsibilities in the future energy system has emerged as a major impediment to the adoption of smart appliances. Stakeholders are hesitant to invest resources in long-term mechanisms and solutions due to unclear future roles and responsibilities within the energy system. Providing regulatory clarity and guidance regarding these roles is critical for enabling stakeholder to align their strategies with long-term objectives, thereby fostering coordinated development of the energy sector and innovation. Well-defined regulatory direction can facilitate strategic planning while ensuring fair competition and supporting the overall transition to a sustainable energy system.

The margins for households are too thin.

The interviews conducted in this research revealed that current economic incentives for households to invest in flexible smart appliances are insufficient, which in turn limits their participation in demand response programs. To overcome this barrier, the implementation of Direct Load Control programs has been suggested as a potential direction. These programs could provide structured incentives and real-time control capabilities, thereby enhancing the stability of the grid. By enabling utilities to manage peak demand and consumption more effectively, DLC programs can reduce the need for costly grid upgrades while also lowering operational costs, ultimately resulting in savings for end-users while contributing to a more resilient grid.

Lack of standards and communication protocols.

This research highlighted the significant barriers resulting from the absence of standardized communication protocols among smart appliances. This lack of interoperability limits the effectiveness of the integration into the electricity grid, underscoring the need for direct regulatory intervention to mandate a common communication standard. The establishment of these protocols should ensure seamless communication between devices, optimizing the potential of energy management systems and enhancing the effectiveness of flexibility and demand response programs. The benefits of this approach include improved grid stability, efficient energy usage, and the potential for innovative services that can be used to leverage the full integration of the smart grid.

Data Sharing

Effective data sharing is vital for enabling real-time allocation of supply and demand and optimizing the use of smart appliances. However, current regulations and market structures hinder this process. The absence of clear policy frameworks and guidelines for data sharing creates significant barriers.

How can these bottlenecks be explained?

This question aims to explain why these bottlenecks have surfaced and justify their existence. In doing so, critical transactions theory is used. Critical transactions theory provides a framework in which the scope of control and speed of adjustment required for the bottlenecks can be determined, after which they have been positioned within this framework. At the intersection of the corresponding scope of control and speed of adjustment, organizational modes have been suggested as structures to maintain the functioning of the critical functions to which the bottlenecks relate. When positioning each bottleneck within this framework, it became clear that the suggested modes of organization did not align with the current and real-life organizational circumstances regarding the bottlenecks. This misalignment was used to argue for the theoretical explanation and existence of the bottlenecks.

How can these bottlenecks be alleviated to mitigate low-voltage congestion?

This section elaborates on how the recommendations to alleviate the bottlenecks to mitigate low-voltage congestion have been formulated. The goal of this section was to address bottlenecks that have the potential to mitigate low-voltage congestion, as this is the main point of focus due to the urgency of the risks associated. As explained in section 6.2, while the four bottlenecks have the potential to do so, alleviating data sharing does not. In the long term, smart metering and data sharing will be the new standard. However, in the short term, system operators' projections sufficiently allow to predict consumption and production, as stated by a representative from Liander. Therefore, the first three bottlenecks have been used to develop recommendations.

Critical transactions theory suggests modes of organization that serve as structures to maintain the performance of the underlying critical functions. These modes of organization have been used as a starting point for developing recommendations to alleviate bottlenecks.

This research illuminates the role of market forces in addressing congestion on the low-voltage network. Its results question the market's ability to address the short-term bottlenecks and, therefore, explore more directive measures as the main thread for the recommendations.

This resulted in the following recommendations. For the first bottleneck, decision-making on the following decision variables is recommended; the responsible party for load control, DSO position, timing for mechanisms, and scope of control for control-based mechanisms. For the second bottleneck, direct-load-control-based mechanisms are suggested to facilitate the DSO in directly controlling the load on the distribution grid in times of peak demand. For the third bottleneck, mandating one single standard has been suggested as a recommendation to unify the fragmented landscape of smart appliance standards and norms.

10.2. Reflection

This section presents the research's reflection. This reflection includes the academic relevance, societal contribution, and recommendations for future research.

10.2.1 Academic relevance

In this thesis project, interviews with stakeholders and industry experts were conducted to identify bottlenecks for the widespread adoption of smart appliances. A literature review was conducted to develop and formulate an academic knowledge gap. The identified gap was mainly *that the barriers that hinder the successful and widespread adoption of DR and smart appliances are unknown*. This literature review and the identified gap can also be used to position this research within the existing literature. The Netherlands has unique characteristics, such as a fully unbundled energy system, high penetration of renewable energy sources, and a government that propels towards making smart metering the new standard of the future energy system. For countries with similar characteristics, the outcomes from this research contribute to the applicability and ability of smart appliances to mitigate congestion on the low-voltage grid.

The strength of this project academically is that it provides a structured overview of congestion problems on the low-voltage grid. The complex dynamics of the Dutch energy grid and the unique characteristics of the low-voltage grid make it hard to get a comprehensive overview of the steps necessary to design the market, roles, and responsibilities in such a way that the reliability and resilience of the Dutch electricity is safeguarded.

By conducting interviews with stakeholders such as system operators, retail parties, knowledge institutions, and regulatory authorities, and aligning visions, this research gives a comprehensive overview of the issues and dynamics at play at the low-voltage grid. This holistic approach towards collective visions, roles, and responsibilities can be used to identify which approach would be successful in addressing low-voltage congestion and implement the mechanisms necessary.

10.2.2. Societal relevance

This research was carried out taking into account the short-term risks of low-voltage congestion. Issues from congestion could affect households as soon as 2026 onwards. If low-voltage congestion is not addressed in the short term, 1.5 million small-scale consumers are at risk of being affected by too low or too high voltage levels and even outages.

Therefore, reflecting on the societal relevance of the project, it becomes clear that the outcomes can aid greatly in the mitigation of low-voltage congestion by alleviating the bottlenecks for widespread smart appliances. In doing so, smart appliances can be utilized to facilitate demand response programs and load shifting to reduce peak loads and mitigate congestion. With this in mind, this research can be used by regulators as a document for guidance and clarification on the dynamics at play at the low-voltage grid. In addition, this research can be used by system operators and market participants to develop mechanisms and frameworks to efficiently integrate smart appliances. Overall, this research structures the issues existing at the low-voltage grid and serves as guidance in navigating this complex landscape and the challenges involved.

10.2.3. Future work

To address the challenges described and pave the way for a sustainable and resilient future energy grid, several recommendations for future research will be suggested.

First of all, section 7.3 argues that critical transactions theory falls short in describing the challenges associated with data sharing in an increasingly digitalizing energy system. Where sharing data is often approached from a technical-economic perspective, this research argues that data sharing requires a more nuanced approach fit for the context of the changing energy system, where social factors such as privacy and data equality are taken into account. Therefore, future research should focus on taking these social factors into account when exploring barriers and opportunities within the data-sharing domain.

Second, as argued in section 8.4, one unified landscape for standards regarding smart appliances, where one standard is the norm, is recommended. During the interviews, the S2 standards was discussed as a potential candidate favored by the interview participants. Future research should aim to analyze which standards technically, economically, and socially would best fit the goals and characteristics of the Dutch energy system. In addition, researchers should be aware of this bottleneck repeating on a European scale, where the ecosystem remains fragmented but on a larger scale. This could again limit the integration and unification of standards within the energy domain.

Third, in the recommendation section trade-offs are discussed to consider when developing policies regarding low-voltage intervention. Trade-offs such as autonomy versus control, complexity versus user engagement, data privacy versus grid optimization, and economic incentives versus reliability should be further explored to better guide regulatory decision-making and navigate the complex challenges of the low-voltage electricity grid.

Fourth, this research identifies a potential blind spot among stakeholders regarding medium-term capacity utilization on the low-voltage grid. Since the stakeholders involved in interviews include key players like system operators, regulatory agencies, and retail providers, future research should further confirm the possible existence of this blind spot and address this issue.

10.2.4. CoSEM alignment

The low-voltage electricity grid is a dynamic environment with many interconnected components and players that interact with each other in various ways. Therefore, it can be labeled as a typical complex system (Ladyman et al., 2021). Focusing on smart appliances and the bottlenecks to their adoption, the research has a clear technological component, which includes the technical issues as well as the recommended management strategies. By formulating recommendations in both the technical and regulatory domains, this research also demonstrates the inclusion of a regulatory component.

In addition, the research covers values from both the public and private domain, since both system operators and market participants are included in the research perspectives to identify bottlenecks and formulate recommendations. Furthermore, the research has systematically gathered and analyzed these bottlenecks and utilized theories and methods from the TU Delft

Faculty of Technology, Policy, and Management. By utilizing the Critical Transactions framework, developed by Rolf Kunneke, this research addresses both the technical and economic perspectives of the issues at hand from a system engineering perspective.

Throughout this research, section 3 will provide an extensive literature review to dive into this subject and develop a knowledge gap in the selected literature, eventually formulating the research question. Section 4 will elaborate on the research methodology to address this research question and propose sub-questions aiming to comprehensively answer the research question. Section 5 will present the results of the research. Section 6 provides the theory used to analyze these results and functions as a starting point for the recommendations. In section 7, the theory from section 6 will be borrowed to academically explain the results and position these results within the theory. Additionally, this section will also reflect on the theory for justifying the results. Section 8 will provide recommendations on addressing the issues identified. Section 9 will interpret the findings and discuss the research. Lastly, section 10 concludes on the research and comprehensively answers the formulated research question.

10.2.5. Personal reflection

Conducting this research has been a professional, enriching experience, offering me the opportunity to gain a profound understanding of the complexities involved in the current energy transition. Engaging with multiple experienced stakeholders and industry experts has highlighted the importance of interdisciplinary approaches and collaborative efforts in addressing issues at the intersection of technology and regulation. This thesis has also underscored the need for a flexible mindset and innovation in guiding the transition towards sustainable energy practices. On a personal level, this research has solidified my commitment to contributing to the field of sustainable energy management, equipping me with valuable skills in aligning efforts, which I will bring with me in my future professional career.

10.2.6. Final thoughts

As discussed in this research, the integration of flexible appliances holds the potential to enhance the overall efficiency and reliability of the Dutch electricity grid. By addressing these bottlenecks through targeted recommendations and interventions, the Netherlands has a position to pave the way for a sustainable and resilient energy system.

The energy grid in general and the existing challenges in this research are complex and multifaceted, requiring a coordinated approach that involves multiple perspectives, like regulatory intervention technological innovation, and active consumer engagement. The recommendations designed in this research offer a roadmap for overcoming these challenges and achieving a more flexible and efficient energy system.

The successful implementation of these recommendations will depend on the collective efforts of the involved stakeholders, which include regulatory bodies, industry participants, and end-users. By working together, these parties can develop an energy system that not only meets current demand but is also suited to face the challenges of the future.

Ultimately, the transition to a flexible, resilient, and sustainable energy system is not just a technological or economic challenge but also a social one, as discussed in this research. This means it requires a paradigm shift in how we approach energy consumption and management.

This research has provided a foundation for understanding key issues and opportunities existing within this transition and offers a path forward for achieving a more sustainable energy future for the Netherlands.

This journey towards a more sustainable energy future is ongoing and dynamic by nature. As new technologies emerge and the behavior of consumers evolves, continuous research and adaptation will be essential. By remaining flexible and responsive to potential changes, the Dutch electricity sector can become a model region for other countries striving to reach similar goals. This research marks a step forward in that journey by contributing to the collective effort to create a more resilient and sustainable energy system.

This research marks a significant step forward in the collective effort to develop a more sustainable and future-oriented energy system. The insights gained from this research can inform policy decisions, guide future research, and inspire practical actions which drive innovation and power the transition to a smart and flexible energy grid. The Netherlands, with its commitment to sustainability and innovation, is well-positioned to lead this transition, setting an example for nations globally in addressing the complex challenges of modern energy systems.

11

References

2030 climate targets. (z.d.). Climate Action. https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2030-climate-targets_en

Adeoye-Olatunde, O. A., & Olenik, N. L. (2021). Research and scholarly methods: Semi-structured interviews. *JACCP: Journal Of The American College Of Clinical Pharmacy, 4*(10), 1358–1367. https://doi.org/10.1002/jac5.1441

Batlle, C., & Ocaña, C. (2013). Electricity Regulation: Principles and Institutions. In *Power systems* (pp. 125–150). https://doi.org/10.1007/978-1-4471-5034-3_3

Bots, P. W. G., & Van Daalen, C. (2012). Designing socio-technical systems: Structures and processes. *CESUN 2012: 3rd International Engineering Systems Symposium*. https://repository.tudelft.nl/islandora/object/uuid%3A827ee52f-b0cc-40b2-90c0-00e3c57078d1/datastream/OBJ/download

Climate Change 2022: Impacts, Adaptation and Vulnerability. (z.d.). IPCC. https://www.ipcc.ch/report/ar6/wg2/

Cundy, A., Bardos, R., Puschenreiter, M., Mench, M., Bert, V., Friesl-Hanl, W., Müller, I., Li, X., Weyens, N., Witters, N., & Vangronsveld, J. (2016). Brownfields to green fields: Realising wider benefits from practical contaminant phytomanagement strategies. *Journal Of Environmental Management, 184*, 67–77. https://doi.org/10.1016/j.jenvman.2016.03.028

Eric, V. D. (2005). Liberalizing the Dutch Electricity Market: 1998-2004. *Social Science Research Network*. https://doi.org/10.2139/ssrn.869728

Escobar, J. J. M., Matamoros, O. M., Tejeida-Padilla, R., Reyes, I. L., & Espinosa, H. Q. (2021). A Comprehensive Review on Smart Grids: Challenges and Opportunities. *Sensors*, *21*(21), 6978. https://doi.org/10.3390/s21216978

Fonteijn, R., Van Amstel, M., Nguyen, P. H., Morren, J., Bonnema, G. M., & Slootweg, J. (2019). Evaluating flexibility values for congestion management in distribution networks within Dutch pilots. *The Journal Of Engineering*, *2019*(18), 5158–5162. https://doi.org/10.1049/joe.2018.9314

Forsyth, P., Nzimako, O., Peters, C., & Moustafa, M. N. (2015). Challenges of modeling electrical distribution networks in real-time. *2015 International Symposium On Smart Electric Distribution Systems And Technologies (EDST)*. https://doi.org/10.1109/sedst.2015.7315270

Griffee, D. T. (2005). Research tips: Interview data collection. *Journal Of Developmental Education*, *28*(3), 36–37. http://files.eric.ed.gov/fulltext/EJ718580.pdf

Hennig, R. J., De Vries, L. J., & Tindemans, S. H. (2023). Congestion management in electricity distribution networks: Smart tariffs, local markets and direct control. *Utilities Policy*, *85*, 101660. https://doi.org/10.1016/j.jup.2023.101660

Hunter, D. J., McCallum, J., & Howes, D. (2018). Defining Exploratory-Descriptive Qualitative (EDQ) Research and Considering Its Application to Healthcare. -. http://eprints.gla.ac.uk/180272/

Hussin, F., Hassan, M. Y., & Lo, K. L. (2006). Transmission Congestion Management Assessment in Deregulated Electricity Market. -. https://doi.org/10.1109/scored.2006.4339348

In de regio | Liander. (z.d.). https://www.liander.nl/regio%27s

Johannesson, P., & Perjons, E. (2014). An Introduction to Design Science. In *Springer eBooks*. https://doi.org/10.1007/978-3-319-10632-8

Kolster, T., Krebs, R., Niessen, S., & Duckheim, M. (2020). The contribution of distributed flexibility potentials to corrective transmission system operation for strongly renewable energy systems. *Applied Energy*, *279*, 115870. https://doi.org/10.1016/j.apenergy.2020.115870

Kosmadakis, G., Karellas, S., & Kakaras, E. (2013). Renewable and Conventional Electricity Generation Systems: Technologies and Diversity of Energy Systems. In *Lecture notes in energy* (pp. 9–30). https://doi.org/10.1007/978-1-4471-5595-9_2

Kunneke, R., Groenewegen, J., & Ménard, C. (2010). Aligning modes of organization with technology: Critical transactions in the reform of infrastructures. *Journal Of Economic Behavior & Organization*, *75*(3), 494–505. https://doi.org/10.1016/j.jebo.2010.05.009

Ladyman, J., Lambert, J., & Wiesner, K. (2012). What is a complex system? *European Journal For Philosophy Of Science*, *3*(1), 33–67. https://doi.org/10.1007/s13194-012-0056-8

Lipscomb, M. (2012). Abductive reasoning and qualitative research. *Nursing Philosophy*, *13*(4), 244–256. https://doi.org/10.1111/j.1466-769x.2011.00532.x

Maidment, C., Virgurs, C., J. Fell, M., & Shipworth, D. (2020). Privacy and data sharing in smart local energy Systems: Insights and recommendations. In *EnergyREV*. https://www.energyrev.org.uk/media/1480/energyrev_privacyinsights_report_202011.pdf

Marktwerking elektriciteit & gas - Energie Nederland. (z.d.). Energie Nederland. https://www.energie-nederland.nl/onderwerpen/marktwerking-elektricteit-gas/

Ministerie van Economische Zaken en Klimaat. (2022, 27 juli). *Ontwerp beleidsprogramma klimaat*. Publicatie | Rijksoverheid.nl. https://www.rijksoverheid.nl/onderwerpen/klimaatverandering/documenten/publicaties/2022/06/02/ontwerp-beleidsprogramma-klimaat

Ministerie van Economische Zaken en Klimaat. (2023, 1 december). *Nationaal Plan Energiesysteem definitief vastgesteld*. Nieuwsbericht | Rijksoverheid.nl. https://www.rijksoverheid.nl/actueel/nieuws/2023/12/01/nationaal-plan-energiesysteem-definitief-vastgesteld

Ministerie van Economische Zaken en Klimaat. (2024a, januari 22). *Actieagenda netcongestie laagspanningsnetten*. Rapport | Rijksoverheid.nl. https://www.rijksoverheid.nl/documenten/rapporten/2024/01/22/bijlage-1-actieagenda-netcongestie-laagspanningsnetten

Ministerie van Economische Zaken en Klimaat. (2024b, januari 22). *Probleemanalyse Congestie in het laagspanningsnet*. Rapport | Rijksoverheid.nl. https://www.rijksoverheid.nl/documenten/rapporten/2024/01/22/bijlage-2-probleemanalyse-congestie-in-het-laagspanningsnet

Moldoveanu, C., Brezoianu, V., Vasile, A., Ursianu, V., Goni, F., Radu, C., & Ionita, I. (2010). Intelligent system for the on-line real time monitoring of high voltage substations. -. https://doi.org/10.1109/isgteurope.2010.5638936

Moraga-González, J. L., & Mulder, M. (2018). Electrification of Heating and Transport: A Scenario Analysis for the Netherlands Up to 2050. *Social Science Research Network*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3206280

Morstyn, T., Teytelboym, A., & McCulloch, M. (2019). Designing Decentralized Markets for Distribution System Flexibility. *IEEE Transactions On Power Systems*, *34*(3), 2128–2139. https://doi.org/10.1109/tpwrs.2018.2886244

Nagesh, D. Y. R., Krishna, J. V. V., & Tulasiram, S. S. (2010). A real-time architecture for smart energy management. -. https://doi.org/10.1109/isgt.2010.5434771

Netherlands, S. (2022, 5 december). *Electrification in the Netherlands 2017–2021*. Statistics Netherlands. https://www.cbs.nl/en-gb/longread/aanvullende-statistische-diensten/2022/electrification-in-the-netherlands-2017-2021?onepage=true#:~:text=In%202021%20the%20electricity%20consumption,to%20the%202017%2D2021%20average.

Netherlands, S. (2024, 7 maart). Nearly half the electricity produced in the Netherlands is now renewable. *Statistics Netherlands*. https://www.cbs.nl/en-gb/news/2024/10/nearly-half-the-electricity-produced-in-the-netherlands-is-now-renewable#:~:text=Nearly%20half%20the%20electricity%20produced%20in%20the%20Netherlands%20is%20now%20renewable,-07%2F03%2F2024&text=A%20total%20of%20120%20billion,percent%20from%20the%20previous%20year.

Nunkoosing, K. (2005). The problems with interviews. *Qualitative Health Research*, *15*(5), 698–706. https://doi.org/10.1177/1049732304273903

Pawar, B., Batzelis, E., Chakrabarti, S., & Pal, B. (2021a). Grid-Forming Control for Solar PV Systems With Power Reserves. *IEEE Transactions On Sustainable Energy*, *12*(4), 1947–1959. https://doi.org/10.1109/tste.2021.3074066

Pawar, B., Batzelis, E., Chakrabarti, S., & Pal, B. (2021b). Grid-Forming Control for Solar PV Systems With Power Reserves. *IEEE Transactions On Sustainable Energy*, *12*(4), 1947–1959. https://doi.org/10.1109/tste.2021.3074066

Petrou, K., Quiros-Tortos, J., & Ochoa, L. F. (2015). Controlling electric vehicle charging points for congestion management of UK LV networks. -. https://doi.org/10.1109/isgt.2015.7131843

Qiu, M., Gao, W., Chen, M., Niu, J., & Zhang, L. (2011). Energy Efficient Security Algorithm for Power Grid Wide Area Monitoring System. *IEEE Transactions On Smart Grid*, *2*(4), 715–723. https://doi.org/10.1109/tsg.2011.2160298

Regels over energiemarkten en energiesystemen (Energiewet). (2024, 27 februari). Tweede Kamer Der Staten-Generaal. https://www.tweedekamer.nl/kamerstukken/wetsvoorstellen/detail?cfg=wetsvoorsteldetails&qry=wetsvoorstel:36378

Revel, D. (2011). IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. -. http://rechercheisidore.fr/search/resource/?uri=10670/1.wyvfiq

Robinson, S. (2008). Conceptual modelling for simulation Part I: definition and requirements. *Journal Of The Operational Research Society*, *59*(3), 278–290. https://doi.org/10.1057/palgrave.jors.2602368

S2Standard.org. (2024, 17 mei). *S2 - S2Standard.org*. S2Standard.org - S2 Standard For Unlocking Flex. https://s2standard.org/

Salet, W. (2021a). Public Norms in Practices of Transitional Planning—The Case of Energy Transition in The Netherlands. *Sustainability*, *13*(8), 4454. https://doi.org/10.3390/su13084454

Salet, W. (2021b). Public Norms in Practices of Transitional Planning—The Case of Energy Transition in The Netherlands. *Sustainability*, *13*(8), 4454. https://doi.org/10.3390/su13084454

Siemes, M. (2024, 8 april). *ANALYSE: Hoe Duitsland netbeheerders in staat stelt het opladen van elektrische auto's te sturen bij netcongestie*. ElaadNL. https://elaad.nl/analyse-hoe-duitsland-netbeheerders-in-staat-stelt-het-opladen-van-elektrische-autos-te-sturen-bij-netcongestie/

Tanrisever, F., Derinkuyu, K., & Jongen, G. (2015). Organization and functioning of liberalized electricity markets: An overview of the Dutch market. *Renewable & Sustainable Energy Reviews*, *51*, 1363–1374. https://doi.org/10.1016/j.rser.2015.07.019

Unuofin, J. O., Iwarere, S. A., & Daramola, M. O. (2023). Embracing the future of circular bio-enabled economy: unveiling the prospects of microbial fuel cells in achieving true sustainable energy. *Environmental Science And Pollution Research*, *30*(39), 90547–90573. https://doi.org/10.1007/s11356-023-28717-0

Van Blijswijk, M. J., & De Vries, L. J. (2012). Evaluating congestion management in the Dutch electricity transmission grid. *Energy Policy*, *51*, 916–926. https://doi.org/10.1016/j.enpol.2012.09.051

Van Westering, W., & Hellendoorn, H. (2020). Low voltage power grid congestion reduction using a community battery: Design principles, control and experimental validation.

International Journal Of Electrical Power & Energy Systems, *114*, 105349. https://doi.org/10.1016/j.ijepes.2019.06.007

Wang, J., Feng, G., Zhou, Y., Guo, Q., Tan, C. K., Song, J., & Wang, Y. (2023). Data sharing in energy systems. *Advances in Applied Energy*, *10*, 100132. https://doi.org/10.1016/j.adapen.2023.100132

Wason, P. C., & Johnson-Laird, P. N. (1972). *Psychology of Reasoning: Structure and Content*. https://ci.nii.ac.jp/ncid/BA06901849

Wat doet Stedin | Stedin. (z.d.). Stedin. https://www.stedin.net/over-stedin/wat-doet-stedin#:~:text=kernactiviteiten-,Wij%20zijn%20netbeheerder%20in%20het%20grootste%20deel%20van%20Zuid%2DHolland,%2C%20Amstelland%20en%20Noordoost%2DFriesland.

Wedia. (z.d.). *Dutch energy giant to offer contracts with real-time energy prices*. IamExpat. https://www.iamexpat.nl/expat-info/dutch-expat-news/dutch-energy-giant-offer-contracts-real-time-energy-prices

Welsh, E. (2002). Dealing with Data: Using NVivo in the Qualitative Data Analysis Process. *Forum Qualitative Sozialforschung / Forum: Qualitative Social Research*, *3*(2). https://doi.org/10.17169/fqs-3.2.865

Wetten.nl - Regeling - Warmtewet - BWBR0033729. (2024, 1 januari). https://wetten.overheid.nl/BWBR0033729/2024-01-01

Yang, Y., Wang, M., Liu, Y., & Zhang, L. (2018). Peak-off-peak load shifting: Are public willing to accept the peak and off-peak time of use electricity price? *Journal Of Cleaner Production*, *199*, 1066–1071. https://doi.org/10.1016/j.jclepro.2018.06.181

Yao, W., Zhao, J., Till, M. J., You, S., Liu, Y., Cui, Y., & Liu, Y. (2017). Source Location Identification of Distribution-Level Electric Network Frequency Signals at Multiple Geographic Scales. *IEEE Access*, *5*, 11166–11175. https://doi.org/10.1109/access.2017.2707060

Zhou, B., Li, W., Chan, K. W., Cao, Y., Kuang, Y., Liu, X., & Wang, X. (2016). Smart home energy management systems: Concept, configurations, and scheduling strategies. *Renewable & Sustainable Energy Reviews*, *61*, 30–40. https://doi.org/10.1016/j.rser.2016.03.047

Thomaidis, N. S., Santos-Alamillos, F. J., Pozo-Vázquez, D., & Usaola, J. (2016). Optimal management of wind and solar energy resources. *Computers & Operations Research*, *66*, 284–291. https://doi.org/10.1016/j.cor.2015.02.016

A

Appendices

A.1. Interview Summaries

This section outlines the summary of each interview. At the end of the summary, a list will be provided of the perceived bottlenecks by the representative. In section B, all bottlenecks have been explained.

ElaadNL

The representative from ElaadNL discusses the multifaceted challenges of integrating electric vehicles and smart charging into the power grid. Elaad focuses on both public and private chargers and their offerings to potentially integrate flexibility. Their aim is to standardize existing protocols to ensure interoperability for smart charging across a diverse range of devices in order to facilitate seamless integration with the grid. In doing so, ElaadNL collaborates with regulatory bodies.

During the interview out, the interviewee points out that for effective flexibility management on the low-voltage grid, consumers need to be financially stimulated. However, the current regulatory environment, characterized by non-stimulating network tariffs and the net metering rule (salderingsregeling), does not encourage consumers to incorporate flexibility measures. The interviewee highlights how some concepts have been proven address congestion, like adjusting the power delivered to EVs based on voltage levels, but notes these are not yet widely implemented in the Netherlands.

The central issue therefore lies in unlocking this flexibility. ElaadNL debates whether this should be done by end-users - like through EV chargers, heat pumps, solar panels, and home batteries - or through centralized home energy management systems. However, potential conflicts arises from the interplay between different entities, like regional grid operators and balancing authorities, who issue contradictory instructions.

Therefore, the interviewee emphasizes the need for a clear, regulatory and market framework which outlines the roles and responsibilities of parties involved. Such a framework should facilitate the effective management of flexibility. This framework should include market-based flexibility solutions, new network tariffs, and other possible direct intervention measures. Without any decision on a way forward, the current system will continue to face inefficiencies and potential conflict.

Bottlenecks:

- Lack of standardized protocols
- Margins for households
- Misaligned incentives households
- Novelty of the problem
- Lack of regulatory guidance and uncertainty

Withthegrid

The major topic of discussion were the financial and technical challenges associated with the adoption of smart appliances. The representative from Withthegrid pointed out that the business case for small consumers is too weak because the financial returns from flexibility are low compared to the costs of implementing the necessary hardware and software. In addition, integrating flexibility solutions at the household level requires significant IT infrastructure, further complicating the trade-offs for households. This IT infrastructure also posed a logistic challenge, since providing all Dutch households with the suited energy systems combined with the size of available data would pose a significantly large operation.

Bottlenecks:

- Margins for households
- IT Infrastructure
- Lack of standardized protocols
- Signaling congestion

Liander / ElaadNL

The representative from both Liander and ElaadNL highlights the fragmented nature of the energy landscape, which involves a various amount of small parties, who all contribute to a specific part of the energy chain. This fragmentation creates significant challenges for reaching consensus on which actions to take. The interviewee underscores the necessity for clear regulations and guidelines which should facilitate effective data sharing and management among all stakeholders involved in the low-voltage electricity network.

Furthermore, the interviewee also points out that while there are many potential solutions, or combinations of solutions, to manage energy flexibility, the lack of a unified approach make it difficult to implement these mechanisms efficiently. The interviewee also emphasizes the importance of having a coherent strategy approach, which can bring together all key parties and align their efforts towards one common goals.

Bottlenecks:

- Absence of flexibility in portfolio
- Fragmented energy landscape
- Immature flexibility market

EDSN

The representative from EDSN discusses the challenges associated with allocating resources for small consumption connections, particularly in the context of congestion on the low-voltage electricity network. In doing so, the interviewee highlights potential solutions which involve specific data collection and analysis to allow for effective congestion management. The interviewee also stresses that integrating new systems and technologies into the existing proposition is crucial when efficiently addressing these challenges.

Furthermore, the interviewee also emphasizes the importance of being able to utilize accurate and real-time data to make informed decisions about managing the supply and demand in the grid. The interviewee mentions that doing so requires a significant investment in new technologies and a commitment to the current data collection methods. The integration of new systems has to be performed in a way that complements and enhances existing infrastructure.

Bottlenecks:

- Data sharing
- Energy Law
- Misaligned incentives households
- Novelty of the problem
- Privacy
- Communication

Shell Recharge Solutions

The representative from Shell Recharge Solutions elaborates on the technical challenges related to the visibility of data behind transformers and the bottlenecks to utilizing real-time data. In doing so, the interviewee highlights the importance of proactive data collection and the need for clear roles and responsibilities among various stakeholders to enhance congestion management.

The interviewee underscores that one of the main obstacles is the lack of IT infrastructure for analyzing and collecting data. This includes the need for advances metering infrastructure and communication network. These networks can provide timely and accurate information about the state of the grid. However, the interviewee suggests this could also be a process which should receive time to reach to a mature market. The interviewee also emphasizes the importance of collaboration among industry stakeholders to ensure that the collected data is used effectively to manage the grid.

Bottlenecks:

- Different interpretation of protocols
- Immature market for flexibility
- Lack of regulatory guidance and uncertainty
- Lack of contract formats including flexibility
- Reliability

Equans

In this interview, the representative focuses on the pilot projects which are aimed at managing congestion at the small industry level. The interviewee emphasizes the importance of a collaborative approach among all stakeholders to be able to develop effective solutions. The interviewee notes that while some clients are not willing to participate in flexibility projects, there is a significantly growing recognition of the need for comprehensive solutions around the concept of flexibility.

The interviewee also discusses the challenges associated with scaling these pilot projects to a broader surface. This involves the need for regulatory support, financial incentives, and technological innovation to ensure the developed solutions can be implemented on a larger scale.

Bottlenecks:

- Lack of standardized protocols
- Data security
- Incentives for manufacturers
- Lack of contract forms including flexibility
- Margins for households
- Misaligned incentives for households
- Privacy
- Reliability

Mffbas

In this interview, the significance of data sharing as well as standardization protocols, such as the S2 protocol, are discussed. This interviewee notes that the barriers posed by a fragmented standards landscape require a unified approach to make smart appliances controllable and efficient. The interviewee emphasizes the importance of incentives for consumers to encourage the adoption of these technologies.

Furthermore, the interviewee points out the challenges related to the scalability of solutions, noting that while there are many promising technologies and innovations, implementing them on a large scale requires significant coordination and investment. The interviewee also highlights the importance of having clear regulatory guidance to support these developments and the implementation of these solutions. It is also stressed that without an unified approach and clear incentives, it will be very difficult to achieve this levels of flexibility and interoperability needed to manage the grid efficiently.

Bottlenecks:

- Data sharing

Liander

Another interviewee from Liander elaborates on the technical and practical difficulties which arise when trying to scale flexibility options, particularly in the context of broader European standards. Currently, many standards and protocols among the Netherlands and Europe exist.

Also, not all appliances are controllable and run on different protocols. Therefore, the interviewee advocates a more standardized approach across the wider European electricity sector to facilitate more effective control and integration of devices. As an example the interviewee mentions the S2 protocol. However, the interviewer also mentions manufacturers of smart appliances might provide barriers in doing so, since they have no incentives to produce according to one standard.

The interviewee also touches upon the potential of using digital twins and smart measurements to enhance predictive capabilities for managing the grid. It is noted that these technologies can provide valuable insight into the state of the grid. However, implementing these technologies on a large scale requires significant investments and aligned efforts among stakeholders.

Furthermore, the interviewee mentions that in liberalized markets such as the Netherlands there are market forces at play in addressing these issues. Allowing the market to address this eventually results in optimalisation of solution, however, this has caused for a lot of discussion and it is yet unclear in how this could possibly unfold to serve congestion on the low-voltage grid.

Bottlenecks:

- Incentives for manufacturers
- Lack of standardized protocols
- Immature flexibility market
- Lack of regulatory guidance and uncertainty
- Margins for households
- Misaligned incentives for households
- Not steerable
- Signaling congestion

ANWB Energie

During the interview with ANWB Energie, this representative was able to provide insights from the consumer perspective on energy consumption and the integration of flexibility, particularly in relation to electric vehicles. During this interview, the interviewee highlighted the potential of dynamic contracts, which expose consumers to real-time energy price fluctuations, which could serve as means to incentivize more efficient energy use. The interviewee mentions that the recent energy crisis stimulated the consumer awareness and the benefits of dynamic contracts, which tend to be more cost-efficient in the long run.

The interviewee also elaborates on the business models for future energy solutions, including the integrations of smart charging and home batteries into the grid. The interviewee states that for these models to be successful, consumers require more information about the energy usage. This should result in more engagement which can be fostered through educational initiatives and transparent communication about the benefits of dynamic pricing and relevant smart energy solutions.

Bottlenecks:

- Margins for households
- Ease

- Education

Stedin

During this interview, the challenges of low-voltage congestion and the technical aspects of grid management are discussed. The interviewee elaborates on the difference between overloading and overvoltage and both their impacts on the grid. The interviewee emphasizes the need for better data collection and real-tie visibility.

It is pointed out that while there are models to predict grid behavior, actual data from the field is limited. Therefore, Stedin is installing mor meters to gather real-time and accurate data, which will in turn improve the management of the grid. The interviewee mentions, however, that currently DSO predications have proven to be more accurate than predictions based on smart meter data. Therefore, real-time data-based predictions will only be beneficial in the medium-term. The interviewee also highlights the regulatory and technical barriers in fully utilizing smart meter data for grid management, stressing the lack of clear regulatory frameworks to address these challenges.

Bottlenecks

- Lack of standardized protocols
- Lack of regulatory guidance and uncertainty
- DSO Blind on LV
- Absence of flexibility in portfolio
- Lack of contract forms including flexibility

A.2. List of all Bottlenecks

1. *Lack of regulatory guidance and uncertainty*

The uncertainty regarding the future market design, roles, and responsibilities limits the adoption of smart appliances on the low-voltage grid. The lack of regulatory guidance regarding market design and stakeholder responsibilities causes hesitation among market parties and system operators, limiting strategic planning and integration of flexibility solutions.

2. *Margins for households*

One of the most significant barriers is the inadequate financial return for households. The potential earnings from demand response and flexibility are minimal, which discourages small end-users from investing in the necessary hardware. The current market structure does not support small consumer participation, and the costs of purchasing and installing technology often outweigh the savings for households. This indicates that the incentives regarding the integration of flexibility in every day lives of consumers is inadequate.

3. *Lack of standardized protocols*

The optimal integration of smart appliances is hindered by a lack of standardized communication protocols among appliances. Most appliances cannot communicate with each other or Home Energy Management Systems (HEMS), which complicates their integration.

4. *Misaligned incentives for households*

The net metering rule, or ‘salderingsregeling’, in the Netherlands misaligns incentives for households to shift their electricity load because it does not reflect the actual value of electricity at different times. Under net metering, households receive a one-to-one credit for the electricity they produce and deliver the grid, regardless of when it is used. This flat valuation ignores the varying value of electricity throughout the day and even seasons, influenced by demand and supply. As a result, the value of electricity, and therefore the incentive to change the consumption pattern, is not accurately represented in the electricity price.

5. *Lack of formats and contractual agreements integrating flexibility*

Currently, there is a lack of formats for contractual agreements which include flexibility mechanisms. Companies, and clusters of companies, want to engage in demand response and arrange load scheduling and consumption among themselves in order to optimally allocate electricity. However, the frameworks and contracts which facilitate this are lacking.

6. Immature market for flexibility

The market for flexibility solutions facilitated through smart appliances is still immature. Currently, there are no well-developed markets which facilitate the integration of flexibility and support the widespread adoption of smart appliances.

7. Signaling congestion

Some agreements and responsibilities regarding the signaling of congestion are yet uncertain. Decision variables within this proposition have yet to be made, like which party signals the congestion, or, to who? You could send the signal to a cloud, but to which one if there are multiple clouds? These are decisions on roles and responsibilities which have not been outlined.

8. Reliability

For consumers, reliability of appliances is important for them to participate in demand response. Any perceived or real issue with the reliability of appliances can deter them from adopting these technologies. Especially for companies, where electricity supply is often crucial for operations and a disruption could result in significant losses, this is essential.

9. Privacy

Concerns over privacy are a major concern in the adoption of smart appliances. Stakeholders on the low-voltage grid are hesitant to share their energy data due to fears of exposing sensitive information and potential misuse of their data. To gain consumer trust and facilitate better data sharing and integration of smart technologies, ensuring robust privacy protections is essential.

10. Novelty of the problem

Congestion on the low-voltage grid is a relatively new problem, unlike the medium-voltage and high-voltage grids that have established congestion management mechanisms and frameworks. The novelty of this problem, which has arisen in a relatively short amount of time, result in the mechanisms for congestion management as well as the market being underdeveloped. The market for flexible solutions is immature, lacking a clear design, regulatory frameworks incorporating flexibility, and adequate incentives.

11. Incentives for manufacturers

Manufacturers lack incentives to align their protocols with standardized requirements. Without clear financial or regulatory incentives, manufactures are reluctant to make their appliances compatible with emerging smart grid technologies.

12. Data sharing

Effective data sharing is vital for enabling real-time allocation of supply and demand, optimizing the use of smart appliances. However, current regulations and market structures hinder this process. The absence of clear policy frameworks and guidelines for data sharing creates significant barriers.

13. Absence of flexibility in the portfolio of system operators

There is a lack of mechanisms that facilitate flexibility for end-users in the portfolio of system operators. This limitation restricts the integration of flexibility into the operations of distribution system operators, making it difficult to exchange smart meter data between devices and energy suppliers.

14. Communication

In the past, system operators primarily had to focus on the physical arrangement and maintenance of the electricity grid in the Netherlands, without needing to explicitly communicate their design choices and its implications to grid users. However, as the energy grid approached its capacity limits, (distribution) system operators now must inform end-users about these constraints and guide them on the effective operation of the grid as well as their consumption patterns. This need for smart and effective communication is a relatively new challenge for system operators, who have little experience in such communication practices.

15. Data security

Data security is a significant concern, where challenges exist related to unlocking and securely sharing data between parties. Fears of unauthorized access to household installations and potential control of appliances further complicates this issue. In addition, a breach of energy consumption data could result in further risks for companies and their competitive advantage in particular.

16. Different interpretation of protocols and standards

The lack of standardization in communication protocols among different smart appliances is a significant issue. Even when using the same protocol, varying interpretations by manufacturers lead to compatibility problems, further complicating the integration efforts.

17. DSO blind on the Low-Voltage grid

DSOs lack detailed overview on the consumption of end-users on the low-voltage grid, impairing their ability to manage local congestion and integrate flexible solutions effectively. Unlike higher-voltage grids with established monitoring systems, the absence of data sharing frameworks on the consumption of end-users complicates the grid optimization and congestion management operations of DSOs.

18. Ease

The ease of use affects the adoption of consumers. The need for significant changes in consumption patterns discourages the consumer in adapting to this change. Consumers prefer straightforward solutions that fit seamlessly into their everyday lives and patterns; adapting their energy consumption to their everyday activities instead of vice versa.

19. Education

There exists a knowledge gap among users regarding the benefits and usage of smart appliances. Consumers are undereducated on the subject of flexibility, and are therefore unaware of the value and functionality of demand response.

20. The Energy Law

Criticism arose in the interviews when discussing the regulatory frameworks in place which optimally allow for flexibility practices. Currently, data sharing for optimal use and allocation of electricity on the low-voltage grid is a grey area for system operators. Regulatory frameworks, such as the Energy Law, should provide frameworks to allow for data sharing. This law, however, is not in place yet, in addition to uncertainties regarding the specific content and frameworks the law will entail.

21. Fragmented energy landscape

The energy market, its players, and their responsibilities are fragmented. Having a rather complex market model, a significant amount of players control and operate a relatively smart part of the operations chain. This makes discussing the general direction of the system and the mechanisms implemented complicated.

22. Non-steerable devices

A large share of the existing appliances is not designed to be remotely controlled or steered. This lack of steerability limits the ability to integrate these appliances into smart grid systems for demand response and flexible energy management. This bottleneck has however been encountered by another system operator representative, who argued that a large share of the appliances was steerable. In addition, making them steerable only required a minor technical change. This was not perceived as being one of the main challenges.

A.3. Merged Bottlenecks

Bottleneck merged	Initial bottleneck	Mentioned in number of interviews
Lack of regulatory guidance and uncertainty	• Lack of regulatory guidance • Absence of flexibility in portfolio • Lack of formats and agreements including flexibility • Signaling congestion: who? • Energy Law • Fragmented energy landscape	6
The margins for households are too thin	• Margins for households • Misaligned incentives	6
Lack of standards and protocols	• Lack of standards and protocols • Signaling congestion: to who? • Different interpretation of protocols • Not steerable	6
Novelty of the problem	• Novelty of the problem • Immature market • Reliability	4
Data sharing	• Data sharing • DSO blind on LV • Data security • Privacy	4
Communication	• Communication	1
Ease	• Ease	1
Education	• Education	1

A.4. Process of selecting the bottlenecks