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Transition Towards Smart Grids From a Socio-Technical Perspective

Farshid Norouzi

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Dissertation

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To Sepideh, who stood by me steadfastly during the hardships

Contents

SUMMARY

The transition from the current paradigm of electricity systems to a more efficient and environmentally sustainable form while maintaining power system reliability and stability is a complex and challenging task. Integrating renewable energy sources (RESs) into the electrical grid alone will not accelerate the transition, as they cannot independently drive the fundamental systemic changes. Large-scale renewable energy sources (RESs), such as offshore wind farms, are still being developed within the traditional centralised power system framework. A true shift toward decentralisation requires fundamental changes in electrical systems, which can be achieved by adopting smart grids.

The transition towards smart grids is not just a technological challenge and involves the interplay between human behavior and innovation. Therefore, the availability of technologies within a given society must be considered alongside social acceptance, institutional frameworks, regulations, and policies. These factors involve various stakeholders, including technology developers, adopters of the technologies, regulatory authorities, policymakers, system operators, and energy suppliers, all of which have interests of their own, some of which may conflict. The first step toward accelerating the transition process requires understanding the interaction between technical and non-technical factors. Consequently, an interdisciplinary approach is essential, integrating methods and theoretical insights from multiple disciplines.

In the first step of this thesis, the barriers to smart grid development are analysed by adopting a holistic lens. Global smart grid projects are reviewed, and the barriers are categorised into regulatory, market, social, and institutional dimensions. The interactions among these barriers are also explored.

The second step focuses on smart grid innovation in the specific context of the Netherlands, which was chosen as a case study due to the context-dependent nature of the transition. Theoretical frameworks of the Technological Innovation System (TIS) and transformational failures from the sustainable transition field are used to systematically analyse the actors, technologies, institutions, and network configurations related to smart grid development. By using these frameworks, a history-event-based analysis conducted from 2000 to 2021 reveals the transformative and systemic challenges that hinder the widespread adoption of smart grid technologies in the Netherlands. Among these challenges, the lack of market formation and the need to scale up projects and technologies are critical failures.

In the third phase, a techno-economic study is conducted to analyse the effects of different pricing policies in an assumed smart microgrid equipped with photovoltaic (PV) systems and battery energy storage (BES) in the Netherlands. As the interests of end-users and system operators often conflict, this study provides policy implications to support the further adoption of the PV-BES system within the assumed smart microgrid context.

Finally, the focus shifts to a model-free Energy Management System (EMS). Unlike a model-based EMS, a model-free EMS utilising a reinforcement learning algorithm is developed to evaluate how machine learning algorithms can support the scaling up of EMSs in smart microgrids. The results indicate the capability of reinforcement learning as an adaptive approach for different policy scenarios.

SAMENVATTING

De overgang van het huidige paradigma van hoe elektriciteitssystemen werken naar een efficiëntere en meer milieuvriendelijkere vorm, waarbij betrouwbaarheid en stabiliteit van het systeem behouden blijft, is een complexe en uitdagende taak. Het louter integreren van hernieuwbare, duurzame energiebronnen (HEB's) in het elektriciteitsnet zal de overgang niet versnellen, aangezien zij niet zelfstandig de fundamentele systeemveranderingen kunnen aansturen die nodig zijn. Grootschalige duurzame energie-opwek zoals met windparken op zee, wordt momenteel nog ontwikkeld binnen het traditionele, gecentraliseerde kader van hoe energiesystemen georganiseerd zijn. Een echte verschuiving naar decentralisatie vereist fundamentele veranderingen in elektrische systemen. Hierbij kan grootschalige adoptie van smart grids een belangrijke rol spelen.

De overgang naar smart grids is niet alleen een technologische uitdaging, maar ook een kwestie van interactie tussen menselijk gedrag, instituties en innovatie. Daarom moeten de beschikbaarheid van technologieën in een bepaalde samenleving worden overwogen, waarbij er ook aandacht is voor niet-technische aspecten zoals sociale acceptatie, institutionele kaders, regelgeving en beleid. Deze factoren hebben betrekking op verschillende belanghebbenden, waaronder technologieontwikkelaars, gebruikers van de technologieën, regelgevende autoriteiten, beleidsmakers, netbeheerders (DSO's en de TSO) en energieleveranciers, die vaak hun eigen agenda's hebben, wat dikwijls kan leiden tot tegenstrijdige belangen, wat samenwerking bemoeilijkt. De eerste stap om het transitieproces te versnellen, is meer inzicht verkrijgen in de interactie tussen technische en niet-technische factoren. Daarom is een interdisciplinaire benadering essentieel, waarbij methoden uit verschillende wetenschappelijke disciplines worden toegepast.

In de eerste stap van dit proefschrift worden de barrières voor de ontwikkeling van smart grids geanalyseerd vanuit een holistisch perspectief. Daarbij wordt een overzicht gegeven van ontwikkeling van smart grid-projecten in de wereld, en worden barrières geidentificeerd die kunnen worden ingedeeld in regulering-, markt-, sociale en institutionele dimensies. Ook worden interacties tussen deze barrières verkend.

De tweede stap richt zich op smart grid-ontwikkeling in Nederland, dat als casestudy is gekozen vanwege het contextafhankelijke karakter van de transitie. Hiervoor worden de theoretische raamwerken van het Technologisch Innovatiesysteem (TIS) en van transformatiefalen uit het domein van duurzame transities toegepast om systematisch de actoren, technologieën, instellingen en netwerkconfiguraties met betrekking tot de ontwikkeling van smart grids te analyseren. Een historische analyse van 2000 tot 2021 brengt de transformatieve en systemische uitdagingen aan het licht die de grootschalige adoptie van smart grid-technologie in Nederland belemmeren. Onder deze uitdagingen vallen onder meer het gebrek aan marktvorming en de noodzaak om projecten en technologieën op te schalen.

In de derde stap wordt een techno-economische studie uitgevoerd om de effecten van verschillende prijsbeleidsscenario's te analyseren in een veronderstelde smart microgrid

die is uitgerust met zon-fotovoltaïsche (PV) systemen en batterijopslagsystemen (BES) in Nederland. Omdat de belangen van eindgebruikers en netbeheerders vaak conflicteren, geeft deze studie beleidsaanbevelingen voor de verdere ontwikkeling van smart microgrid-innovaties in het land.

Tot slot is er in de vierde stap aandacht voor een modelvrij Energie Management Systeem (EMS). In tegenstelling tot een modelgebaseerde EMS, wordt een modelvrije EMS ontwikkeld op basis van een 'reinforcement learning'-algoritme om te evalueren hoe 'machine learning'-algoritmes kunnen bijdragen aan de opschaling van EMS in smart microgrid-technologie. De resultaten geven de capaciteit van reinforcement learning aan als een adaptieve benadering voor verschillende beleidsscenario's.

1

INTRODUCTION

1.1. BACKGROUND AND MOTIVATION

The transition of electricity systems toward more sustainable and intelligent configurations has become a central theme in energy research and policy discourse. This transition involves fundamental changes in technologies, business models, institutions, and user practices, and is often conceptualised through the Multi-Level Perspective (MLP) framework [1]. According to the Multi-Level Perspective (MLP), socio-technical transitions emerge through interactions among three analytical levels: niches, which serve as protected spaces for radical innovations and alternatives to existing systems; regimes, which represent the dominant socio-technical configurations such as prevailing technologies, markets, and policies; and landscapes, which encompass broader contextual pressures like climate change, geopolitical shifts, and societal values [2]. As illustrated in Figure 1.1, in the electricity sector, smart grids and microgrids are considered niche innovations that challenge the centralised, fossil-fuel-based energy regime currently in place [3].

The smart grid is defined as a grid that uses digital technology to improve reliability, security and efficiency (both economic and energy) of the electrical system from large generation, through the delivery systems to electricity consumers, and a growing number of distributed-generation and storage resources [4]. More recent literature emphasises that smart grids are not merely technical systems but complex socio-technical assemblages that require new roles for actors, redefinition of regulatory norms, and novel forms of user engagement [5]. At a conceptual level, the definition of the smart grid becomes increasingly complex as we descend from system-level visions to the institutional and socio-economic layers. For example, while the high-level objective may be "grid modernisation," it remains ambiguous who the primary users are (e.g., utilities, prosumers, communities), what types of markets are envisioned (e.g., ancillary services, peer-to-peer trading), and under which regulatory frameworks these transformations should unfold [6]. These uncertainties make it difficult to prescribe uniform policy pathways, highlighting the importance of context-specific innovation processes.

Embedded within the broader smart grid vision is the microgrid concept as a key component. The transition to a smart grid requires the integration of distributed renewable energy sources through microgrids, which enable bi-directional energy flow

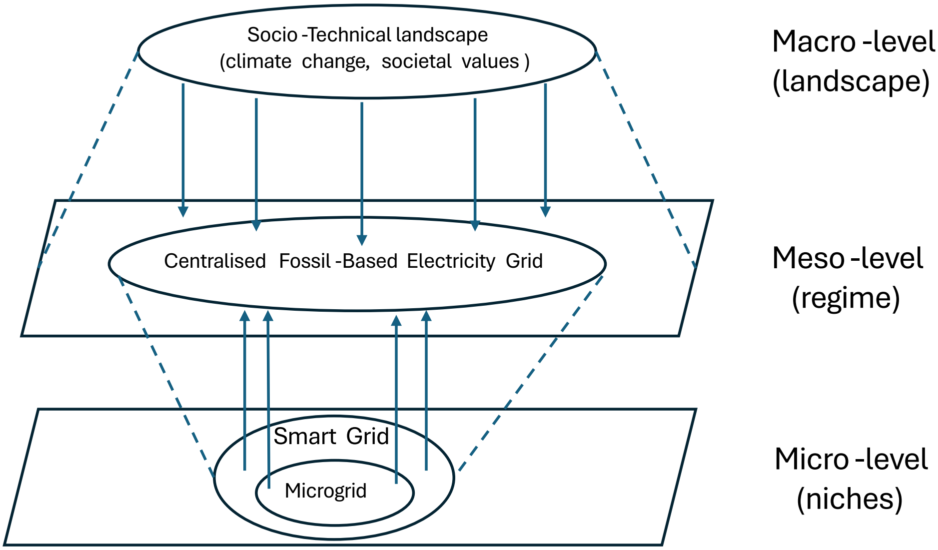

Figure 1.1: Multi-level perspective on socio-technical transitions (adapted from [2])

and communication, support energy storage adoption, and facilitate effective energy management [7]. A microgrid can be defined as "the system-concept of multiple but coordinated loads and generation units, and of islanding from the grid, that operates as a controllable structure to the main grid and constrained within well-defined electrical boundaries" [8]. Microgrids typically include renewable energy resources (e.g., solar PV), energy storage systems (e.g., batteries), and advanced control systems, and are often proposed as a solution to enhance system stability [9]. However, like smart grids, microgrids also face uncertainties regarding ownership models, user roles, and long-term economic viability [10].

Combining the flexibility and intelligence of the smart grid with the decentralisation and autonomy of microgrids leads to the emerging concept of the smart microgrid. A smart microgrid integrates digital communication, advanced control, and data analytics within a microgrid infrastructure to enhance system optimisation, user participation, and dynamic operation [11, 12]. Embedding microgrids in a smart grid offers opportunities to increase the penetration of renewable energy sources and enhance reliability by dividing the distribution system into smaller microgrids with greater controllability and flexibility [13]. Smart microgrid can be defined as an "intelligent electricity distribution system that interconnects loads, distributed energy resources, and storage within clearly defined electrical boundaries to act as a single controllable entity with respect to the main grid" [12]. While smart grids and smart microgrids are being adopted in more regions, they are accompanied by the introduction of new regulations, market structures, institutions, and actors. This suggests that the ongoing socio-technical transition in the electricity sector requires further investigation [3, 14]. Such a study can provide valuable insights into supportive policies, regulatory frameworks, and the interactions between actors, which may serve as a foundation for future system design after identifying potential weaknesses in existing policy and regulatory structures. This is particularly important given the geographical dependency of energy transitions.

1.1.1. PROBLEM STATEMENT AND OBJECTIVES

To date, research on smart grids and their subsystems, such as smart microgrids [15], has often examined technical, social, political, and governance-related aspects in isolation [10]. However, the success and pace of energy transitions depend on the dynamic interaction among social, financial, technological, economic, and governmental factors, along with the interventions designed to support them. To fully analyse these dimensions and their relationships, smart grids and smart microgrids should be regarded as complex and multifaceted innovations. This requires a socio-technical approach to evaluate the current practices in designing and implementing smart microgrids within a given socio-technical context. Further analysis that considers the smart grid as an innovation emerging within a niche market can support two main objectives:

(i) *Untangling the interactions among various aspects of the transition towards smart grids.*

(ii) *Providing policy implication insight for future designs to accelerate the adoption of smart grids.*

1.2. SCOPE

Defining the scope of the research involves identifying relevant actors, networks, institutions, and infrastructures related to the development of the smart grid. These boundaries are shaped by factors such as the target audience of the research, whether the technology is considered a product or a knowledge domain, the disciplinary breadth of the analysis, and the spatial level at which the transition is studied [16]. Transitions in energy systems are highly context-dependent, shaped by sociocultural, territorial, and infrastructural factors such as norms, practices, institutional frameworks, and economic conditions [17]. This thesis examines the development of smart grids and the smart microgrids embedded within them in the Netherlands, a country that provides a rich empirical basis due to a wide range of documented pilot projects and initiatives [18]. While the broader context of the smart grid transition is addressed, particular emphasis is placed on smart microgrids as subsystems of the smart grid. This narrower focus enables a more detailed technical analysis within the broader socio-technical framework, specifically examining the technical capabilities of energy management systems and the integration of intelligent concepts.

The thesis begins with a systematic review in Chapter 2, which identifies key technical barriers to the development and integration of smart grids and embedded smart microgrids. The chapter provides a conceptual and empirical foundation by classifying key obstacles and enabling factors across technical, regulatory, and social dimensions.

Shifting the focus to a specific context, Chapter 3 applies the Technological Innovation System (TIS) framework to assess the development of smart grid technologies in the Netherlands. Although the terminology in this chapter broadly refers to the "smart grid," the empirical data is related to smart microgrid initiatives.

In Chapter 4, the focus shifts to a specific case study of a residential smart microgrid that integrates photovoltaic (PV) systems and battery energy storage (BES), identified as one of the main technologies driving the energy transition in the Netherlands [19]. This study examines how various policy settings can impact the further adoption of PV-BES in an assumed smart microgrid.

Chapter 5 investigates the potential of reinforcement learning (RL) to enhance the energy management systems (EMS) of smart microgrids. By leveraging RL as a model-free, adaptive control strategy, the chapter demonstrates how real-time learning can improve operational performance under uncertain and dynamic conditions.

For the assumed smart microgrid, the main functionalities include integrated distributed generation, controllability, and the capability to operate in either connected or autonomous mode [20]. In Chapter 4 and Chapter 5, the smart microgrids are assumed to be connected to the main grid through a point of common coupling (PCC), with power flow managed via an energy management system for the integrated renewable resources.

1.3. RESEARCH QUESTIONS

To achieve the research objectives in Section 1.1.1, each chapter is designed to answer specific research questions, as follows:

1. *What socio-technical factors hinder the adoption and diffusion of smart grids in electric systems?* (Chapter 2)
   Global experiences from smart grid projects and related technologies provide valuable insights into adopting a multi-actor perspective. Drawing on these global experiences helps classify the barriers to smart grid implementation and analyse the interactions between technological and non-technical factors. By examining diverse case studies and real-world applications, we can better understand the role of various stakeholders such as policymakers, energy providers, technology developers, and local communities and how their interactions influence the success or challenges of smart grids.

2. *What systemic and transformational failures are identified in developing smart grid innovation in the Netherlands by combining Technological Innovation System (TIS) and a transformational perspective?* (Chapter 3)

   Smart grids are analysed through the lenses of sustainable transition and technological innovation systems to identify transformational and systemic elements. These insights can serve as inputs for addressing policy deficiencies.

3. *How will different pricing policies impact the techno-economic potential of PV-BES in the Netherlands?* (Chapter 4)

   Examining smart microgrids through the lens of sustainable transition and as a technological innovation system reveals that achieving new socio-technical arrangements requires supportive pricing policies to enable these technologies to reach their full potential. The case of storage devices, particularly when combined with PV systems, provides a valuable example for investigating how policy design can increase the chance of technology adoption within smart microgrids.

4. *How does the machine learning-based EMS perform in comparison to conventional EMS under different pricing policies?* (Chapter 5)

   The second insight from sustainable transition and technological innovation system analysis reveals that current smart microgrid projects need to be scaled up. Therefore, the technologies involved must be capable of performing efficiently across diverse policy arrangements and regulatory conditions. The potential of machine learning in developing model-free EMS to support the scaling of future projects is an area worthy of exploration.

1.4. METHODOLOGY

In Chapter 2, a two-phase literature review was conducted to identify and categorise key barriers to smart grid development, using a snowballing approach to broaden the reference base with relevant studies and project reports. Chapter 3 presents a historical analysis through the technological innovation system (TIS) framework and the transformational failures' framework, identifying innovation drivers as well as systemic and transformational failures. In Chapter 4, a genetic algorithm was applied to optimise real-world data and enhance policy effectiveness, while Chapter 5 explores the use of machine learning for data forecasting and reinforcement learning as a model-free approach. The research methodologies employed are summarised in Figure 1.2.

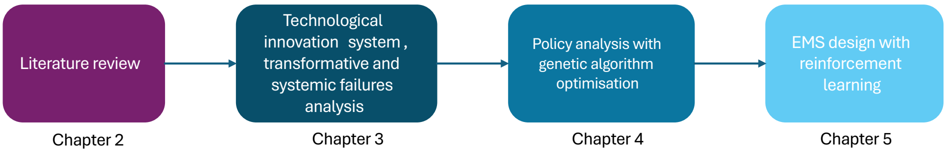

Figure 1.2: Overview research methodologies used in this thesis

1.5. THESIS OUTLINE

The thesis is organised into six chapters, as outlined in Figure 1.3. The four primary research questions are addressed in Chapter 2 through Chapter 5. Beginning with an overview of the research motivation, objectives, and anticipated outcomes, Chapter 1 establishes the foundation for this study, including the definitions of smart grid and smart microgrids.

Chapter 2 presents a global review of the sociotechnical barriers to the development of smart grids and smart microgrids within smart grids. It emphasises the importance of understanding how technical challenges, such as control complexities (particularly for smart microgrids) and inadequate design tools, interact with regulatory, social, and institutional obstacles, including rigid policy environments, market limitations, and weak community engagement. This chapter positions the smart grid not as isolated technical interventions, but as innovations embedded in complex systems of governance and practice. It provides a conceptual and empirical foundation for the rest of the thesis.

The findings include the need for analysis of pricing schemes to incentivise end-users to adopt renewables, which is a focal point of Chapter 4.

While this broad perspective is valuable for understanding the general landscape, innovation and energy transitions are highly context-specific. The Dutch electricity system features unique regulatory frameworks, market dynamics, and institutional actors that shape the development and adoption of smart grid technologies differently than in other regions. Therefore, shifting the focus in Chapter 3 to a Technological Innovation System (TIS) approach allows for a detailed and context-sensitive analysis of the innovation processes specific to the Netherlands. The TIS framework is particularly suited for studying energy transitions toward smart grids because it examines the key actors, networks, institutions, and functions that drive or hinder technological innovation within a defined context [21]. By applying TIS, this study can move beyond identifying barriers to uncover how the Dutch innovation system facilitates or constrains knowledge development, resource mobilisation, market formation, and policy guidance around smart grid technologies.

Chapter 4 and Chapter 5 discuss the Energy Management System (EMS) element, which provides signals to optimise the performance of storage based on load and resource forecasts in order to minimise costs and maximise self-consumption [22].

Building on the findings from Chapter 2 on incentivising end-users, Chapter 4 focuses on a case study of a residential smart microgrid combining photovoltaic (PV) systems with battery energy storage (BES). The high penetration of PV-BES in the Dutch residential sector makes it an ideal subject for policy implications discussion. This chapter analyses how different pricing schemes, such as net metering, feed-in tariffs, time-of-use, and dynamic pricing, impact economic outcomes for both end-users and system operators. Through realistic market simulations, the case study offers policy insights on designing incentives to accelerate decentralised energy adoption while ensuring system efficiency and grid integration. This analysis also addresses systemic issues identified in Chapter 3, particularly concerning energy storage legitimacy.

An insight from the Dutch TIS analysis is the urgent need to scale up smart grid solutions, not only in physical infrastructure but also in operational flexibility and system intelligence. This includes, for example, developing self-organising mechanisms to scale up specific smart technologies, such as automatic meter reading [23]. This need aligns with the definition of scalability, which refers to the ability to increase in size, scope, or range [24].

This need underpins Chapter 5, which investigates the use of reinforcement learning (RL) as a scalable, model-free control strategy for energy management systems (EMS). The approach addresses the need for solutions that can scale in capability, in terms of technology and algorithms [25]. The focus is on operational scalability, meaning the ability to adapt to different system configurations, pricing policies, and user behaviors without prior system-specific programming. In this chapter, an RL-based EMS, combined with LSTM forecasting, is benchmarked against conventional optimisation methods. Results show that the RL-EMS outperforms static models in both financial returns and responsiveness to real-time pricing, offering a promising approach for smart microgrid control in dynamic electricity markets.

Finally, Chapter 6 synthesises the findings, explicitly addresses the research questions defined in Section 1.3, and reflects on the broader implications of the work. It outlines the key contributions of the thesis, discusses methodological and technical limitations and directions for future work.

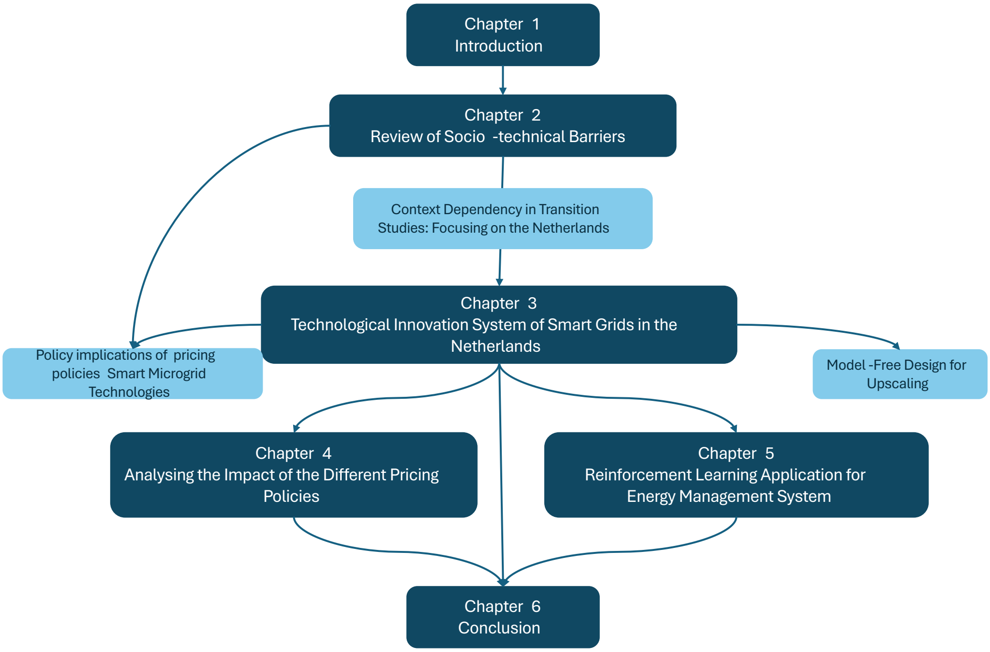

Figure 1.3: Outline of the thesis chapters

2

Review Of Socio-Technical Barriers

This chapter is based on:
F. Norouzi, T. Hoppe, L. Ramírez-Elizondo, P. Bauer, "review of socio-technical barriers to Smart grid development", *Renewable and Sustainable Energy Reviews*, 2022, vol 167, 112674.

Smart Grids (SGs) can be seen as a promising option when it comes to addressing the urgent need for sustainable transition in electric systems from the current fossil fuel-based centralised system to a low-carbon, renewable-based decentralised system. Unlike previous studies that were restricted to a limited number of actors and only took a mono-disciplinary research approach, this current review adopts a multidisciplinary, socio-technical approach and addresses the factors that have been hindering the development of SGs and considers how these barriers interact. This chapter contributes to the body of literature on the development of SGs by mapping and discerning technical, regulatory, market, social and institutional barriers for different types of actors, including technology providers, consumers, Distributed Generation (DG) providers and system operators, based on information derived from laboratory reports, demonstration pilots, and academic journals. In addition, attention is paid to how these barriers interact based on real-life experimentation. A holistic picture of barriers and their interaction is presented as well as recommendations for future research.

2.1. Introduction

Environmental concerns and climate crises have increased in the last decades. CO_2 emissions reached almost 35 billion metric tons in 2019 and are expected to hit more than 43 billion metric tons in 2040 [26]. Internationally, the Paris Agreement requires countries to contribute to maintaining the global average temperature increase below the specified threshold of 2 °C. This demands emergency action by all parties to reduce greenhouse gas (GHG) emissions [27]. At a national level, European Union (EU) members are following the ambitious EU climate action policies that aim to cut at least 40 % of GHG emissions (from the 1990 levels); improve energy efficiency by 32.5 %; and reach at least a 32 % share for renewable energy.

Energy sectors are seen as the main parties responsible for a sizable share of CO_2 emissions due to their reliance on fossil-fuels. In addition, electric power systems at a national and international level are encountering energy shortages, unsatisfactory efficiency and ageing distribution systems, which all require substantial capital costs if they are to be addressed [28].

To tackle these problems, scholars have proposed decarbonising the electric system by implementing renewable energy sources (RESs) and improving efficiency by utilising Distributed Generations (DGs) [29]. However, in practice, a transformation to a sustainable system from the current paradigm and technologies in the electric power system without losing any quality of services in terms of power system reliability and stability is a daunting task [28]. The transition from a centralised to a decentralised system can be made in different ways, ranging from Smart Grid (SG) technologies to MicroGrids (MGs) and Virtual Power Plants (VPPs) [30].

Merely integrating RESs into electric systems will not accelerate the transition in the electricity grid process because RESs alone are incapable of creating a fundamental change in the system [31]. Large-scale RESs such as offshore wind parks are still set up within power system's traditional and centralised context [32]. However, combining small-scale RESs with energy storage devices and varied loads close to the distribution system's resources would allow the development of an MG [33].

Historically, MGs have only been used to provide electricity for remote locations with limited transmission lines. However, new rationales for the use of MGs have recently emerged, and provide more applications. Scholars [34] discern multiple functions for MGs: the nature of the connection with the main utility, a precise energy and power balance within the MG, energy storage, demand management, and a seasonal match between generation and load. The first function implies that an MG works in the grid-connected mode under normal conditions. However, when emergencies occur, MGs can be disconnected from the main utility in an islanded mode. This switching between connection and disconnection occurs at the Point of Common Coupling (PCC) (see Figure 3.1) [35]. To summarise, MG functions require sophisticated control systems to secure electrical parameters and facilitate the power flow between the MG and the main grid. These control systems are critical for the safe operation of MGs. From an upstream network perspective, an MG is an ideal controllable and coordinated load [36].

Another concept linked to DGs and RESs is VPP. This refers to the remote dispatching of DGs, stored energies, or demands that rely on smart infrastructure and sophisticated control methods. A VPP aggregates all the generated power from different resources and dispatches it according to the specified power generation programme [37]. A VPP cannot be treated as a physical power plant and is not limited to a certain geographical location or a specific set of resources [37].

Achieving the full value of MGs and VPPs depends on the deployment of SGs, which explains why policymakers are focusing on rolling out smart infrastructures to achieve climate and energy targets [38]. Although the current power system is already equipped with Energy Management Systems (EMSs), modern Supervisory Control and Data Acquisition (SCADA) systems, and advanced data processing software such as Advanced Distribution Automation (ADA) for controlling and monitoring purposes, these smart devices do not cover all the parts of the grid, like DGs and end users' equipment in a unified way [37]. In brief, SGs have various objectives, including:

(1) enhancing of the power quality; (2) developing demand response programmes and facilitating the participation of end users; (3) automatic monitoring and two-way communication; (4) accommodating new services and products in the electricity market and (5) integrating DGs and storage devices into the electric grid [27].

Figure 2.1 presents a typical SG including MGs. EMS uses SCADA and ADA to optimise RESs and exercise Demand Side Management (DSM) in this system. The SCADA system is usually responsible for the status in the generation and transmission line and cannot manage DGs directly in the distribution system. ADA therefore takes control over switches, valves, and relays of distributed components and enables DSM by sending real-time pricing signals to homes, industrial loads, and even Electric Vehicles (EVs).

The smart grid is the central concept driving the transition in energy systems. It refers to an electricity network that uses digital technologies to improve the reliability, security, and efficiency of the entire system, including economic and energy aspects. This network covers everything from large-scale power generation through delivery systems to consumers, while also integrating a growing number of distributed generation and storage resources [4]. Within this framework, microgrids are considered smaller systems embedded inside the smart grid. They consist of multiple coordinated loads and generation units that have the ability to operate independently by islanding from the main grid. These microgrids act as controllable units confined within clearly defined electrical boundaries [8].

The smart microgrid concept arises by combining the intelligence and flexibility of the smart grid with the decentralised and autonomous features of microgrids. A smart microgrid incorporates advanced control systems, digital communication, and data analytics into the microgrid infrastructure. This integration improves system optimisation, allows greater user participation, and supports dynamic and adaptive operation [11, 12]. Embedding microgrids within the smart grid creates opportunities to increase the use of renewable energy and enhance reliability by dividing the distribution system into smaller segments with better control and flexibility [13]. Therefore, a smart microgrid can be defined as an intelligent electricity distribution system that interconnects loads, distributed energy resources, and storage within clearly defined electrical boundaries and functions as a single controllable entity relative to the main grid [12].

Despite extensive attempts at national and international levels to accelerate the transition process towards a decentralised system using RESs, technologies linked to this transition (i.e., SGs and MGs) are still mainly found in the niche market where development and diffusion processes are moving fairly slow. To encourage transition, barriers to niche development need to be identified [39].

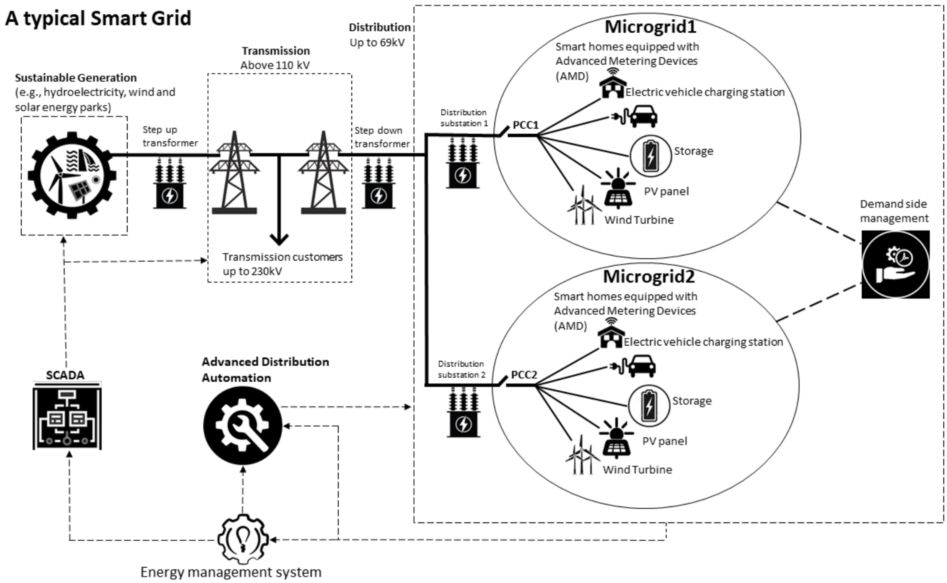

Figure 2.1: A typical Smart grid containing Microgrids.

Previous reviews of SG and MG barriers are rather fragmented. A large portion of the academic literature [30] has focused on addressing definitions, and the evolution of SG and MGs concepts. Some reviews elaborate on policies towards SGs based on the drivers and opportunities. Authors in [40] discern the following drivers: (1) the increasing demand for electricity; (2) the need for a reduction in losses; (3) the integration of renewable energy generation systems; and (4) new business opportunities. These drivers have encouraged the US government to formulate policies to secure the supply of energy, improve its resiliency, and keep energy costs low. The policies target increased energy efficiency and are implemented in MG projects. The challenge of integrating large amounts of RESs in electric systems and climate change mitigation has spurred the EU to invest in SG innovation [41]. In Japan and Korea [42], national security, economic growth and a diversifying energy supply form the basis of policies focusing on SG development [43].

Investment difficulties in SGs are also highlighted in the literature. Zhang et al. [27] have examined investment schemes on SG technologies in Europe and the US. Comparing investment issues revealed that the absence of a clear cost-benefit-sharing mechanism and a lack of worldwide technical standards hinder the integration of equipment manufactured by different companies [44]. Other studies highlight fundamental features and adoption issues of SG technologies [43]. In general, these studies address costs, consumer engagement, data protection, privacy, physical security, cybersecurity, compatibility problems with intelligent devices, and technical standards as important factors to evaluate the progress of demand-side management and distributed generation [45].

Muench et al. [46] carried out a comprehensive barrier review and linked technical barriers to regulatory and institutional barriers. Their review categorised the implementation of SG technologies barriers into: (1) cost and benefit; (2) knowledge; and (3) institutional mechanisms.

According to Curtius et al. [47], having a portfolio of value propositions in place is linked to higher market acceptance. Incentivising industry to increase the range of SG technologies is therefore considered to accelerate overall adoption. Furthermore, amended regulatory frameworks are seen to stimulate innovation capacity. Enabling Distribution System Operators (DSOs) to reclaim their expenses for implementing SG innovations is considered particularly important in fostering SG development [46].

The current literature study is inspired by the fact that previous studies on barriers are monodisciplinary and restricted to a limited number of actors. Therefore, we attempt to undertake a multi-disciplinary portrait of SG's barriers with a multi-actor perspective and a clear classification. This review contributes to SGs' development by addressing the question 'What socio-technical factors hinder adoption and diffusion of SGs and SMGs as one of the building blocks of SGs in electric systems?' Answering this question can highlight possible avenues of future research.

This chapter is structured as follows. After an explanation of the literature review method, the technical and managerial barriers to technology are addressed in Section 2.3. Section 2.4, discusses the regulatory and policy barriers from an actor perspective. In Section 2.5, the study explores acceptance issues from a social perspective and provides a deeper understanding of the concept of community SGs - a key concept concerning the social embeddedness of SG. Based on the identified barriers, Section 2.6 offers a holistic picture of the actors involved and discusses the interactions between the barriers in practice. Finally, in Section 2.7 the main findings are presented, and suggestions for future research are presented in Section 2.8.

2.2. METHODOLOGY

The literature review research process entailed two cycles. First, a database research was performed to obtain an overall understanding of the possible barriers. Scopus, Web of Science, and Google Scholar were used as the primary databases to find articles containing terms and keywords including: "issues", "obstacles", "barriers", "challenges", "Smart Grids", "Microgrids" and "decentralised power systems". Different Boolean operators combined those terms to optimise the results. It was decided to concentrate on studies in European countries and the US as they are considered to be pioneers in SGs and MGs and greater insight would be gained due to the high number of experiments and projects in these countries. The abstracts of sixty academic papers were reviewed in the first stage. This number was then reduced to 22 after a review of their relevance. Analysis of these papers resulted in a classification of the barriers into the following categories: technical, regulatory and policy, social and institutional.

Each of these barrier classifications was then addressed separately in the second cycle. Snowballing was used to identify the additional relevant articles from the reference list of the papers selected. Due to the large number of SG and MG projects in Europe and the US, reports of real-life projects were also included as a complementary resource. Table 2.1 summarises the main references for each identified barrier.

Table 2.1: Summary of barriers to SG deployment reported.

Barrier	Description	Reference
Overall barriers	Definition and concept of SG and MG, drivers, opportunities and barriers	[26, 27, 29, 30, 33, 37–39, 43–46, 48–57]
Technical barriers of MGs	(1) Complicated design of decentralised controllers with plug and play features; (2) Lack of inertia in DG units; (3) Need for further development of control methods for meshed topology;	[35, 58–66]
	(4) Fault current changes by location and capacity of power inverters and lack of grounding system in DC MGs;	[36, 67–72]
	(5) Islanding detection techniques should be improved in terms of speed, power quality and costs.	[73–75]
Technical barriers of SGs	(1) Handling large amounts of data requires more investment and knowledge; (2) QoS should be guaranteed; (3) Communication protocols and standards should be updated.	[76–84]
Design framework	Design frameworks need to be updated according to innovations and the impact of human decisions should be added to frameworks.	[85–93]
Need for assessment	(1) Inaccurate assumptions and data deficit due to privacy and security concerns; (2) Assessment metrics can be influenced by external conditions.	[94–101]
Regulatory and policy barriers	(1) Unclear contractual agreements between market actors; (2) High risks for investment and a lack of financial resources; (3) Privacy and cybersecurity should be ensured by adhering to confidentiality, availability and accountability of data; (4) Inclusion of RESs endangers the interests of system operators and traditional generators; (5) Lack of incentive for consumers to produce flexibility.	[29, 31, 41, 102–129]
Social acceptance barriers	(1) Social acceptance comes in many forms, i.e., community acceptance, socio-political acceptance and market acceptance, and involves more than the persuasion of local residents; (2) Social acceptance at community level depends heavily on identity and members' behaviour, and their active involvement in projects.	[22, 28, 114, 130–149]
Institutional barriers	(1) Lock-in and inertia to change the power system structure; (2) Difficulties in decision-making and investment; (3) Issues with interaction, involvement and coordination between stakeholders regarding the management of energy flows; (4) Local communities lack capacities and have difficulties in making serious investments.	[139, 148, 150–156]

2.3. TECHNICAL BARRIERS

While MGs and SGs share various common technology challenges, some of these are exclusive to MGs because of their exceptional capability to work in islanded mode [52]. With regard to SG technologies, Information and Communication Technology (ICT) has been identified as the central element that facilitates the bidirectional flow of information and real-time data process [81]. In addition to technical factors, this section is followed by addressing the importance of possible design frameworks for optimal interoperability and by addressing technology assessment problem.

2.3.1. MGs CONTROL

The development of sophisticated power electronic interfaces has supported the emergence of MG. Most of the RESs units connect to MGs via these power electronic interfaces. These power electronic devices play a critical role in meeting grid requirements in terms of reliability because RESs can potentially undermine reliability of MG due to their intermittent nature. Inverter-coupled RESs, on the one hand, contribute to stability by coordinating RESs and on the other hand, facilitate providing ancillary services such as peak shaving and reactive power compensation [64].

2

Using drooping characteristics of generators, voltage and frequency can be maintained within the prescribed range when many generation units work in parallel, as in synchronous generators in a traditional electric system [64]. Similarly, in an MG, parallel-connected power converters allow many DG units to function together. As a result, droop control can be used to alter the amount of active (P) or reactive (Q) power allocated to the system by each DG unit [59].

Droop control methods in MGs adopt reactive power-frequency $(Q-F)$ and active power-voltage $(P-V)$ to improve load sharing [59]. However, the droop method has also drawbacks. In islanded mode, the voltage and frequency are profoundly affected by loads and the nature of the distribution line in MGs. Therefore, there is always a trade-off between better load sharing and voltage frequency deviation, which, in turn, results in adding a secondary control level to restore voltage and frequency deviations [60].

A secondary controller's conventional approach is to sense the key parameters (i.e., voltage and frequency) in common bus lines. The output of the secondary controller is sent to each DG control unit to restore the reference values. This two-level control strategy has been completed by adding a tertiary control level responsible for governing the power flow between the MG and the main grid, for economic optimisation based on the energy price, and optimising power quality at PCC through data exchange with the system operators. Figure 2.2 shows how a hierarchical controller works in a decentralised manner with each DG unit controlled depending on the local measurements [62].

To design MGs control, it is crucial to have a flexible controller with a plug and play feature. This means that generation resources can be easily added or removed from the system [63]. A decentralised controller has to be flexible for this purpose, but the design is complicated [62]. In addition, the current MG controllers are designed and tested for radial MG topologies, and meshed topologies need further research [35].

The last point here is that DG units, unlike traditional bulk generators, do not offer natural considerable rotational inertia [66]. Low inertia has implications for frequency dynamics and stability, particularly in an islanded mode. This is due to the fact that frequency dynamics is considerably faster in MGs with low rotational inertia.

Wind turbines (WTs), unlike photovoltaic (PVs), have rotational kinetic energy to help maintain frequency stability in MGs. However, because the rotational element of the WTs is isolated from the rest of the system by converters, it cannot provide instantaneous frequency response. The virtual inertia technique is being used to increase frequency control [65]. However, because it requires reserving a portion of available power to maintain frequency, WTs cannot operate at full capacity. Furthermore, the virtual approach must be improved in terms of response time [61].

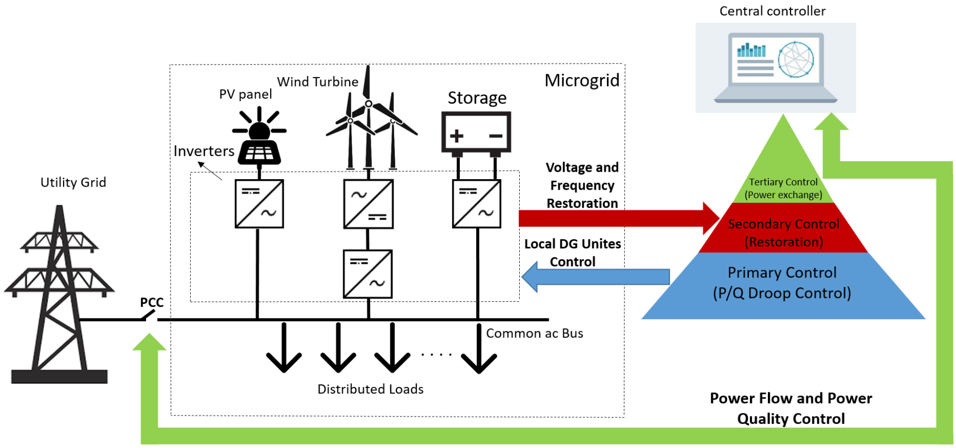

Figure 2.2: Principal of hierarchical controller.

2.3.2. PROTECTION

One of the biggest challenges in developing MGs is malfunctioning of protection schemes [67]. Relays in traditional distribution systems work with fixed settings but this type of protection scheme does not operate appropriately for MGs [36]. Fault currents in MGs change according to the location of the faults and fault current capacity of power inverters [67]. In general, the minimum required fault current in MGs is not available for accurate fault detection. Moreover, fault current reduces significantly in the islanded MGs mode, so the overcurrent relays that are already set to work with higher fault current may not operate sufficiently [68]. Any delay in updating the relay settings during islanding or synchronisation will lead to MGs blackout. In the grid-connected mode, the substation transformer provides effective grounding. However, this transformer is not available in islanded MGs. The current possible solution is to use inverter-based DGs with transformers in grounding configurations [71]. Other studies [69] proposed new adaptive protection schemes in which the relay settings can be adjusted based on received signals from control systems. These solutions require high investment costs and extensive communication networks.

In addition, current protection devices, such as fuses and circuit breakers in DC MGs, faces serious challenges due to the absence of both a grounding system and the zero crossing current [70]. Consequently, any created arc as a result of interruption in the current of DC MGs can hardly be extinguished [58]. To solve the problem of current DC circuit breakers, solid-state circuit breakers (SSCB) have been developed based on semiconductor technology. These devices are feasible options when there is a strict protection requirement. However, they can impose more power losses on the system [72].

2.3.3. ISLANDING DETECTION

The islanding of an MG can be categorised as intentional or unintentional depending on their occurrence. The main focus in islanding detection is on the unintentional (unplanned) one because it can distort power quality and the reliability of the electric system [73]. Some standards secure operational requirements. For instance, IEEE 1547 specifies that MG disconnection must not exceed a maximum of 2 seconds [74].

Passive, active and hybrid islanding methods are recognised in the literature. Passive methods are based on measuring and monitoring critical parameters such as voltage, frequency, or voltage and current harmonics at PCC. These methods assume that the measured parameter does not not exceed predefined thresholds [75].

In active techniques such as Active Frequency Drift (AFD) and Active Frequency Drift with Positive Feedback (AFDPF), a distorted waveform is injected into the system at the PCC. If the MG works in grid-connected mode, the frequency and voltage will remain unchanged due to the stability of the grid, but the voltage or frequency will be drifted up or down in the islanded mode [75].

These different techniques are proposed because proper islanding should fulfill different criteria simultaneously. For example, one of the critical criteria is the non-detection zone which refers to the thresholds of active and reactive power in which islanding cannot be recognised. The second important criterion is the run-on-time which determines the time between opening the circuit breakers at PCC and disconnecting the DGs inside the MG. These criteria are currently hard to apply to the real MGs sufficiently because they have several kinds of DGs with various parameters and are connected to the same PCC [73]. As explained in Section 2.6 this is problematic in real-life experimentation when islanding techniques for MGs and anti-islanding systems of DGs should work together.

2.3.4. SMART DEVICES AND REQUIREMENTS

From a technical perspective, a successful transition towards a smart grid is not achievable without smart infrastructure development. The Joint Research Center (JRC) [76] compiled an inventory of the main SG laboratory activities representing trends in the SG domain and the need for further developments. The report implies that pioneers in the field of SG in European countries work extensively on ICT and Advanced Metering Infrastructure (AMI), grid management, electromobility, and smart homes. Wireless technologies, vehicle-to-grid and charging modes, and monitoring techniques were of particular significance to the majority (about 80 %) of SG laboratories. And the activities did not show any consensus on the standards used.

Based on a study conducted by the US National Energy Technology Laboratory (NETL) [77], sensing measurement, advance component, integrated communications, Improved Interfaces and Decision Support (IIDS) and advanced control methods form the main pillars of Smart systems. Although these requirements are essential for the realisation of SGs, they cannot guarantee the grid's faultless performance because the infrastructure mentioned above should also have some specific requirements:

1. In a SG equipped with a large number of sensing and measurement devices, the amount of data generated will be considerably higher than the current grid because

consumers, generators and distribution systems will generate a large amount of data. Handling the data can by installing additional communication capacity or by data management [78]. An approach proposed for data management is to transform the data into knowledge. This transformation requires specific expertise and techniques that are currently not available [37].

2. The communication infrastructure and networking technologies should have guaranteed Quality of Service (QoS) covering the whole range of the electric system from generation to end users. To detect failures and respond to disturbances, the infrastructure should be reliable, robust, scalable and cost-effective [79].

3. The communication standards and protocols used in SGs should be modified. With current standards, it is challenging to support interoperability between various parts of the electric system. The establishment of worldwide and perhaps open standards could accelerate the penetration of SGs [80].

If these requirements are met, it would be possible to use reliable big data. How this data provides benefits and whether electric utilities are interested in acquiring and storing data depends, however, on their business models. Big data certainly has the potential to control and monitor the system in an optimised manner by, for example, load control, energy management and event detection. However, the best analytic and proper business strategy would have to be implemented to achieve the maximum benefit from digested and stored data [82]. In fact, the potential benefit of SG data exceeds the capital cost of the installation of data generation technologies. Aggregators, consumers and system operators are, however, often reluctant to deploy these technologies because business models taking big data and SG data into account have not yet been developed. In the absence of these business models, investment levels are unclear and lack an effective strategy to integrate data analytics and transfer raw data to meaningful information in operational and decision-making levels. Consequently, current low investments in grid modernisation with smart technologies reinforces stakeholders' inability to handle data economically [83].

Although business strategy plays a salient role in investment for the digitisation of systems, cutting edge technologies also have the potential to significantly reduce costs in data processing flows. In this regard, the Smart Solid-state Transformer (SST) is an Internet of things (IoT) technology that can perform multiple functions such as providing real-time communication and the intelligent management of energy flows. It thus reduces the need for other smart devices in the acquisition and integration of data. Similarly, self-controlled converters can combine grid data with maintenance data and act as an asset management technology to monitor, detect, predict and even mitigate the problems without human interference [84].

2.3.5. Need for frameworks to reduce complexity in design

Smart grid designers and project developers have to deal with the complexity of stakeholders' heterogeneity involved in projects. The technical requirements of each stakeholder should be met in relation to others [36]. An absence of structured knowledge in the domain of smart grids design has already been recognised in the majority of demonstration projects. A useful approach to coordinate stakeholders in the smart grid is to rely on communication infrastructures. Such infrastructure and specifications for different aspects of SGs (e.g., home communication, market communication and distribution network) are accessible due to the presence of the advanced ICT [85]. The US National Institute of Standards and Technology (NIST) combined the communication elements and proposed a framework consisting of seven domains [86].

As illustrated in Figure 2.3, electricity operation forms the heart of this model and is responsible for reliable and resilient power system operation. Operators carry out this task using SCADA, EMS or other control and monitoring systems. Received data from operators is utilised for voltage and frequency regulation or other similar purposes in markets. Service providers as brokers provide customers with electricity services (e.g., billing) [87].

The bulk generation domain connects the generators to distribution systems through the transmission system but coordination between generation, markets and operations domain is needed to measure the power flow. The transmission domain mainly aims to reduce losses and stabilise transmission lines and transformers. Moreover, having an interface with markets leads to the provision of ancillary services. The distribution domain has connections with operations, transmission, markets and consumers and plays a central role in supporting and managing consumption and generating real-time data used in markets. The last domain consists of end users in various forms (i.e., industrial, commercial and householders). Definitions of customers in smart grids differ from traditional costumers in the centralised electric system because distributed generation, storage devices along with ICT can be integrated into this domain [88].

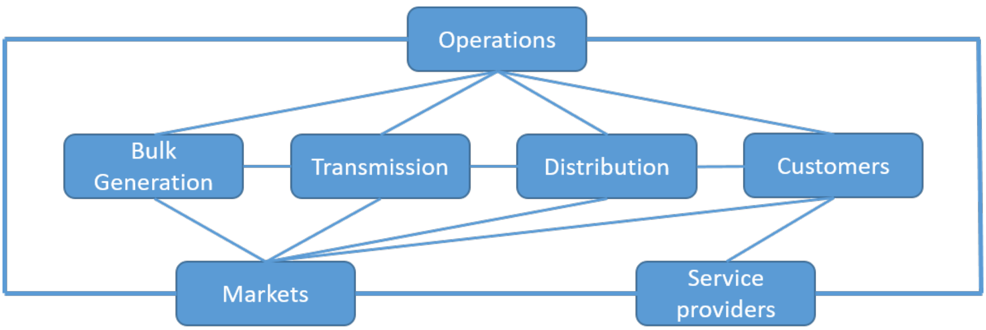

Figure 2.3: The NIST seven-domain framework for SG; adapted from [86].

Another serious attempt to reduce the complexity is made by the coordination of ETSI (European Telecommunications Standards Institute), CENELEC (European Committee for Electrotechnical Standardisation), and CEN (European Committee for Standardisation) where a developed framework supports the European Smart Grid plans [76]. The finalised version of this framework is called the Smart Grids Architecture Model (SGAM) (see Figure 2.4) which accelerates the process of development and facilitates the enhancement of standards. This three-dimensional model is built based on concepts of interoperability and tarpaulin (plane). It completes the NIST framework by

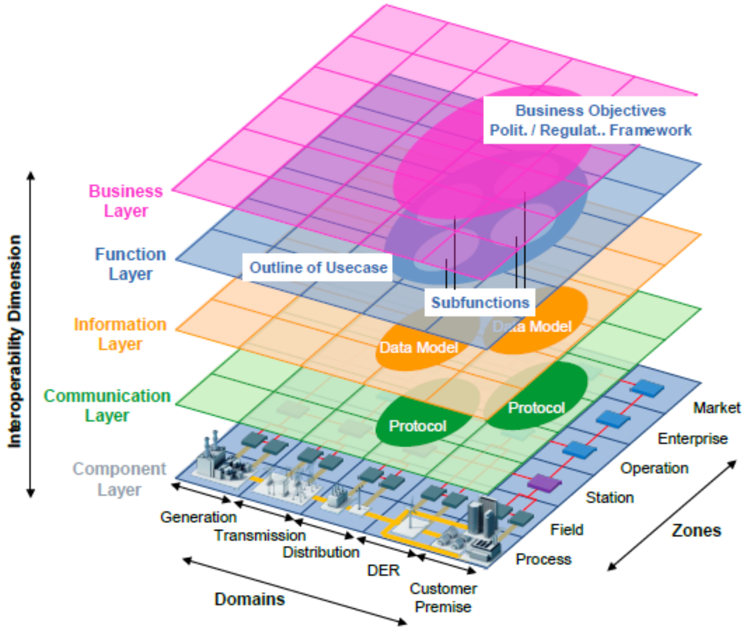

Figure 2.4: Smart grid Architecture Model (SGAM); adapted from [91].

adding new elements aligned to the automation pyramid.

The SGAM plane consists of two dimensions, namely Zones and Domains. Zones reflect power system management levels, and Domains represent the electricity energy supply chain. Aspects of communication, information, function, and business are combined in the third dimension, and each aspect is considered in an individual plane [87]. Although SGAM is highly accepted within the SG community [87], continuous innovation needs updated models. The successful expansion, design and implementation of SG projects depends on effective interoperation [90]. This is a demanding task due to the number of actors and elements in SG and the dynamic behaviour of elements that increases the system's complexity [157]. In certain studies, the concept of "System of Systems (SoS)" is used to describe the attributes of such a system [89]. For many years, the SGAM model's utilisation has shown that the dynamics of elements and the complex nature of SGs brings about unexpected behaviour that is hard to reflect in such models. To avoid the undesirable effects of unpredictability, researchers advocate the combining of different models [90].

The SGAM model and the NIST framework exclusively address the technical aspects of SG systems and ignore the impact and role of human decisions on the behaviour of such systems [92]. Furthermore, the SGAM model uses a non-semantic and static approach. The former means that there is no common understanding and vocabulary among the layers and domains. Therefore, it is unclear how to transfer and exchange data in transparent ways, for example, with customers. The latter implies that the time dimension is not considered in SGAM. Consequently, the transient effects of the ICT infrastructure and the effect of changes in smart electric systems cannot be communicated properly [93].

These shortages in the SGAM model are rooted in the heterogeneity of data and protocols as well as the methods that are used to analyse and interpret data that can be adopted. A possible approach to dealing with the heterogeneity between layers and domains is to implement web technologies, particularly Ontology Web Language (OWL) and combine them with standards such as IEC 61850 and IEC 61968 to collect and exchange data from different applications using different interfaces [87].

2.3.6. NEED FOR ASSESSMENT

Examples of failure in SG projects can be found globally. Most premature failures happen in the early phase of the operation and are mostly linked to short-sighted policies towards high-tech projects [94]. Politicians may misuse the number of installed high-tech projects, including SG projects as an instrument in their party manoeuvres and influence public opinion with impressive statistics [95]. This explains the lack of quality where projects are not supported financially to assess the project outcomes, so the quality of the project will deteriorate [95]. Consequently, no one will take responsibility for failed projects, and the reputation of the technology will be damaged [94].

The project promoter will not be able to prove the viability of projects and such projects will potentially not be entitled to further funding [101]. In contrast, the proper evaluation of outcomes leads to, first, legitimised projects that can benefit from future funding. Second, it leads to the establishment of trust and responsibility among all the actors involved. Third, it confirms the implemented technologies or innovations. Finally, it resolves the conflicting visions and expectations among the actors.

Prior to implementing any assessment, it should be considered that this is a daunting task due to many serious challenges [95]. Having a reliable evaluation is a matter of proper assumption and data accumulation. Experiences of former assessments indicate that the impact of variables on the final results varies in different time intervals. This is particularly noticeable in a Cost-Benefit-Analysis (CBA) where factors such as discount rate, estimated inflation, the energy price, carbon pricing, and tariffs are significantly time-variant [91]. In other words, if the projects last for a long time, which is the case for many SG projects, the accuracy of the assessment will be affected.

Another acknowledged argument is the interpretation of the results. Sometimes the key performance indicators (KPIs) do not show tangible improvement but this can be deceptive since KPIs depend on external conditions. For example, environmental KPIs depend on the amount of energy generated from renewable distributed generators, and this directly depends on regulation and policies (e.g., incentives for DGs to sell their energies inside the SG, and not to the main grid) [97].

The final point in this regard is that of data deficit due mainly to privacy or security concerns. In such circumstances, the evaluation will be based on expert judgment, and the accuracy of this judgment is not always reliable [100].

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2.3.7. Summary of technical barriers

To summarise, the technical barriers to SG development can be classified as: (i) barriers to MGs in particular; (ii) barriers to SGs in general; (iii) the design framework; and (iv) barriers to the assessment of SGs. Barriers to MGs pertain to a complicated design of decentralised controllers with plug and play, a lack of inertia in DG units, malfunctioning protection schemes, the need for the development of further control methods for meshed topology, a lack of grounding system in DC MGs, and outdated islanding detection techniques in terms of speed, power quality and costs. Barriers to SGs pertain to the need for increased knowledge and investment to handle higher amounts of data, QoS yet not being guaranteed, outdated communication protocols and standards. Design frameworks do not yet include novel SG and SG functionalities and need to be updated, and do not yet deal with the potential impact of human decision-making. Finally, current assessment frameworks use inaccurate assumptions and have data deficits. These are to some extent related to short-sighted, politically influenced evaluations of high tech SG projects, but also to privacy and security concerns. And assessment metrics can be influenced by external conditions influenced by political agency, in particular selecting and using certain KPIs.

2.4. Regulatory and policy barriers

Categorising regulatory barriers is not straightforward because regulations influence actors in energy markets in different ways. A tangible example is the integration of RESs in an electric system where support schemes try to increase the share of RESs. However, allowing RESs to connect to the network without considering connection point in terms of transmission and distribution capacity may require network reinforcements and excessive additional costs for system operators. Conversely, any undue restriction brings about economic barriers for RESs providers [158].

Previous studies mentioned regulatory challenges for liberalisation and competition, the sharing of energy and ownership, interconnection with the larger energy infrastructure and the integration of renewable energy [31]. These categorisations do not cover the interactions between actors or the side effects of regulations.

Therefore, we adopt a different approach based on the challenges encountered concerning the creation of SG markets [103] (i.e., investment barriers) and the challenges of SG markets' healthy functioning [104] (i.e., performance barriers). Investment barriers are directly linked to a lack of incentives that demotivate actors from participating in energy markets [102]. On the other hand, performance factors address issues that lead to the malfunctioning or even the collapse of the markets. These factors are attributed to unregulated markets in terms of responsibilities, financial agreements, cybersecurity and privacy issues. Table 2.2 presents an overview of performance and investment barriers.

2.4.1. Market structure

Based on [105], Figure 2.5 illustrates a simple schematic of how SGs potentially work in electricity markets. It has four levels related to certain actors and their role in electricity markets; i.e., as prosumers, aggregators, markets, and as operators. The local SG market

Table 2.2: Classification of barriers to SG market uptake [103].

Performance barriers	Description
Imperfect market	Property rights are poorly defined (e.g., unclear financial adjustment between end users, suppliers, BRPs and aggregators)
Incomplete information	Market parties do not have access to (perfect) information (e.g., how flexibility is handled and distributed in networks, and who should have access to this data)
Imperfect competition	One or only a few parties have, and exercise, market power (e.g., a lack of intermediaries at aggregator level can lead to an oligopoly of aggregators)
Cybersecurity and privacy issues	Consumers do not engage in the market when privacy and cybersecurity is not taken seriously. Polices should ensure confidentiality, reliability, integrity and accountability of information
Investment barriers	**Description**
Uncertainty	A high degree of uncertainty about future revenues and costs (e.g., unclear and sometimes negative outcomes from CBAs, and uncertainties related to energy costs
Lack of incentives for consumers	Marginal costs (e.g., the carbon price is not reflected in the overall electricity pricing) Dynamic pricing schemes do not show conclusive results across different countries
Conflicts between market actors	Undue arguments against DGs from utilities Integrating more RESs exposes distribution system to additional costs Lack of infrastructure for local trading inside SGs The fast phasing out of traditional generators may lead to a lack of energy capacity Net metering schemes can lead to unfair cross-subsidisation of consumers to cover utility service costs Feed-in-tariff (FIT) schemes can be terminated or changed, offering lower and unattractive tariffs to DG RE producers. Moreover, they can also have a long-term negative impact on energy markets, becoming very costly in the end

is the first place for trading electricity. If the required infrastructure for such a market is already in place, not only will the local prosumers enjoy its benefits, but the system operator will face less congestion and overloading issues in distribution lines. However, this is not the case for most of the SG plans because the mechanism of peer-to-peer trading is not available globally [106]. Real-world examples of such mechanisms include the blockchain-based MG energy market in Brooklyn (US) [127], the Piclo platform in the UK, and a project at De Ceuvel in the Netherlands, but this is far from the way today's market models operate [106].

Some agents work as mediators between prosumers and the market level at the aggregator level. The actors at this level are the same as those found in the traditional electricity market (i.e., Balance Responsible Parties (BRPs), energy suppliers) with the expectation of aggregators as the new market entrant [159]. The existence of aggregators is on the grounds that prosumers may not be able to put small chunks of flexible generation and consumption together as a tradable product on the electricity market [118]. Various combinations and arrangements of actors at the aggregator level are proposed but how this is optimised with minimum conflict with other actors integrating aggregators into the electricity markets is debatable [107].

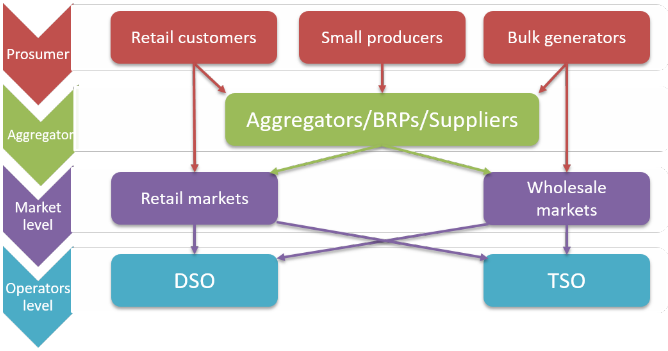


Figure 2.5: Overall market structure of SGs; adapted from [105].

Small electricity producers can participate in the retail market to support network operations when the network faces an energy imbalance. Moreover, SGs bulk generators may participate in the wholesale market and offer their energy resources to TSOs. In both retail and wholesale markets, BRPs are responsible for balancing energy production and consumption within their portfolio.

Finally, DSOs and Transmission System Operators (TSOs) confirm the information about maintaining the balance between supply and demand at the operators level [119].

2.4.2. Market performance barriers

Having the SG market structure in mind, the current structure of SGs is incomplete because contractual arrangements and financial adjustments are unclear [121].

To begin with, prosumers and their interactions with suppliers and aggregators need to be reconsidered [54]. Laws and regulations stipulate consumers' rights and support them in energy markets. However, it is unclear whether these laws and regulations apply to the relationship between aggregators and consumers [120]. In a simple arrangement at the aggregators' level where aggregators, BRPs and suppliers work independently, consumers will have two different contracts with suppliers and delegated aggregators. These contracts may infringe with each other if their terms and conditions are not coordinated or aligned [54].

Mismanagement of the flexibility created by aggregators can lead to an incomplete market. TSOs and DSOs should be able to confirm selected and activated flexibilities , particularly when congestion occurs [120]. How aggregators distribute flexibility data in electric systems remains unclear. In regulated markets, BRPs and suppliers are financially and technically responsible for balancing supply and demand [122]. However, it is argued that the aggregators may cause imbalances by creating and distributing flexibility that is not aligned with BRPs and suppliers' activities. Aggregators may, therefore, have to pay compensation to them [105].

Even though the presented market structure in Figure 2.5 is assumed to be competitive because of the coexistence of multiple suppliers and intermediaries at the aggregator level, it may still face imperfect competition. For instance, considering the aggregators' uncertainties, there will be an insufficient number of entities acting as aggregators, which runs the risk of developing an oligopoly of aggregators. This could have implications for the aggregators, particularly regarding sharing their profits from activated flexibility with consumers [107].

CYBERSECURITY AND PRIVACY ISSUES

Market penetration of sensors, smart meters and ICT are necessary to exchange data between other systems and devices. However, this inevitably paves the way for exposure to denial-of-service attacks, viruses, malware, phishing and other forms of cybercrime. Also, regular measuring and analysis of costumers' energy consumption patterns by smart devices may violate their privacy, and raise security issues [37]. This may scare customers away from participation in demand response programmes.

It is, therefore, evident that protection and defence systems should be continuously upgraded with communication protocols and standards, but adopting the required policies and regulations in SG markets should not be taken for granted. In general, policies should be deployed to incentivise cybersecurity innovation, clearly define the responsibility of actors in data management, improve privacy regulations and facilitate public-private collaboration [128]. To reach these goals with consistent policies the NIST in the US, for example, asks responsible parties to comply with a set of criteria [109].

First, the 'confidentiality' criterion requires personal privacy and proprietary information to be accessed only by authorised entities. The usage information pattern between costumers and aggregators must be protected and handled in a confidential manner. Otherwise, this information can be used for malicious purposes such as theft.

Second, reliable and timely access to information has to be ensured. This is referred to as 'availability'. For example, if the information flow is blocked in the data network, there is an increased likelihood that the control system's operation is disturbed.

A third criterion pertains to 'integrity'. Information must be protected against destruction and modification. Lack of integrity means information can be altered in undetected and unauthorised ways. This can make SGs vulnerable to attacks, with attackers seeking to shut down essential parts of the grid, for example by creating maximum voltage deviations. This can be realised by injecting active or reactive power into the grid. The risk of a successful attack increases when system operators cannot determine power injection integrity. Integrity of data is maintained if a legitimate source generates it. Finally, more protection against attackers is provided by increasing the 'accountability' of information. This means that each action performed by actors or devices can be traced and recorded. This allows grid operators to easily adduce information in court against attackers [109].

2.4.3. INVESTMENT BARRIERS

System operators and policymakers conduct CBA to decide whether to invest in smart grid technologies themselves or to encourage private investment by adopting new policies [160]. The current SG market is characterised by high uncertainty, perceived risks and a relatively long payback period. This is not desirable for (risk-averse) investors [103]. For example, the Belgian government ignored the European directive and postponed the deployment of smart meters because the evaluation of the smart meters rollout programme did not reveal a CBA positive outcome [104].

The issue at stake here is that although the results of CBAs are used, they can hardly be considered reliable. This is mainly due to the complexity of running a CBA on SG technology in an immature market. A CBA can also only provide a monetary assessment. Other added values of SGs in terms of city governance cannot be expressed quantitatively. For example, the electric system resiliency cannot be accurately estimated [123].

Moreover, large investors, such as DSOs and technology manufacturers will only invest in a risky and unclear market when regulations allow them to have higher remuneration rates, which is not the case in many countries [110].

In this regard, different incentive-driven policies have been adopted in the EU and the US. Broadly speaking, they can be divided into cost-based, incentive-based and hybrid-based regulations [103]. Most of EU member states like Germany and Spain, have adopted cost-based regulations in energy prices. This model puts a cap on operating expenditures (OPEX) [110]. Although utilities will enjoy a consistent and fair return on capital investments, it prevents them from reaping benefits. Therefore, cost-based regulations, which are mainly implemented in the form of Rate of Return (ROR), provide investors with weak incentives to reduce costs and increase efficiency because profits are linked to maximising sales.

Currently, most EU member states have switched to incentive-based regulations. This incentive works on the assumption that firms will improve their performance by taking advantage of available information [49]. The predominant types of incentive-based regulations pertain to the price-cap model, yardstick regulation, revenue caps and revenue or profit-sharing schemes [49]. Since this type of regulation can improve the OPEX, it can be implemented in combination with cost-based regulations and forms a hybrid model to deal with (capital expenditures) CAPEX and OPEX simultaneously [102]. As argued by [120], the general issue with these incentives is that they are only implemented in countries with buoyant economies like Germany, the UK, and Denmark.

In a broader perspective, two possible solutions are envisioned to address underinvestment in modernising electric systems with smart technologies. One approach is to reduce the risk of investments by engaging more actors along the value chain, for instance, by using a sharing mechanism, investment returns might be split between utilities and costumers. However, if the returns do not reach the target level, the net loss could be shared [110]. Another solution is the unbundling of the electricity network. Even though this takes place during the liberalisation of electricity networks, it might lead to a reduction in R&D on the short run because business firms are likely stick to their business as usual activities. The consensus is that unbundling boosts investment eventually. In a fully liberalised electricity market, tasks, uncertainties and investment risks are not assigned to one single agent. And in such a competitive market, actors need to adopt a more innovative approach [129].

INCENTIVES FOR CONSUMERS

Exclusively focusing on consumption and generation patterns of prosumers is the prevalent policy with regard to engaging local communities and consumers [111].

Concepts of DSM, Demand Response (DR) and flexibility are intrinsically related to this. However, flexibility has been used more recently to cover almost all aspects, including energy storage and ancillary services [112].

A major challenge for the activation of flexibility is the participation of consumers. The current pricing system discourages consumers from changing their consumption patterns because the marginal costs such as carbon price are not included [124].

To address the lack of incentive, dynamic pricing is proposed and implemented in some countries (e.g., Nordic, Estonia and Spain) [113]. Widely adopted dynamic pricing programmes such as Time-of-Use (TOU), Critical Peak Pricing (CPP) and Real-Time Pricing (RTP) allow for price differentiation between times of peak load and baseline demand [114]. The benefits of dynamic pricing are twofold. First, direct financial benefits for the costumers can be reflected in their energy bills. Second, by reducing peak demand, the use of expensive peaking facilities will likely be avoided and the average wholesale energy price will consequently be reduced [37].

In practice, records of dynamic pricing plans are not conclusive, though. Some dynamic pricing projects have experienced minimal positive outcomes, while others ended up with a considerable reduction in peak load [115]. The success rate of dynamic pricing can be attributed to social acceptance factors such as privacy concerns and consumers' sensitivity to any tariff changes. Consumers also criticise policymakers for failing to provide transparent information about the exact advantages of dynamic pricing when comparing it to flat pricing [124].

Conflicting incentives between RESs, traditional generators and network operators

In general, current regulations allow utilities to impose rules, sometimes unduly, to supposedly ensure the system reliability [49]. Sometimes, this argument is used against the integration of RESs, for example, by regulators who suggest protecting the market from RESs by means of special taxes [116].

It is naive to dismiss the challenges of integrating RESs into the electrical grid. Nevertheless, many of the arguments against RESs are exaggerated. Creating understanding of grid operations and market structures can help regulators and policymakers to avoid believing and adopting these fallacies. Electrical grids as a whole are capable of providing reliable power generation all the time. However, this does not mean that each individual generator is always reliable which might be related to being involved with maintenance or other technical issues [116]. According to Silverstein et al. [126], the majority of outages (over 90 %) occur in distribution and transmission levels and not in generation. Moreover, generators provide ancillary services (e.g., grid-balancing) as a byproduct. As more RESs are integrated and SG technologies are diffused, reliance on ancillary services can be increased. Thus markets can deal with the intermittent nature of RESs [116]. For example, PVs, wind turbines, and EVs can play the role of traditional spinning generators and increase the operating reserve. Power inverters that are installed within these technologies can provide services such as reactive power compensation, voltage regulation, flicker control, active power filtering and harmonic cancellation.

From a utility perspective, the incomes of DSOs and TSOs derived from network tariffs or connection charges must be guaranteed. Consequently, DG providers could consider the option of local electricity trading inside SGs [104, 117]. In practice, however, many DSOs and incumbent energy providers oppose this alternative because of perceived losses in financial revenue. For example, DSOs expect to receive fewer Use of System (UoS) fees.

It has recently become more difficult for traditional generators to compete with other generators using RESs. Wind and solar DGs, on the other hand, have low operating costs, and do not need to purchase fuel. They bid lower prices on energy markets than traditional generators. Giving priority access to RESs exacerbates the situation for traditional power stations, which can be seen as a positive result of policies targeting the phasing out of polluting power stations, but it leads to power security risks, if this happens very quickly. In this respect, the Capacity Market is an alternative option for system operators when it comes to coping with reliability issues. This market works alongside the energy market and ensures sufficient generation or load-management capacity (e.g., with storage devices) when the system is subjected to stress [116].

The problem with creating the Capacity Market is comparable with fallacies encountered with the use of RESs. While market regulators consider the financial risks traditional generators encounter, and the early warning of possible supply interruption, it is hard for them to decide whether there are risks due to lack of capacity, and to what extent this is related to the use of RESs [116].

Compensation for DGs is crucial to regulatory authorities [158]. The primary incentive schemes for DG/RES to participation in the electricity market are net-metering and the feed-in-tariff (FIT) [30]. In the net-metering scheme, producers of RESs obtain tradable green certificates according to their net energy consumption and production. Utilities often oppose these supporting schemes arguing that DGs and RESs do not pay the proportionate UoS fees for the utility services that they receive [30]. This results in unfair cross-subsidisation of consumers who do not possess RESs [41]. Moreover, depending on the price volatility in evolving markets, net metering producers may face uncertainties in terms of seeking revenue.

In contrast, RESs producers can have investment certainty in FIT schemes by receiving a fixed price per unit of their supplied power over a period of time [125]. Although FIT has been proven to be an effective tool to accelerate RESs and DG production, it is not without problems. Price adjustment mechanisms are the major challenges in setting a guaranteed price based on imperfect information. Setting prices too high may lead to eroded support for the scheme. This was the case in Germany where FIT was successfully implemented initially, but over time became less affordable with German taxpayers becoming reluctant continue to paying for it [125].

2.4.4. SUMMARY OF REGULATORY BARRIERS

To summarise, there are multiple issues with policy and regulatory frameworks that hamper SG development. First, there are unclear contractual agreements between market actors. Second, there is underinvestment by market actors because they experience high risk on the one hand and a lack of or no access to sufficient financial investment capital on the other. Third, there are multiple risks regarding handling, storing and sharing data. This is related to risks related to cybercrime, privacy and confidentiality issues, but also to the accountability and availability of data. Fourth, DSOs and traditional power generators (i.e., electricity market incumbents) have little and conflicting incentives to invest and experiment with SG innovations. DSOs, for instance, are restricted by law to explore and test certain functionalities of SGs like energy storage options. Finally, there is a lack of economic incentives in domestic electricity markets to implement flexibility. For example, pricing mechanisms in domestic electricity markets do not reward it, and although household prosumers are allowed to use self-generated electricity or feed it into the electricity grid in many Western-European countries they are not allowed by law to sell it to their neighbours.

2.5. SOCIAL ACCEPTANCE AND INSTITUTIONAL BARRIERS

2.5.1. SMGS AS COMMON POOL RESOURCE

Public acceptance has been used as an indicator of social acceptance since the introduction of RESs. The concept of public acceptance, which stresses aggregated individual acceptance, focuses on the individual energy-producing technologies [130]. For example, several studies have been conducted on the acceptance of wind [145], solar [146] and hydropower [135]. Although studies on social acceptance of RESs production sites have enabled scholars to investigate spatial scale and local ownership factors, this approach is incapable of addressing SGs' acceptance as a complex integrated energy hub [114].

Establishing SGs is not a matter of one actor's or agency preference because SGs include various activities such as generation, storage, ICT and control, and demand response in a locally distributed structure. To establish SGs, collective action is required to address this complexity [132].

Collective action has been described [133] as a decision-making process in which all actors can reflect their interests in reaction to other actors. Institutional change is an essential precondition to creating collective action to establish an SG environment. New institutional approaches towards social acceptance of SMGs deal with electricity as a Common Pool Resource (CPR), instead of a private economic good [124, 161]. The benefit of such reconsideration is to acknowledge the systemic character at hand, and to facilitate the process of policymaking leading to the removal of legal and institutional obstacles. The second advantage stems from features of CPRs where exclusion of each actor is difficult and exploitation by one user reduces resource availability to others [133]. The concept of CPRs implies that the decision-making process is not monocentric. Instead, different layers of actors shape governance in a highly polycentric and semi-autonomous manner with several decision-making centers. Such polycentric systems expedite cooperation and trust among actors and could stimulate innovation and the adoption of SGs [134].

2.5.2. ACCEPTANCE AT MULTIPLE LEVELS IN SOCIETY

The most compatible model of social acceptance with CPRs is suggested by Wüstenhagen et al. [134], where socio-political and market dimensions are added to the community dimension (see Figure 2.6). The socio-political level relates to policy actors and the regulatory authorities' role in providing productive policies in the form of laws and directives for acceptance of innovations and technologies at other levels. At the market level, market actors accept SG technology and invest, providing that policy actors set up conducive and non-discriminatory policies and regulations [134].

However, this model is criticised because it is not clear how different levels interrelate. More specifically, it cannot explain acceptance at the international, national and local scale [136]. Additionally, the role of acceptance through intermediaries is neglected. Intermediaries using their agencies and capacities, can influence the acceptance of innovations like SGs by transferring acceptances to actors at other levels of governance. For example, building professionals and commercial building companies use agents (capability to act in SG markets) and their capacities (knowledge of the value of SGs for householders). However, their role is not included in the suggested model [137]. Finally, the role of communication is neglected. Knowledge developed at both the individual and collective level must be articulated. Without communication, knowledge is pointless. Communication about key innovations like SGs is vital and is clear in theories like the social representation theory [135] and diffusion of innovation [162]. Attention is paid in these to explaining the process by which a new idea or technology is developed and revealed by communication among actors. Communication should be included in the model because different levels may use different communication channels due to their different social positions.

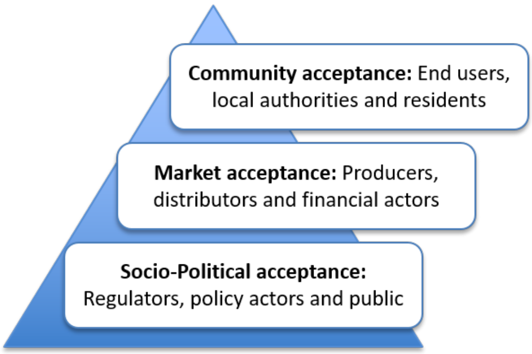


Figure 2.6: Triangle of social acceptance of SG technology at different levels in society [124].

2.5.3. Acceptance of SGs and community energy

The concept of community energy is widely used to describe energy-related communities and projects they develop and operate. However, the concept of community SG, as in social communities engaging in and running SG projects, needs more elaboration as only a few studies have attempted to define it [138]. Two dimensions of community energy are suggested in the literature [139]. First, it is important to address who develops and runs community energy projects (i.e., the process dimension). Second, it is important to consider who is influenced by these project outcomes (i.e., the outcome dimension).

Hana [140] discerned three commonly used terms that determine the meaning of community energy: (i) community as stakeholders, which refers to significant stakeholders in decisions and the implementation of energy initiatives; (ii) community as a space or place, which relates to space where collective action happens; and (iii) as a shared interest or vision, which is about groups of people with shared interests and visions. Linking these dimensions to SGs, the following can be derived: social and economic dimensions of SGs can be seen as the core focus in defining community SG regardless of technologies used in SGs.

Warneryd [148] provides the most suitable definition of MG community as: "A community microgrid is technically a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries which acts as a single controllable entity with respect to the grid. A community microgrid can connect or disconnect from the grid to enable it to operate in both grid-connected or islanded mode. Moreover, a community microgrid is connected with its community through physical placement and can be owned by the said community or other parts." However, this definition does not reflect the features and benefits of SGs to communities. A community SMG can deliver carbon savings, increased grid stability and cost savings for the stakeholders. According to the International Energy Agency (IEA), these potentials can be unleashed by advanced digital technologies to monitor and manage the transport of electricity from all generation sources and storage devices to meet varying electricity demand. Therefore, in community SMG, interaction and the coordination of energy consumption between stakeholders is of key importance.

We contribute to the above definition of MG by drawing attention to the smartness of community and coordinated actions with the following:

"A community SMG can be defined as an intelligent electricity distribution system operated by a community of stakeholders, in which groups of interconnected loads, distributed energy resources, and storage are located within clearly defined electrical boundaries and function together as a single controllable entity relative to the main grid". The community SMG operates through information sharing and communication technologies, utilises locally distributed renewable generation and demand-side resources, and is cooperatively managed to enhance system reliability, resilience, and stability, while maximising market value and minimising costs and environmental impacts [163].

We recognise two possible research avenues to study acceptance of SMGs in communities. First, by addressing ownership and involvement, and second by addressing community members' identity.

2.5.4. OWNERSHIP AND INVOLVEMENT

Implementing any energy project, including the use of SG technology involves actors and ownership issues [132]. Ownership and involvement can result in the strong conviction of community members that the project serves their interests and offers benefits [138]. However, there is a need for more insight into the reasons and opportunities that foster communities' involvement and how involvement is encouraged.

To this purpose, community values should be considered. Historically, reliability and efficiency have been the central values in energy sectors. More recently, environmental sustainability concerns have gained importance [131]. Although energy produced from

RESs addresses sustainability to a large extent, it endangers the supply and consumption balance. SGs have the potential to make a considerable contribution to resolving this conflict, but some values in SGs are only achieved at the expense of others [112]. For example, deploying monitoring and controlling devices might cause conflicts between values, like security and accountability of technology on the one hand, and privacy and democratisation on the other. And violated values cannot be compensated unless SMGs allow the community to be part of the decision-making process or to establish trust between the local community and project developers. Without 'sense of ownership', trust and involvement in decision-making cannot be taken for granted [22].

Community energy initiatives vary in terms of organisational structure. For example, they have different legal forms including public-private partnerships (PPPs), cooperatives and limited liability companies and some are even in municipal ownership. In practice, three local energy governance models can be discerned: 'remunicipalisation', 'revolution' and 'participative governance' [142]. Remunicipalisation refers to an increased role of municipalities in taking control of energy companies and energy infrastructures. Examples in Germany and France show that political parties are becoming more involved in local energy markets. Similarly, as showcased using the devolution model, local authorities and city councils have taken on the responsibility of supporting energy communities. This model, which is frequently observed in Scandinavian countries, eases the information flow and interaction between governments and local citizens. Although the models have certain benefits, they can neither increase the number of citizen-led energy projects or transfer national governments' power and opportunities to local energy producers [142]. In other EU countries including Germany, the Netherlands and Belgium, participative governance approaches are being used in which citizens are allowed to inform climate and energy policies (e.g., by involving in discussion forums and participative budgeting process). This leads citizen empowerment through partnerships and cooperatives (e.g., renewable energy cooperatives; REScoops) but also via housing associations [142].

Favourable outcomes of local community energy models are being jeopardised because relevant national structures like political support, financial requirements and clear rules to govern community energy activities are not in place. From a socio-political perspective, there is a lack of clear support and commitment. To this end, voluntary commitments have the potential to accelerate this process. The Covenant of Mayors is an example of a voluntary movement that the European Commission launched to support local energy authorities in 2008. By adopting this scheme, local authorities across the EU voluntarily commit themselves to promoting energy efficiency and implementation of RESs in their local jurisdictions [142]. However, similar movements are hard to find.

In practice, local community groups typically encounter financial barriers that endanger local energy projects. While upfront subsidies are available for many projects, they usually come with strict limitations, for example in terms of time. Nonetheless, a need for financial instruments remains necessary to support start-ups in local energy communities. A relevant example is the German KFW Bank that provides loans with preferential rates for local energy initiatives [143].

Finally, the importance of regulatory and legal frameworks with regard to the operation of community energy should be mentioned. In particular, terms and conditions for accessing the national electric grid should be clarified. In Ireland, for example, local communities are reporting uncertainties about connection of SMGs to the electrical grid as a major problem. And procedures to connect local energy projects that involve RESs are costly for small-scale energy communities [142].

2.5.5. Identity and behaviour of community members

The identity of geographical locations determines how members interpret values that are relevant to SMGs. Identity can vary depending on, among other things, social norms, income rates, the desire to adopt innovations and invest in them, and the type of enterprise involved [114].

Involvement of community members in SMG projects requires investments that vary according to the financial means available. End users with high income are expected to enjoy the benefits of SMGs more than others. Analysis of SMG demonstration projects with demand response programmes reveals that low-income households reap fewer benefits [149].

Moreover, members differ significantly in the amount of space they can offer RESs [150]. In addition to householders, other local stakeholders, such as schools, are important for community identity because they can provide more rooftop surfaces to install PV panels. Other examples pertain to hospitals and military bases where the importance of resiliency and the reliability of power require an independent operating power system for emergencies. They may also consider attuning their load profile with other stakeholders' consumption patterns [22]. The identity of a community is also influenced by the nature of the enterprises. The adoption of SMGs technology is meaningfully higher in communities where tourism is the main source of income [22].

Community identity is also linked to behavioural barriers and this is often explained by the aid of demand response [147]. Sometimes customers are reluctant to change their behaviour even when clear benefits are offered and the need for adoption is clear. This related to the notion of 'bounded rationality', for example with costumers resisting the adoption of controlling devices for consumption optimisation [28]. This is understandable from the standpoint of customers seeking utility maximisation. Penetration of demand response technology means loss of control over devices and costumers' comfort. Unpleasant experiences for the customer from poorly designed technologies may exacerbate the situation [144]. Another example of bounded rationality is linked to flexibility providers who sometimes avoid increasing flexibility and profit by installing storage devices. This can be interpreted by the risk involved in the development of the business because they feel it challenging to leave their comfort zone, and they are happy with the current profit [132].

Although community energy members' economic situations and identity are inevitable consequences of the class differences in society, some actions can mitigate it. For example, free access for all community members to information about SMG projects on the one hand and the active participation of end users in the decision-making process on the other are considered important to alleviating inequity [150].

2.5.6. Institutional barriers

Path dependency and lock-in

The 'rules of the game' in electric systems have historically been developed to support the incumbent centralised power system [150]. The existing pattern of rules, in the first place, consists of physical infrastructures of power systems that have materialised in a path-dependent paradigm, leading to a situation of 'lock-in' and inertia to change by incumbents. Accompanying change is challenging for incumbents because it is considered to violate the current way of working, and is not in line with current belief systems. Lock-in also applies to the use of information and data in the electric system's infrastructure. Metering routines, data collection methods and data provision for consumers are examples.

Wolsink [124] has discerned five categories of rules of the game that can lead to lock-in in community energy, i.e., (1) government policies and interventions, legal frameworks, government organisations in departments, ministries and agencies; (2) dominant technologies, including standardisation; (3) organisational routines and relations; (4) industry standards and specialisations; and (5) societal expectations and preferences

Considering this categorisation, some scholars (e.g., [151]) have analysed institutional lock-in using a decision-making process perspective, whereas others have used an institutional economic perspective (e.g., [138]).

Institutional economic barriers

By adopting the New Institutional Economics (NIE) framework, Minghui et al. [138] analysed government institutions and the structure of transactions in energy communities.

They hold that an institution's reconfiguration should be performed through transaction alignment and economising on associated transaction costs. After examining the relevant terms of applying SMG to community energy, such as ownership, governance and features of the contracts among parties, it has been suggested that the technical assets involved in SMG projects are often associated with idiosyncrasy, low frequency and uncertainties that have profound implications in the adoption of new governance structure, investment and ownership.

Investment in SMG assets is considered idiosyncratic mainly because they concern specialised equipment and can rarely be deployed to other uses or find alternative consumers outside the SMG. With the current institutional arrangements, investors view SMG assets as a sunk investment. Transactions in SMG projects are infrequent because stakeholders are not inclined to maintain long term relationships. Moreover, actors show opportunistic behaviour misuse the situation without worrying about their reputation [138].

Complexity of decision-making

The difficulty of decision-making regarding SGs derives from assigning new responsibilities and the redistribution of power among electricity market actors. This may occur when designing institutional rules while using a participatory approach, instead of top-down policy making, to give a proactive role to community members, and stakeholders [153].

Researchers have developed theoretical frameworks as guiding tools that can eventually be used for system analysts and policymakers. An example of this is the Institutional Analysis and Development (IAD) framework that is used to analyse institutional settings [156].

To this end, Lammers and Hoppe [152] tried to establish 'which institutional conditions enable or disable decision-making processes regarding the introduction of smart energy systems' by applying the IAD framework to four SG projects in the Netherlands, and analysing institutional condition (e.g., rules in use) empirically. The results show that existing rules are not appropriate for SG development for a number of reasons. First, local community members, particularly householders, are usually not aware of plans for developing energy projects in their district. The disengagement of end users is consequently perceived as a barrier, particularly in the implementation and development stages of projects. Second, the formal and informal positions of the actors are not communicated in projects, and no specific project actor plays a key role in the developing SG projects. This is also reflected in poor cooperation between actors and consortium members who take on a passive observer role in projects. These passive roles are also associated with legal barriers, which deter DSOs and housing associations from making any investment in projects. Additionally, despite providing subsidies for projects to facilitate ruling out such projects, disagreement between consortium members on sharing costs and benefits serves as a disabling condition for projects . Following these insights the authors suggest that institutional conditions, including decision-making, should be evaluated in the early stages of project development to avoid setting over-ambitious and unattainable goals [152].

2.5.7. Summary of social and institutional barriers

In brief, barriers to the social acceptance of SMGs and local institutions are as follows. First, there is a need to acknowledge systemic, complex and polycentric character of SMGs. An SMG can be viewed as a CPR. Therefore, managing and implementing SMGs requires concerted collective action, not only action by an individual initiator or agent. When planning SMG projects, attention is required regarding the local situational context in which SMGs are to be implemented. This includes attention to addressing local acceptance of SMG technology. Acceptance, however, comes in many forms, i.e., community acceptance, socio-political acceptance and market acceptance, and involves more than just the persuasion of a number of local residents.

Next, the planning of SMGs in local projects needs to focus on institutional conditions and rules. This pertains to interaction, involvement and coordination between stakeholders concerning the management of energy flows. These conditions are, however, hardly ever met in practice. More insight into the reasons and opportunities that foster communities' involvement and how involvement materialises is needed.

2.6. Holistic approach and interaction between barriers

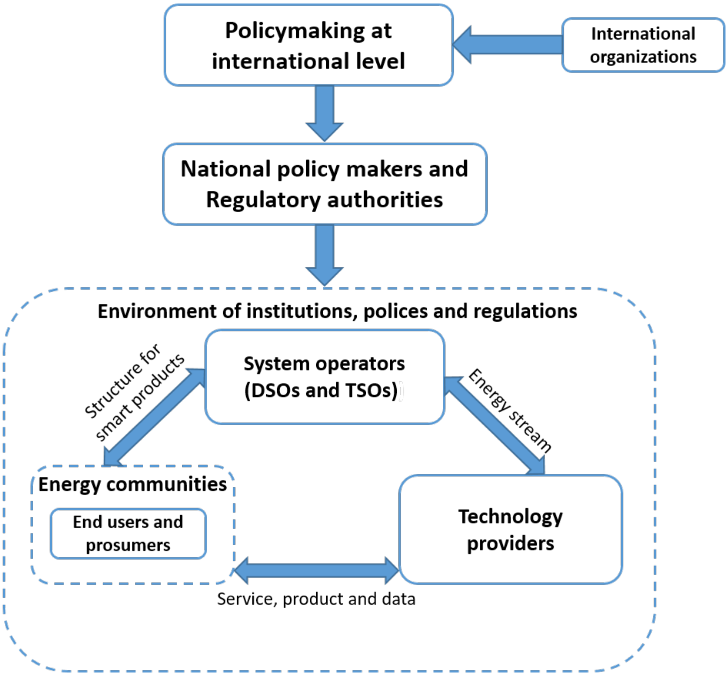


Figure 2.7: Holistic picture of interaction between actors.

The barriers discerned in the previous sections are based on extensive academic laboratory conditions (for technical barriers) and theoretical studies (i.e. regarding regulatory and social barriers). To enrich the results, taking a holistic viewpoint is required to combine the findings from the literature study with actual case implementation studies. Analysis of real case experiments is critical because laboratory conditions are removed and the interaction between problems can be observed.

As depicted in Figure 2.7, the interplay between actors has a hierarchical order starting from policymakers (e.g., at the UN or EU level). This level is responsible for setting targets and guidance. Internationally, global organisations, such as technology development organisations or knowledge development organisations, like the International Smart Grid Action Network (ISGAN), can influence energy policies by providing reports and data. After regional authorities adopt the policies at national level, there are interactions between technology providers, customers and system operators (e.g., DSOs and TSOs) that determine the extent to which the rules and policies are materialised [41].

In MG pilot projects (central) grid-connected or islanded modes are usually considered for regulatory reasons. This, however, ignores dual-mode switching. Similarly, most SMG pilot projects are restricted to small neighbourhoods with a low number of buildings or households. Therefore, controllers and protection schemes can be easily configured because there is only a small proportion of power grids within experimental project's boundary. In the Boralex project, in Canada [164], system operators confined the negative impact of SMG on the grid through standards and grid codes. Notably, in demonstration pilots such as Sendai Microgrid in Japan, DSOs imposed regulations against protection related issues in terms of anti-islanding [165].

Although most of the proposed solution discussed in Section 2.3.3 emphasised islanding detection at the PCC, in practice, inappropriate anti-islanding techniques applied to SMGs can lead to putting an unintentional islanded mode of some DG units inside SMGs into operation. This can lead to a negative effect in terms of neighbouring loads. This turns out to be most problematic in islanded mode cases when DG units inside SMGs use similar islanding detection systems [56].

On the other hand, system operators apply Low-Voltage Ride-through Capability (LVRT) requirements for generators to stay connected during a short period under-voltage conditions in the grid to prevent widespread loss of generation. However, analysing various LVRT experiments [166] reveals that time requirements of LVRT can vary between 150 ms and 1.5 s. This can be problematic because both anti-island mechanisms and seamless islanding detection methods usually act faster (310 ms and 10 ms, respectively).

In addition, SMGs ideally control the voltage range and frequency at PCC by adjusting the reactive and active power levels. However, system operators, for example, Am Steinweg MG in Germany, are reluctant to trade power with SMGs because it requires modification of a protection scheme at the distribution system [167].

In interaction between regulations , energy suppliers, and technical barriers in SGs, the nature of the incentives for suppliers is problematic in practice. In brief, some financial incentives, such as time-invariant FIT, encourage DG units to work at a maximum operational capacity. Asmus et al. [168] show the implication that the initial SMG business model will turn into a DG business model. Therefore, other services such as the control functionalities of the SGs to support islanded mode or energy management options will no longer be implemented.

Considering end users, analysis of a number of projects implemented in European counties [38] reveals practical reasons why adopting smart technologies and promoting DSM programmes are not routine practice yet. With current electric systems, the value of DSM is neglected by utilities. Common practice for solving the congestion problem is generating capacity and system reinforcement. DSM becomes a possibility only in some system segments with costly network reinforcements. On the other hand, current analysis shows that the operational complexity of dealing with DSM is relatively high for system operators. Some experiments [169] also show that the current network structures could not support multiple applications like AMI, ADA and automated demand response (ADR).

2.7. CONCLUSION

The present study was conducted in response to the need for a holistic and comprehensive overview of the barriers to SG development and their interaction. This chapter contributes to the body of literature on SG innovation, notably by using a multidisciplinary socio-technical approach that considers all the relevant stakeholders, including technology designers, market actors, RESs providers, system operators and consumers. This study identifies the barriers, and addresses them separately and in terms of interaction.

In terms of the interaction of possible technologies and the interests of system operators, the coexistence of some technologies such as island detection to protect the grid and anti-islanding to protect some parts of SGs is inevitable (see Section 2.3.3). However, there is serious concern that anti-islanding functionality can work adequately with current limited islanding detection methods. Similar problems occur when DSOs cannot apply their desired power control at the PCC because SG is supposed to be an independent identity.

This issue is interwoven with market conditions and regulatory issues. For instance and as discussed in Section 2.3.1 and Section 2.6, although hierarchical controllers have been developed and perform for MG, this controlling strategy is still unable to address DSO concerns about handling the provided active power (i.e., to determine who the potential buyer is). And there is also a lack of regulations for reactive power trading in most countries.

The present study found that the main problems for market actors are rooted in the fact that they are not motivated to invest in SGs because this novel concept that comes with uncertainties and perceived risks. This is related to uncertainties in the value chain and because incentives like price caps are designed based on theoretical assumptions that are far from actual implementation conditions in reality.

Moreover, social acceptance of SGs among local communities and end users suffers from a multidimensional problem between technology structures, regulations, and institutions. Even though ICT technologies are presumably ready for DSM programmes, the electrical grids are not sufficiently prepared or updated to handle most SG technologies. There are also incompatible standards that are not specified for different customers and regional areas. As ownership and involvement are considered at the community SG level, business models cannot engage local communities in projects. Acceptance and the adoption of SGs by local communities also requires changing end users' views and even behaviours while taking community members' identities, preferences and behavioural profile into account.

2.8. Future work

The unanswered question is how policymakers could intervene to resolve the multidimensional problems discerned in the present study. Since SGs can be applied or adopted differently according to regional requirements, there is a need for context-based analysis to study the inter-dynamics between institutions, technology and actors. Using an approach that only addresses attempts to solve or mitigate separate barriers falls short and leads to ineffective solutions. A broader systemic perspective of socio-technical innovations is required. Therefore, we suggest applying theoretical approaches and research methods from the Innovation Studies research domain to discern potential interventions to resolve these barriers. This could, for example, be done in line with a study by Negro et al. [170] who addressed the failures of RESs from an innovation perspective. Potentially, such an approach could be extended and applied to SGs when viewing the latter as an integrated system innovation.

Global governance has recently emerged to facilitate the niche market development and adoption of promising technologies as a way to accelerate climate mitigation efforts. This governance approach is attempting to address the problems that technology providers or market actors cannot solve individually or at a national level because such problems go beyond national borders and require a cross-national response. This refers to collective problems that require experience, policy mobilisation and the inclusion of a wider set of governments and international actors. However, in the operational stage, actors involved in SG niche market development come into conflict with each other due to, for example, resource scarcity and geopolitical issues. Negotiations, agenda-setting, monitoring, and the enforcement of agreements can resolve conflicts between nation states. This continuing process requires supranational institutions and organisations to manage affairs and accommodate diverse interests. Therefore, we suggest that future studies consider the role and influence of supranational institutions and intergovernmental agreements to address and resolve the barriers using international cooperation schemes.

3

TECHNOLOGICAL INNOVATION SYSTEM OF DUTCH SMART GRIDS

This chapter is based on:
F. Norouzi, T. Hoppe, L.M. Kamp, C. Manktelow, P. Bauer, "Diagnosis of the implementation of smart grid innovation in The Netherlands and corrective actions", *Renewable and Sustainable Energy Reviews*, 2023, vol 175, 113185.

With its potentially disruptive nature, the smart grid can be viewed from both a transformational and an innovation systems perspective. Synthesising these, a research approach is adopted in which a Technological Innovation System (TIS) analysis is combined with a transformational perspective to identify a broader range of success and failure factors. This chapter analyses smart grid innovation system development. The main research question is: What systemic and transformational failures are identified in the development of smart grid innovation in the Netherlands from 2001 to 2021 by combining TIS and a transformational perspective? The question is answered by mapping the events to TIS functions and identifying both 'systemic failures' and 'transformational failures'. Transformational failures are linked to events outside the smart grid TIS that work against the alignment and harmonising of activities within the TIS. Results show that the smart grid innovation system experienced three periods and that it suffers from various structural and transformational failures. TIS functions like knowledge diffusion, and the creation of legitimacy were only fulfilled to a limited extent. Consequently, smart grid innovation is currently still not considered a mainstream technology in the energy transition, and there is little attention to the role of end-users. The study ends with suggestions for future research, including the suitability of the research approach for other contexts and when applied to other energy system innovations.

3

3.1. Introduction

Recently, in many countries, the electricity sector has witnessed a change towards using Renewable Energy Systems (RESs) [171]. This change can arguably be seen as an initial phase of system-wide transformative change. In this phase, the central theme is the technical and economic validation of RESs as a feasible option which prompts their diffusion in electricity systems [172]. Recently, this theme is changing because the concern is not merely phasing out fossil fuel resources but also the electricity system's overall functioning [173]. In this regard, the integration of RESs requires balancing between demand, supply and storage, ensuring power quality, avoiding congestion in transmission, distribution, and storage systems. These requirements and related problems challenge the operation of electricity grids to reconsider all parts of the supply chain, not just generation [4].

To this end, the smart grid concept was introduced to improve the functionality of electricity systems [174]. This concept aims to support decentralised electricity technologies mainly in generation, system operation and ideally also transmission in both national and international grids [175].

Abbreviations

ACM	Netherlands Authority for Consumers and Market
DLC	Direct Load Control
DSO	Distribution System Operator
DSM	Demand Side Management
EDSEP	Experiments decentralised, sustainable electricity production
EMS	Energy Management System
IPIN	Innovation Programme Intelligent Grids
MEP	Environmental Quality of Electricity Production
NMP4	Fourth Dutch National Environmental Policy Plan
RES	Renewable Energy System
RET	Renewable Energy technology
RVO	Netherlands Enterprise Agency
SEC	Smart Energy Collective
SET-Plan	Strategic Energy Technology Plan
TIS	Technological Innovation System
TKI	Top Consortium for Knowledge and Innovation
TSO	Transmission System Operator

Precisely describing a smart grid appears challenging. The smart grid can be implemented in several ways depending on the application [176]. However, there is a general consensus regarding its main features [177]. Focusing on these features helps in understanding the disruptive nature of smart grids. The smart grid can be understood as a rebranded definition of a power distribution system with renewables, automation, and power electronic converters. More recently, smart grids are being rebranded again as cyber-physical systems, or even as microgrid clusters [178].

Whenever the definition of smart grid is leveraged to bi-directional high voltage transmission, its scope also covers HVDC-based super grids with voltage source converters [179]. The key characteristic of a smart grid is bi-directional active-controlled power flow at the distribution level [180]. This implies that consumers become prosumers of energy equipped with distributed RESs. Dealing with a bi-directional power flow requires including other concepts like flexibility in the electricity system to deal with balancing issues [4]. Flexibility, in turn, can be realised by multiple technologies like storage devices, vehicle-to-grid systems, and the microgrid concept. Modern IT structures, control strategies, and Energy Management Systems (EMS) are the backbone of smart grid design [181].

Fig. 3.1 presents a typical smart grid. This is based on the authors' understanding of smart grids based on state of the art in academic works [182]. This visualisation helps to discuss its transformative nature. As Fig. 3.1 illustrates, a smart grid includes the concept of Demand-Side Management (DSM), which comes from the end-users' response to balance the generation and load [183]. A microgrid concept can also be considered to be present in the distribution system. Although microgrids can exchange power with the main grid in the grid connect mode, distributed generation (DG) of electricity can go along with this to make microgrids independent from the main grid in an autonomous configuration. This takes place within the Point of Common Coupling (PCC), if required [184].

The transmission level of the electricity grid is equipped with EMSs, modern Supervisory Control and Data Acquisition (SCADA) systems, and advanced data processing software such as Advanced Distribution Automation (ADA) for controlling and monitoring purposes. These technologies improve DSM by sending and receiving data from the distribution level [185].

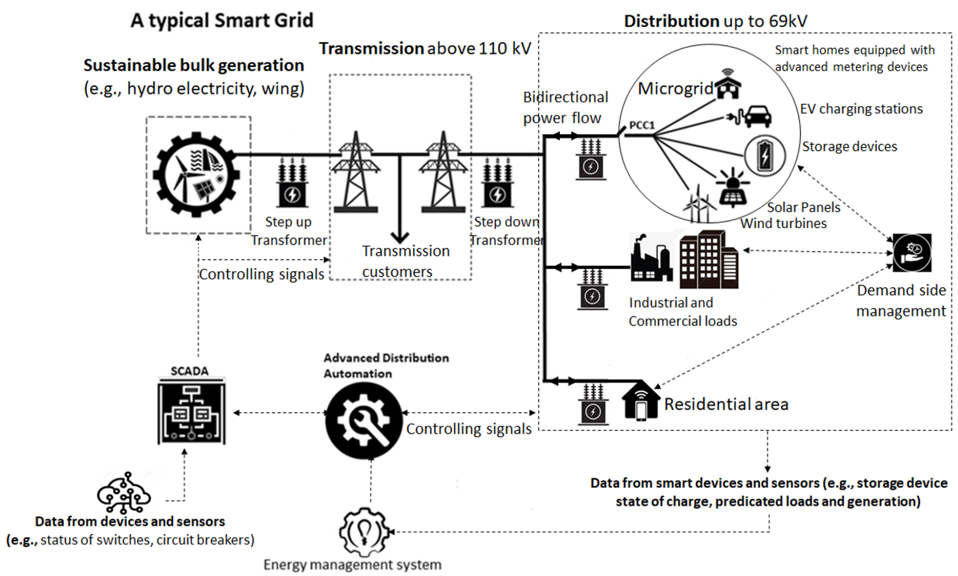


Figure 3.1: A typical Smart Grid containing Microgrids and equipped with SCADA, ADA and EMS.

Transformative and disruptive characteristics of smart grids can be outlined as follows. First, smart grids introduce new ways of balancing demand and supply. This allows for new modes of ownership and decentralised production. For example, ownership of production can be in the hands of individual households or of citizen collective entities such as energy communities [186]. These energy communities have the potential to influence incumbent structures and institutions of the traditional, centralised electricity system model [187]. Smart grids are therefore associated with disrupting and changing the current hegemonic mass-market logic supporting incumbent firms and with supporting niche markets focusing on small groups of prosumers [138]. However, achieving such a disruption would require adopting new technologies to facilitate direct trading, demand response and local balancing which would, in turn, disrupt the business models of incumbent firms [188].

Another potential disruptive feature of the smart grid is its economic efficiency. Currently, traditional business models related to electricity generation are mainly based on centralised fossil fuel-based electricity generation. The key economic value of smart grids stems from optimising and adjusting electricity usage [187]. In addition, there is increasing demand for a higher quality of supply in terms of electrical harmonics, variation in voltage magnitude and continuity of service among consumers [189]. In the presence of modern communication infrastructures such as ADA and SCADA, electricity companies have to become more capable of rapidly detecting and handling supply quality problems. This creates more opportunities to gain economic value from increased system reliability [187]. Consequently, these changes in revenue streams will attract new actors to facilitate demand response, create flexibility for system operators (e.g., by means of aggregators), and install new equipment or services for customers as well as system operators [186]. The purpose of this new configuration in electricity systems is not merely sustainability but also moving towards goals related to other values (e.g., creation of local energy markets and fostering energy democracy) [123]. Based on this information, smart grid can be considered as a disruptive (transformative) innovation [190].

Many studies on Renewable Energy Technologies (RETs) apply systemic and transformational approaches. This includes [170] in which systemic problems in developing RETs are analysed, mainly in European countries. Even though this study reviewed the most market and systemic failures [191], it did not cover transformational failures. In addition, in various countries, parts of smart grid systems such as energy storage technologies [192] and electric and hybrid-electric vehicles [193] have been analysed to identify barriers and drivers.

Furthermore, studies have been conducted to analyse smart grid development in the Netherlands by focusing on its central components. These include identifying the motivations and needs of energy communities in forming virtual power plants [194], the role of ‘information flows’ and smart grid technologies in creating sustainable energy practices [195] and the hurdles for new entrants to invest in the smart grid market [196]. Furthermore, smart grid projects have been analysed from the lens of institutional design [152], and institutional regulations applicable to smart grid deployment projects [197].

Transformative change in the energy sector entails a long journey that can take various pathways. However, these pathways are typically non-linear, unpredictable, complex and chaotic [198]. Taking a retrospective empirical approach, this work tries to uncover and explain the pathway for smart grid innovation, focusing on events that contributed to the current situation of smart grid innovation in the Netherlands. It does so by using Technological Innovation Systems (TIS) as a theoretical perspective, and by adopting a systemic and transformational failures perspective. In summary, this study attempts to answer the following question, “ What systemic and transformational failures are identified in the development of smart grid innovation in the Netherlands from 2001 to 2021 by combining TIS and a transformational perspective?” This question is answered by using historical event-history analysis to identify both systemic failures inside the smart grid TIS and transformational failures outside this TIS. The critical point is that external factors such as policy measures influence the TIS internal performance and the other way around. The interaction between the technological system and the socio-technical system provides a holistic picture of the dynamics of factors. This aids in comprehending the relationship between technological innovation system failures and external transformational failures.

This study contributes to the acceleration of the understanding of the transition of electrical systems by taking a new approach and examining smart grid innovation from the perspectives of technological innovation and sustainable transition. The study’s findings can be of use to policymakers who want to develop unified policies to address previous policy deficiencies in smart grid introduction.

The literature review shows that smart grid innovation has thus far not been studied from a holistic socio-technical system perspective. It has also received scant scholarly attention in terms of systemic and transformational failures that impede the introduction of smart grid innovations. Analysing a case study on smart grid innovation in a country whilst using a longitudinal research design can be useful and aid academic research agendas. This particularly holds for showing how to apply a technological innovation system perspective to smart grid innovation whilst mapping systemic and transformational failures.

This study is structured as follows. Section 3.2 presents the theoretical framework, which includes TIS, feedback loops, and systemic and transformational failures. Section 3.3 explains the required steps for the analysis. This includes research design, case selection, data collection and treatment, and data analysis, i.e., identification and mapping of systemic and transformational failures, and validation of the results. In Section 3.4, the results of the longitudinal analysis are presented. Section 3.5 discusses the main findings and compares the findings with some other European countries by using quantitative metrics. This Section also provides policy suggestions to address the identified failures. Finally, the study concludes in Section 4.7 by answering the research question and proposing suggestions for future research.

3.2. TECHNOLOGICAL INNOVATION SYSTEM AND FAILURES IN INNOVATION

The concept of Technological Innovation has its root in evolutionary economics and was introduced by Carlsson and Stankiewicz [199] to elaborate on the nature of technological changes. Later the concept of the Technological Innovation System developed as an analytical tool for illustrating and understanding the dynamics of technological innovations [200]. In the case of developing smart grid technologies, many recurring themes and events have been reported by studies [43]. Focusing on the dynamics that led to the current situation of the smart grid in the given country or region helps to find the problematic patterns.

This is also the reason why TIS was adopted for analysing smart grid system innovation in this study. A TIS perspective can be used to assess or evaluate smart grid performance, innovation system growth, and decline. However, TIS should be seen as using a focused analytical lens that does not reflect on all aspects that are relevant to smart grid as a socio-technical system in a holistic sense. This implies that the causal drivers and barriers of smart grid development should be analysed in a broader societal context. Policies, regulatory settings, and user practices, for example, should be considered to understand the external performance of smart grid innovation. Consequently, this study employs a framework [201] to analyse the smart grid's technological innovation and transformative nature. By integrating a transition perspective into TIS, this framework will broaden the environment of TIS. This allows, for example, to also address attention to failures related to governance and policy arrangement externally to TIS. These are part of a wider set of failures that are classified under the term 'transformational failures'. They complement systemic failures obtained from the (internal) TIS analysis. These failures are explained in Section 3.2.2.

3.2.1. System functions and feedback loops

TIS explains the process by which an emerging technology develops [202]. The central idea is that innovation develops and diffuses within a system, a so-called technological innovation system, or TIS [203]. A TIS consists of actors, technologies, institutions, and networks (configurations) of them (more details of these main building blocks of a TIS can be found in [204]). These are called structural elements. These structural elements are built up by specific processes such as knowledge development and market formation. These processes are called 'system functions' [202]. Clear indicators can be defined to analyse each system function. Table 1 shows the list of functions and examples of these indicators [205].

Within system thinking, feedback loops determine the dynamics of the systems [206]. It is a feature of a system where the output of one node eventually affects the input of the same node. All systems' dynamics can be explained by understanding how the feedback loops interact. Positive (or self-reinforcing) and negative (or self-correcting) feedback loops are the only two types that interact to create dynamics [207]. While large socio-political systems contain many feedback loops, the behavior of systems are controlled by only a few of these loops [206].

Development and growth of a TIS can be explained by the cumulative causation in which different functions reinforce each other [204]. Suurs distinguished particular feedback loops, which are called motors of innovation [16]. In addition, there are four distinct stages in the development of a TIS. Fig. 3.2 exemplifies the concept of a feedback loop for the first stage of TIS development. In each of these stages, another typical motor of innovation can be observed [208]. The four main stages and motors of innovation are:

- The 'science and technology push motor' refers to a feedback loop in which knowledge development and diffusion have a central role. Policy makers support the innovation via R&D support, and the innovation is developed and tested via

Table 1: Functions of innovation system and their indicators [204].

Functions	Examples of indicators
F1: entrepreneurial activities	commercial experiments, business opportunities, new entrants and established firms and portfolio expansion for companies
F2: knowledge development	Investment in R&D projects (learning-by-searching), patents, publications, laboratory experiments (learning-by-doing) and increasing in the number of researchers in universities and firms
F3: knowledge diffusion	workshops, conferences, joint projects, networking activities, end-users' experience with new technologies and reports of projects
F4: guidance of the search	setting ambitious goals by decision-makers, increasing the expectations of a technology, technological guide and changing in belief system of decision-makers regarding a technological innovation
F5: market formation	new standards, tax exemptions, Overall changes in the market environment for a technology and increase in number of users of a given technological innovation
F6: resource mobilisation	investment and subsidies, development of required infrastructure and availability of experts (mobilisation of human resources)
F7: creation of legitimacy	political lobbies against or in favour of a certain technological innovation, activities to convince the government to support or hinder a technology, and increases in the number of NGOs and private sector companies that support or hinder a technological innovation

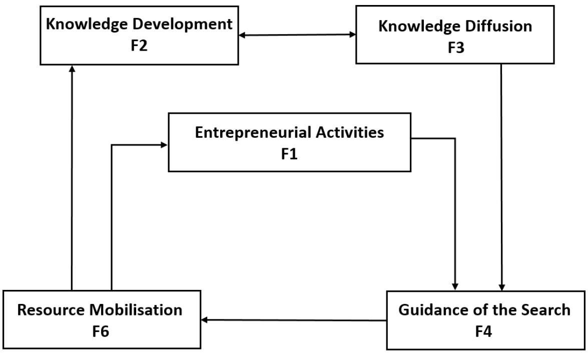


Figure 3.2: Feedback loops in the Science and Technology Push Motor.

experimental projects and R&D programmes. The main functions in this phase are knowledge development [F2], knowledge diffusion [F3], guidance of the search [F4], and resource mobilisation [F6].

- The 'entrepreneurial motor' refers to a feedback loop in the following stage which is typically characterised by growth in the number of active entrepreneurs.

These active entrepreneurs try to legitimise the innovation [F7] and mobilise more financial resources [F6] or change the institutions favouring innovation. In addition, market formation [F5] becomes important. knowledge development [F2] and knowledge diffusion [F3], which were significant functions in the preceding stage, are still important.

- The 'system building motor' refers to a phase in which there is an increase in infrastructural development, institutional reconfiguration and actor networks. During the system building motor, entrepreneurial activities [F1], knowledge development [F2], knowledge diffusion [F3], guidance of the search [F4], resource mobilisation [F6] and creation of legitimacy [F7] play dominant roles.

- The 'market motor' refers to a feedback loop in the last stage. In this phase, the innovation has institutionalised into society, and the main function is market formation [F5]. All other functions also play a role in this feedback loop, except for creation of legitimacy [F7] because the market environment is partly created by formal regulations.

3.2.2. Systemic and transformational failures

Assuming the systemic nature of innovation, there are problems and weaknesses within a TIS that are due to poor structural conditions (i.e., weak infrastructure, institutions, or actor networks) [209]. This is referred to using the concept of systemic failures [210], which develops a rationale for the occurrence of problems in a given TIS. Recently, a complementary approach was developed to identify the failures that impede or slow down transitions towards sustainability besides systemic TIS failures. Weber and Rohracher [201] argue that due to the long-term nature and the different character of societal transformation compared with processes in the TIS, other kinds of failures should also be considered for addressing broader socio-technical systems change. These additional types of failures mirror recent debates on the sub-optimal performance of the innovation process in stimulating innovation activities towards reaching desired long-term transformative changes. These failures are strategic in nature, and they target the need for appropriate innovation policies to stimulate and prioritise the process of transformative changes. These four transformational failures are 'directionality failures', 'reflexivity failures', 'policy coordination failures', and 'reflexivity failures' [201]. The details of transformational and systemic failures are outlined in Table 2.

3.3. Research design and methodology

In this work, a longitudinal research design is used to analyse the development of smart grids in the Netherlands over the 2001-2021 period. By the end of 2019, around 31 residential smart grid projects focusing on the role of various actors (e.g., end-users, technology providers, and system operators) had either been initiated or had already been finalised, resulting in a large number of reports and text documents [18]. In addition, the case of smart grid in the Netherlands has scientific value because its development has different and contradictory aspects. For example, EV infrastructures [211] and smart meter technologies are being developed with a promising pace [212]. However, other aspects, such as the renewable energy diffusion rate or demand side management market, lagged behind other comparable European counties [213, 214]. Understanding the origins of discrepancies in the development of smart grid technologies facilitates comprehension of the electricity system's transition process.

This study uses event-history analysis as developed by Van de Ven and Poole [215]. This method has been applied in previous TIS studies to identify patterns of technological development by using qualitative data (see, for example, [216]). A standard and procedure were used for identifying the events, mapping them, and assigning them to the TIS functions. During event-history analysis, simple incidents and events are distinguished. Here, an incident is seen as an empirical observation. However, an event is categorised as a critical moment that explains the formation of a pattern. Following this standard prevents choosing certain events subjectively [215].

After finding the events, they are sorted by date in chronological order. They are then categorised into system functions. To map events to certain functions, events are evaluated by the indicators of each function. For example, a new standard would serve as an indicator of a market function. Mapping the standard-related event to the market function means that the market's current state is affected by the event. This usually leads to another event(s). Eventually, the pattern of events is shaped.

One important criterion for mapping an event into transformational elements is that transformational factors are usually outside the TIS. They are typically found in the policy domain or social domain. These transformational elements eventually influence TIS functions. This stresses the importance of the formation of patterns in mapping a given event into certain transformational elements. For example, a lack of shared vision between policymakers may lead to undermining the guidance of research inside a TIS.

In brief, mapping an event into a function is to observe a change in the function status within a feedback loop system. The accurate mapping of the events by using an indicator requires in-depth knowledge of the TIS case study. Therefore, the results of the study are validated by interviewing smart grid TIS experts to reduce subjectivity.

Fig. 3.3 illustrates the steps for the analysis of systemic and transformational failures in the development of innovation. The analysis measures the system functions and identifies systemic TIS failures in the innovation-oriented stage. This links up with the system's internal functioning failures. In the transformational-oriented analysis, transformational failures are identified by searching for failures that hinder transformative change to fulfill specific societal needs.

3.3.1. Data collection

Collecting relevant data begins with choosing a TIS boundary [217]. This study treats smart grid innovation systems as integrated systems. It implies including all technologies in the supply chain from generation to end-users. Although various technologies such as PV, storage devices, and DSM technologies [4] certainly compete for more resources or legitimacy and sometimes complement each other, the smart grid can be considered as an individual yet integrated system [218]. Therefore, in this study, other complementary innovations, including smart meters, RETs, and storage devices, are treated as required necessary infrastructures, not as individual technologies.

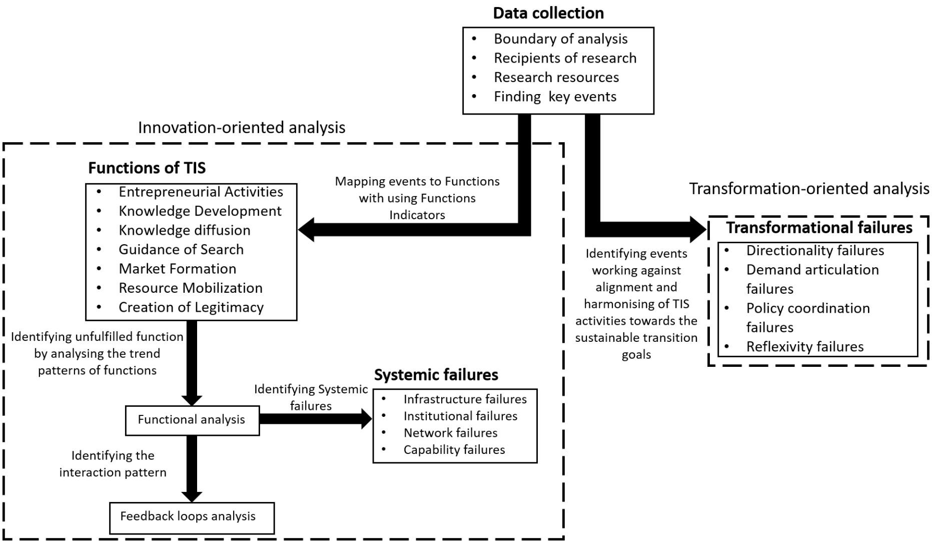


Figure 3.3: Method for the analysis of the causes of systemic and transformational failures in the development of innovation.

The primary resource for the qualitative analysis pertains to official documents and reports from governmental and scientific organisations and archives of news articles and scientific papers and websites. Official documents are obtained from database of the Netherlands Enterprise Agency (RVO), reports on the official website of the Ministry of Economic Affairs and Climate Policy, publications in the European Commission, and reports from the International Energy Agency (IEA) and European Patent Office. The main resource for news articles is the Nexis Uni database. Scopus, Web of Science,

Table 2: Summary of systemic and transformational failures adapted from: [191, 201].

Systemic failures	Transformational failures
Infrastructure failures refer to the absence (or weakness) of required physical and knowledge infrastructures to promote the innovation	Directionality failures refer to lack of creation of a shared vision for the role of innovation in solving societal challenges
Institutional failures refer to the absence (or weakness) of sufficient institutions (e.g., regulations, legislation, standards, values and social norms) to support the innovation	Demand articulation failures refer to a lack of space for learning and anticipation of users' preferences
Network or Interaction failures refer to the absence (or weakness) of sufficient interaction, networking and trust between actors	Policy coordination failures refer to the lack of coordination across various policy levels which can lead to incoherence in policy implementation or deviation from strategies
Capability failures refer to the absence (or weakness) of relevant actors, competencies and capabilities to utilise available infrastructures	Reflexivity failures refer to the lack of continuous monitoring and anticipating the progress of transition

and Google Scholar are used for scientific papers by searching with Boolean search operators for “Smart Grid”, “Microgrid”, and “Smart energy system” in combination with “Netherlands” and/or “Dutch”.

In the initial search, 185 news articles, reports, and journal publications were found. The exclusion criteria were then put into practice. The study boundary and the authenticity of the data served as the primary criteria. A few resources were excluded because they referred to certain smart grid technologies without considering how these technologies affected overall smart grid deployment (i.e., as an integrated system). These articles discussed a distinct technology, making it hard to determine the pattern of events. Moreover, some news articles were excluded because the validity of their sources could not be verified. The selection of the documents involved reading, interpreting, and textual analysis of summaries and abstracts of text documents.

The system functions and transformational components are used to categorise and store historical events in a database. The relationship between the events was discovered using the chronological order of the occurrences. Finally, the experts evaluated the early patterns of the events to ensure their validity. Some events and documents were eliminated on the advice of experts because it was impossible to verify them. Additionally, relevant resources were added via snowballing and feedback from experts. Finally, 21 news articles, 33 governmental reports, and 37 journal publications were used for the analysis.

3.3.2. MAPPING EVENTS TO THE SYSTEM FUNCTIONS

According to Hekkert and Negro [202], retrieving all relevant data for TIS studies is impossible in practice. Hence, in the data reviewing process, attention should be paid to finding key events and turning points, such as a rapid change in the number of entrepreneurial activities. System function indicators are used as a heuristic tool to identify meaningful events and link them to corresponding functions. In the TIS analysis, an event can be considered an instance when it has some public importance or rapid impact on actors, institutions, or technology. After identifying the events, they are compared with the function indicators to determine the best match. For example, the initiation of certain research projects with a large number of involved actors can be considered a meaningful event linked to the knowledge development function (i.e., ‘[F2]’). This knowledge development may lead to technological advancements.

3.3.3. IDENTIFYING FAILURES

With respect to systemic failures, a TIS analysis can be conducted to explore where these failures occur. As Bergek et al., [219] argue, neither functional analysis nor structural analysis constitutes a sufficient basis for identifying failures. Consequently, Wieczorek and Hekkert [191] argue that functions attach meaning to structures and that meanings generate structures. Therefore, in this study, an integrated structural-functional analysis is applied. This holds that unsatisfied TIS functions are analysed through the lens of structures. The trend pattern technique is used to identify the fulfillment of a function. Here, events related to different functions are subjected to quantitative analysis based on their accumulated numbers [200].

The trend pattern in this study is displayed by the number of positive and negative events for each function. In addition, the most important quantitative indicators of smart grid development are presented in Section 3.5. The level of TIS function fulfillment in the Netherlands can be compared to that of other European countries using the data provided by this quantitative analysis.

After the function analysis, the systemic innovation policy framework proposed in [191] is used to identify and discern systemic failures to identify the causes of problems in the Dutch smart grid TIS. Table 3 shows the indicators used for identifying systemic failures. These indicators pertain to the absence or incapability of relevant actors, the absence or poor quality of institutions, the absence or inadequacy (malfunctioning) of infrastructures, and a lack of interaction between actors [191].

With respect to transformational failures, the classifications provided by Weber and Rohracher (see [201] and Table 2) offer useful guidance. To apply this approach in identifying transformational failures, attention is paid to considering the system as a whole. As conceptualised by Weber and Rohracher [201], transformational failures can be perceived as blocking mechanisms embedded in wider societal systems [220]. They were retrieved as the bottleneck working against sustainable transition goals rather than failures hindering the innovation system from serving innovation and market purposes [221].

For this study, two steps are taken to assess the transformation procedure towards a decentralised electricity system. First, the analysis distinguished between the key events that comprise all parts of the socio-technical system in the broader sense (e.g., policy coordination elements) and the events that are linked to structural innovation system elements (e.g., institutions) at the TIS level [222]. The overarching events in the broader sense level determine how TIS functions are appropriately aligned and harmonised. For example, if policies are misaligned at different levels of government and if visions are misaligned (e.g., between different economic sectors or policy domains), then the likelihood of realising the required institutional settings to promote technology adoption is considered as low [222].

3.3.4. Identifying feedback loop between TIS functions

Although the trend pattern method enables studies to observe to what extent functions are fulfilled, it is also necessary to conduct an additional interaction pattern method for providing qualitative explanations for the observed sequence of events and constructing a storyline. Moreover, having cumulative causation in mind, this method facilitates understanding the role of system functions within chains of events. It can be used to identify feedback loops between certain TIS functions [16].

As a result, a combination of trend and interaction pattern methods is adopted in this study. The trend pattern method is used to identify significant changes in the number of functions' events to distinguish between different periods and the fulfillment of TIS functions. In addition, the interaction pattern technique is used to unfold the feedback loops between TIS functions. The aim is also to observe cumulative causality in this regard. The interaction analysis aims to reveal whether interaction between the TIS functions results in the construction of a complete innovation motor [203].

Table 3: Identifying systemic failures based on functional-structural analysis of an innovation system [191].

Evaluated	Indicators of structural elements	Indicators of systemic failure
Functions 1-7	Actors: government, NGOs, knowledge institutes, companies and civil society	Relevant actors are absent or may lack necessary competences
	Institutions: rules, regulations, norms, and expectations	Specific institutions are absent or are considered as weak
	Interactions: individual or organisational contacts	Interactions are missing or quality of interactions are considered to be weak
	Infrastructure: physical, knowledge, or financial	Specific infrastructures are absent or infrastructures are considered to be weak.

3.3.5. VALIDATION

To increase the validity of the research and avoid weaknesses resulting from a research's single viewpoint, the findings are validated through triangulation. To this end, results were discussed and validated with experts and practitioners who have participated in key events of the smart grid innovation journey. The experts that were consulted are shown in (see Appendix Table A1). In order to encourage the interviewees to express their opinions freely and to obtain more information, a semi-structured interview was developed. The guidance of the semi-structured interview can be found in Appendix Table A2. Following the validation interviews, any discrepancies in the analysis were resolved by discussing the conflicting viewpoints and reaching a consensus by using the guidelines explained in Section 3.3 as the common ground. The results of the interview are reflected in Sections 3.4 and 3.5. The interviewees' inputs include correcting the mapping of events to TIS functions, interpreting events, and giving more data regarding the identified event.

3.4. RESULTS: CHRONOLOGICAL OVERVIEW OF KEY EVENTS

3.4.1. FIRST PERIOD: 2001-2012

Several structural elements for the Dutch smart grid TIS existed before 2000 in terms of actor networks, technology and institutions. However, the adoption of the Fourth Dutch National Environmental Policy Plan (NMP4) by the National Government in early 2001 was a notable event leading to a considerable chain of events. The plan's goal was to accelerate sustainable transitions in areas like sustainable electricity and mobility and green resources [F4] [223]. This visionary plan was relevant to the smart grid because one of its major goals was to increase energy efficiency and focus on renewable energy (interviewee #5). This ambitious plan proclaimed that environmental issues were in need of a transformation approach in various technological, economic and socio-cultural domains [224]. Consequently, the Ministry of Economic Affairs became responsible for the implementation of NMP4 in March 2001. The Ministry was looking for a conducive condition for businesses to contribute to the transition in the energy system [225]. Therefore, it started encouraging research into different fields, including smart grid technologies via the Innovative Research Programme for Electromagnetic Power Technology (in Dutch: Innovatief Onderzoeksprogramma Elektromagnetische Vermogenstechniek, IOP-EMVT) [226]. This program included the 'Intelligent Power Systems' project, which was conducted by Delft University of Technology and Eindhoven University of Technology and funded by SenterNovem, an agency of the Ministry (interviewee #1) [F2, F6] [226].

These fundamental research projects initially focused on technical aspects of smart grids, including standards for the quality of grid voltage connected to intermittent distributed generators, stability analysis, algorithmic forecasting of uncertain demand, and remote power flow measurement and voltage regulation by smart sensors [227]. However, these projects were later expanded into a new research area within the Energy Research Subsidy (In Dutch: Energie Onderzoek Subsidie, EOS). This research was conducted on ICT, consumer behaviour, and social and market development (interviewee #1) [F2, F3] [228]. The EOS and IOP-EMVT programmes together had budgets of over 30 Million Euros annually from the Dutch government and the Dutch Research Council (in Dutch: Nederlandse Organisatie voor Wetenschappelijk Onderzoek) (2008-2011) [F6]. Together, they formed the cornerstone of smart grid experimentation in 2002-2011 period [228].

This knowledge development led to encouraging entrepreneurial activities [226]. Such entrepreneurial activities can be perceived from two angles. First, some entrepreneurial activities can be seen as grassroots initiatives, defined by Seyfang & Smith as "networks of activists and organisations generating novel bottom-up solutions for sustainable development; solutions that respond to the local situation and the interests and values of the communities involved" [229]. In this respect, Dutch grassroots initiatives for generating renewable energy first developed in the 1980s and 1990s. After some years of stagnation, these research programmes opened a window of opportunity for them. For instance, local farmers participated in the "Farmer Seeks Neighbor" project by getting loans for solar panels from local communities in 2006 [230]. In the same year, the civic climate activist group "Urgenda" was established by two Erasmus University Rotterdam academics representing Dutch citizen interests in a fast transition towards a sustainable society. Urgenda earned a reputation later, in 2019, for winning the Urgenda Climate Case urging the national government to take a more active stance to combat climate change [231]. In fact, as elaborated by Oteman et al. [230], growing grassroots activities had the potential to increase local acceptance of renewable resources as well as to provide financial benefits to local energy cooperatives. Therefore, this study considers increase in the number of grassroots activities as entrepreneurial activities [F1] and market formation (interviewee #3) [F5]. It is also a positive indication of smart grid institutionalisations and as cultural change in favor of it (interviewee #1) [transformational element as demand articulation].

Second, another way to look at entrepreneurial activities is by considering the business sector's commercial activity [115]. There are positive indications of growth in the Dutch smart grid domain with new companies emerging, such as Almende, an engineering company working on R&D solutions applicable to several domains of ICT, or existing firms expanding their portfolios to cover smart grid-related projects (interviewee #5). An example is the Tenergy group which was established to work on the digitisation of electrical systems with expertise in ICT, the energy market, power imbalance, and data measurement since 2004 [F1] [232].

At the same time, a net metering scheme, 'Environmental Quality of Electricity Production' (MEP), was introduced by the national government to stimulate the adoption of RETs (particularly for small solar energy producers) [233]. The scheme was connected to the EU Directive No. 2003/55/EC (PbEG L 176) and the national Electricity Act 1998 and the national Gas Act 2000. MEP played a very positive role in capacity growth of PV systems until 2013 [F4] [234]. Moreover, actors had the opportunity to share knowledge and experiences during MEP. By using a multi-actor simulation tool (FleXnet), actors could discover and share the outcomes (technical and economic) from the integration of distributed RESs into the electric grid under different scenarios (interviewee #1) [F3] [235].

The cycle of positive events did not last long. Over the 2004-2012 period, there national government coalitions collapsed (i.e., in July 2006, in February 2010 and in April 2012), resulting in inconsistent energy (transition) policies. Moreover, government coalitions often only had short-term priorities influenced by policies that supported economic growth (interviewee #2). During the process of reaching a compromise between economic interest and environmental sustainability concerns, the former gained the upper hand due to the global financial crisis [236] (2008-2010) [transformational directionality failures], and after 2007 the NMP4 policy had reached a point of stagnation [-F4]. During this time, Dutch policies were criticised for being incapable of incentivising investment in smart grid innovation (interviewee #5) [223].

As an illustration, contradictory policies led to the partial implementation of the MEP scheme. MEP aimed to stimulate renewable and combined heat and power generated electricity by subsidising per kWh of locally produced renewable energy [237]. Renewable energy and Combined Heat and Power producers could receive a subsidy up to ten years to compensate for market price difference between the production costs of these types of energy systems and conventional energy systems. However, in 2007, the Dutch government decided to terminate the scheme based on the assumption (which later proved to be wrong) that the Netherlands would meet its renewable energy target in 2010 with ongoing subsidised projects (interviewee #4) [transformational reflexivity failure] as well as having ran out of subsidy budget because of the many requests that were made [223].

After 2005, the Dutch government perceived the potential of smart meters for facilitating energy saving and stimulating the introduction of tariff schemes [238]. The EU Directive 2006/32/EC [239] on energy efficiency and services also helped the Dutch national government justify the smart meter's mandatory roll-out (interviewee #2). However, this top-down approach by the Dutch government, which ignored consumer preferences and privacy rights, encountered a public protest in 2009. The rollout of smart meters failed after a judge ruled against the government because smart meter installation was considered to infringe on the right to privacy [transformational demand articulation failure] [240].

Another factor that contributed to shortening the cycle of positive events was the initiation of the liberalisation of the Dutch energy market in 2004. This led to increased competition and lowering of electricity pricing as a result of privatisation and removal of natural monopolies in the electricity system's operation by unbundling the system operation from potential market activities such as production and supply [241]. Studies about the effects of unbundling and privatisation on the energy market show little consensus on this matter, though [242]. The liberalisation of the Dutch energy market resulted in suspending sustainable energy innovation system activities in terms of R&D and knowledge development (interviewee #5). Moreover, the liberalisation in the Netherlands happened in a fairly non-transparent way. In an insecure environment, energy companies searched for cost-saving and business-as-usual activities, meaning that they reduced risky and challenging plans linked to smart grid innovation (interviewee #5) [243]. The effect was that certain research programmes were terminated, and almost no demonstration pilots or field tests subsidised via the EOS scheme took place until 2009 [-F2] [244].

However, the liberalisation of the energy market can be considered a double-edged sword. In 2007, the separation of electricity generation and delivery from the management of the regional electricity grid can be seen as a contributing factor for weakening the incumbent producers, therefore creating room for the emergence of new suppliers (e.g., Oxxio company in 2006) and the introduction of Distribution System Operators (DSOs) [119]. Furthermore, structural changes in electricity markets were auspicious for the future of smart grids [245]. After the liberalisation of the energy market, electricity-supplying or energy service-providing companies switched to activities linked to customers by, for example, focusing on intelligent networks (interviewee #4) [F1].

The EU's Strategic Energy Technology Plan (SET-Plan) began in 2008, which was a turning point in the development of smart grids. The smart grid became one of the main topics of this plan [246]. Policymakers of the EU believed that energy efficiency would become a promising way to reduce greenhouse gas emissions and secure energy supply [transformational element as a direction creation] [226]. This was a motivation for the European Commission to move forward with smarter, more integrated, and decentralised forms of energy delivery for consumers. In hindsight, this can be considered a stepping stone for the development of low-carbon technologies in which specific attention is paid to bringing down costs and boosting efficiency [226]. For the implementation of the SET Plan the ERA-Net Smart Energy Systems Initiative started to coordinate and facilitate deep knowledge sharing between regional and European smart grid initiatives by financing joint projects (2008-2014) (interviewee #1) [F4, F6] [247]. In the Netherlands, this was used by the Ministry of Economic Affairs to establish the Intelligent Networks Task Force1 in October 2009 [248]. Its goals were to provide coherent strategies for Intelligent Grids, to draw up an action plan for the realisation of Intelligent Grids in the Netherlands, and to organise cooperation between interested parties at the national level to the necessary extent. Two years later, Task Force 1 released a discussion document, "Towards intelligent grids in the Netherlands". It emphasised moving ahead on making Dutch electricity grids 'smart' by using solar energy under the assumption that home use would become more affordable than traditional energy pricing. This was considered a critical moment for smart grid innovation because government legitimised it for the first time (2011-2012) [F7] [248].

Fig. 3.4 summarises the key events observed during the first period (2001-2012). The positive and negative elements are indicated by '✓' and '∗', respectively. The turning point emerged as the Dutch government showed enthusiasm (with at least four key positive events) in capturing the potential of the smart grid innovation. This led to providing universities and other education institutes with resources that were essential to engage in experimental research and develop and diffuse knowledge (with seven positive events) about smart grids. The analysis of this period does not show any positive event to create considerable momentum for increasing market demand. Some entrepreneurial activities are visible with three positive events. However, these three events did not lead to creation of legitimacy. In general, the role of [F2], [F4] and [F6] were most visible and together formed a positive feedback loop, which is an indicator for a 'science and technology push motor'. The main missing function was knowledge diffusion [-F3]. This leads to a lack of feedback from society to stimulate the guidance of the search [-F4] in the proper direction. Not fulfilling the requirements for knowledge diffusion [-F3] is indicated by the lack of platforms for learning about smart grid [systemic infrastructure failure] as well as a lack of actors stimulating knowledge diffusion [systemic capability failure]. In addition, several transformational elements had a negative outcome in this phase.

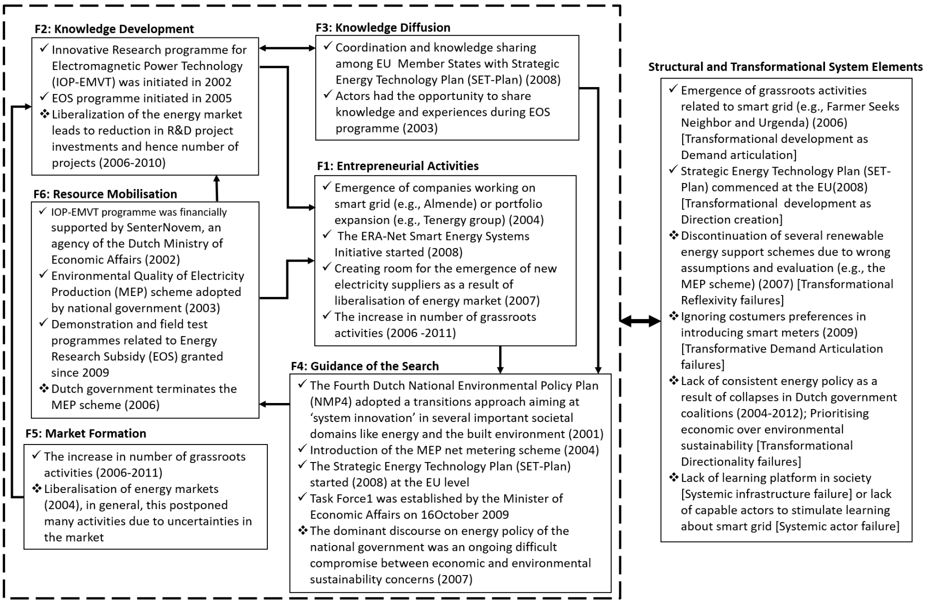


Figure 3.4: Overview of functions and failures in the first period (2001-2012).

3.4.2. SECOND PERIOD: 2012-2016

Entrepreneurs and early adopters of smart grid technology began to play a central role in the launch of demonstration and pilot projects beginning in 2012. Theoretically, the successful growth of a TIS depends on expectations and promises and on the willingness of firms to participate in high-risky projects [16].

To realise the SET plan and comply with European legislation in modernising the national 1998 Electricity and Gas Act, the Dutch government took the next step in 2011. NL Agency, a Dutch public sector agency and responsible for developing road maps to sustainability, innovation, international business, and cooperation, commissioned "Guidelines for applying laws and regulations for the Smart Grids Innovation pilot projects" [F4] [249]. These pilot projects were to organised under the Innovation Programme Intelligent Grids (in Dutch: Innovatieprogramma Intelligente Netten; IPIN), which launched a series of key events [F4]. From early 2012 until late 2015, at least twelve demonstration pilots were carried out to explore the potential of integrating technological innovations in terms of demand response, storage devices, and DGs. The Ministry of Economic Affairs supported these projects, investing around 63 million Euros [F6] [250, 251]. IPIN and related supportive schemes (e.g., Sustainable Energy Production Incentive Scheme (SDE) in 2013) benefited from the relative political stability in the Netherlands after a new government coalition (Rutte II) came into power (2012-2017) [236]. This led to the establishment of the so-called "National Energy Agreement for Sustainable Growth" (2013), which contained the provision of energy conservation and boosting energy from renewable sources (interviewee #3) [252]. Having this as a meta-governance structure helped to keep a shared vision and avoid discrepancies during the experimenting period [253].

In parallel, the formation of the Top consortium for Knowledge and Innovation Innovation (in Dutch: Topconsortium Kennis & Innovatie; TKI) in 2012 reflected institutional change for smart grids that stimulated increased coordination between the government, private sector, universities, and research centers (interviewee #5) [transformational element as policy coordination] [254]. TKI also contributed to entrepreneurial activities by sharing knowledge and research plans with other TKIs or research organisations in the top sectors[1] [F1] [256].

Before setting up and implementing IPIN projects, twenty companies founded the Smart Energy Collective (SEC) [256]. SEC aimed to set up large-scale demonstration projects in the field of intelligent energy networks in the Netherlands and overseas. It had the ambition to take the lead in smart grid services and networks. At the time, it was the most comprehensive initiative in the Netherlands working on the development of intelligent energy services with approximately 5,000 private and business consumers [F1] [257]. The bodies of SEC included private sector companies like ABB, Alliander, Enexis, Eneco, and Essent, but also the DSO Stedin and the Transmission System Operator (TSO) TenneT [258].

Other networks and initiatives were established shortly after IPIN demonstration pilots began in order to jointly develop testing grounds. More than 30 companies joined Netbeheer Nederland (the branch organisation of the Dutch grid operators) smart grid projects to set up living labs in various regions across the country [259]. A good example is Power-Matching City in the city of Groningen [260], where smart meters, decentralised energy technologies (e.g., solar PV, wind and hybrid heat pumps) and ICT infrastructure were installed for a few households to test stabilisation and optimisation of the system [259]. Regional initiatives such as the New Energy Business Community

[1]The Dutch government identified nine sectors in which the Dutch economy is particularly strong. More details can be found in [255].

(in the Northern part of the Netherlands), Smart Energy Technologies & Systems (in the Twente region in the Eastern part of the country), the Amsterdam Innovation Motor, and the Utrecht Sustainability Institute were either empowered by IPIN demonstration pilots or directly involved in IPIN itself. This also applied to citizen-led energy cooperatives like TexelEnergie and LochemEnergie (interviewee #2) [transformational element as demand articulation] [261]. Furthermore, almost simultaneously, other kinds of entrepreneurial activities targeted local initiatives. In this regard, REScoopNL, the federation of Dutch energy communities, was founded in 2013 to empower local communities and citizen working on local energy production ambitions. This includes the installation of wind turbines, solar panels, and hydroelectric power plants, as well as the provision of knowledge and the sharing of the financial risk associated with community-led projects [F1] [230].

Besides an increase in entrepreneurial activities in the (2012-2016 period), some elements of market formation came to the fore. For example, actors participating in the IPIN demonstration pilots realised that setting new standards is essential because interoperability between testing sites was vital for scaling up. Dutch technology suppliers also needed to strengthen their worldwide efforts to capitalise on the international smart grid market [262]. Therefore, parties in the IPIN demonstration pilots tried to adopt the Open Smart Grid Protocol to assure reliable delivery of command and control information for smart meters, solar panels and other smart devices (2012) [F5] [263].

In addition to the observed positive results of IPIN (e.g., an increase in entrepreneurial activities), negative events had occurred. The first pertained to relative exclusion of end-users from the learning process during experiments (interviewee #2). Although a number of IPIN demonstration pilots certainly included end-user acceptance and behaviour as key themes at the start of the project (e.g., in Smart Grid Lochem [264]), end-user behaviour, acceptance, and involvement did not receive sufficient support and attention, also not in knowledge dissemination after IPIN had ended [265].

The dominant top-down approach delineated why the outcomes from the projects were limited to technical validation. A critical point here is the short-sighted consideration of smart grids by developers as a tool to maximise the efficiency of the system and subsequently to impose top-down technological solutions [266]. IPIN demonstration pilots and similar experiments were typically designed by IT-based initiatives or organisations (e.g., ICT Group Netherlands and iLeco) from the Dutch energy top sectors [267]. Reviewing the title of the IPIN demonstration pilots [18] reveals a predominant technical and engineering approach with a focus on the supply side of the electricity system but with little attention to the demand side. This also meant the exclusion of end-users from technology design [267], and their needs and desires for transition [transformational demand articulation failures]. This is also shown in a study by Planko et al. [268] who found six networks in smart grid innovation in the Netherlands as Testing and Development Network, Standardisation Framework, Device Standardisation, Industry Association, Product and Service Development, and Knowledge Exchange. There were no end-user networks found among these networks.

Furthermore, the dominant role of some actors constrained knowledge development by other actors. As stated in an official report [248] in the majority of projects DSOs played the main role. This was considered undesirable by other actors because the dominant role of the DSO deprived other parties from providing certain technical services (interviewee #3) [-F5].

The second issue concerns poor knowledge diffusion. In the IPIN demonstration pilots, the process of knowledge diffusion was limited to organisations and initiatives that were linked to either the government or energy sector incumbents [269]. Therefore, constraints were placed on start-ups to access reports of projects because they were made confidential or were not released at all [-F3]. For example, the official evaluation of the IPIN demonstration pilots [270] was not dedicated to the programme individually, provided little detail, and was part of a larger policy evaluation of a number of innovation programmes by the national government. In this report, the performance of the IPIN demonstration pilots was simply stated to be at a "reasonable" level without providing any further details or presenting results in terms of a sound policy evaluation (e.g., addressing programme impact, effectiveness, and cost efficiency). This conclusion about IPIN was confirmed during a validation interview with interviewee #2, arguing that "IPIN was suddenly terminated in 2015 without proper feedback for interested stakeholders including end-users" [transformational reflexivity failure].

In addition, the IPIN demonstration pilots suffered from a lack of actual programmatic control. Interviewee #2 (the former IPIN programme manager) argues that it is hard to call IPIN or its successor, SDE, actual 'programmes' because the philosophy behind them was not more than the proverb, "To seed a field, and then see what flowers grow." "However, a gardener was missing out." [transformational reflexivity failure].

The national government agency RVO was aware of the shortcomings of knowledge diffusion and the exclusion of end-users. However, when IPIN was first implemented (2012-2014), it attempted to address this issue by organising a series of workshops [251]. These workshops concentrated on themes like reflecting on users' feelings, doubts, visions, and experiences and opening up discussions and communications with end-users [F3].

The third adverse point pertained to a number of governance obstacles. For example, although developed technologies allowed the active participation of customers in demand response, there were no financial incentives due to static electricity prices (interviewee #2). Furthermore, regulations served as an obstacle for peer-to-peer electricity trading because actors in the electricity market are required to obtain a legal permit to supply energy [152]. Moreover, in some cases, actors needed flexibility in market and grid activities. For instance, some experiments required controlling storage and generation activities simultaneously, which meant that the re-bundling of grid operation and market activities were needed. Regulations governing the conduct of DSOs did not allow system operators to take control over storage devices in terms of ownership and operation. This led to unfavourable conditions for the experiments and knowledge diffusion [-F2, -F3] [271].

Last but not least, actors involved in IPIN demonstration pilots were not able to mobilise capacity and neither generated synergy with the aim to change the current embedded regional and national electricity systems [271]. The IPIN management made one attempt to infer institutional change. "We made an inventory of the legal obstacles, and it was submitted to the legislator" according to the IPIN demonstration pilots coordinator (interviewee #2). However, public authorities were not satisfied and argued that they needed many more practical cases before taking action [-F7]. In addition, interviewee #2 stated that actors need to take more action in order to be heard by regulating authority and that there is a need for a powerful representative to reflect on the needs actors have in the energy market [-F7] [272].

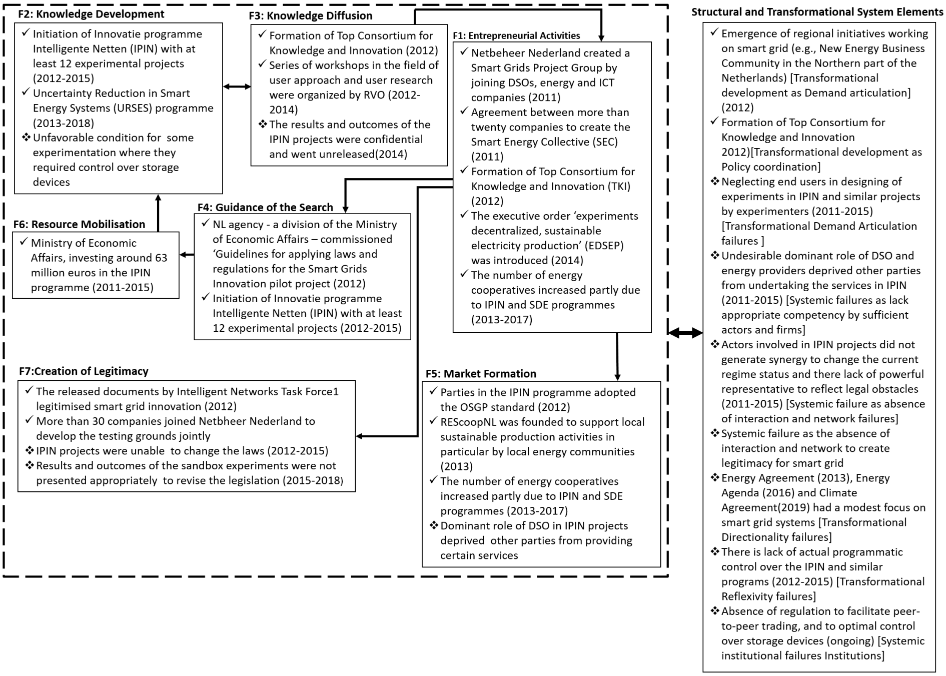


Figure 3.5: Overview of the of second period (2012-2016).

As can be observed in Fig. 3.5, the national government was actively involved in the smart grid innovation system to initiate demonstration projects and to support the projects by implementing schemes having subsidies and grants. Moreover, various entrepreneurial activities took place (with five positive events). However, entrepreneurial activities alone could not legitimise the smart grid. Although the government continuously fed the innovation system, this was due to high interest in the government for sustainable development rather than entrepreneurial activities or creation of legitimacy by the entrepreneurs (see the negative outcome of [F7] in Fig. 3.5) This was due to the systemic failure as the absence of actor interaction and networks. Resource mobilisation by government programmes prevented the system from breaking down and cascading negative events (interviewee #1). In addition, although the market function experienced two positive events, it could not contribute to the guidance of the search in the desired direction due to the substantial number of systemic failures, mostly in terms of ignoring end-users' needs, wants and interests, and the absence of powerful actors in creating a strong network. This is linked to the dominant role of DSOs in IPIN demonstration pilots and systemic failures occurring, indicating a lack of appropriate competency by sufficient actors and firms. In addition, the quality of experimentation suffered from a lack of customer incentives and regulations that hindered peer-to-peer electricity trading [systemic institutional failure]. In general, quite a number of failures and the absence of a positive feedback loop were observed over 2012-2016.

3.4.3. Third period: 2016-2021

During the third period, a considerable number of transformational failures occurred, followed by a new approach for experimentation (e.g., sandbox experiments, upscaling the projects, and experimenting to reach new socio-technical arrangements).

Upscaling the projects (e.g., from the IPIN demonstration pilots) became an important discourse among policymakers by the end of 2015 [273]. The focus of the projects during the second period was on technical feasibility. However, the IPIN demonstration pilots were ultimately unable to create a market, nor did IPIN result in any transformative change (interviewee #2) (except for some projects arguably being replicated elsewhere in the Netherlands) [274]. The demonstration pilots faded after IPIN had ended, public funding stopped, and sufficient user demand had not yet been created [275].

To this end, after 2015, RVO in cooperation with the Top consortium for Knowledge and Innovation (TKI) Urban Energy, continued investment in research programmes to explore how smart grids could potentially be deployed [274]. Concurrently, the smart city concept became popular, reflecting the common belief towards scaling the projects. Moreover, large gatherings at both the EU and national level took place focusing on smart cities shifting the attention away from smart grids to a higher level of aggregation, also including other sectors than the electricity sector. This is showcased by events like Amsterdam's smart city event 2016 and the Conference on "Smart, Innovative & Sustainable urban mobility" [275] [F3].

Although RVO and TKI supported the scaling approach to smart grids, a policy directionality failure was evident at this time. The smart grid as an innovative concept was not embraced or sufficiently legitimised by the government. Notably, the 2013 Dutch Energy Agreement [276] had a modest focus on decentralised systems, and measures were aimed at supporting large investors and incumbents in the electricity sector. As discussed by Oteman et al. [230], this meta-governance arrangement was mostly based on the economic attainability of the energy transition, employment opportunities, and profitable investment. Additionally, the majority of the actors involved in the strategic design of the Energy Agreement were the national government, the traditional energy sector, and business representatives, who paid little attention to small-scale bottom-up projects carried out by local stakeholders, grassroots energy communities, or start-ups in smart grid innovation (interviewee #5). A similar approach was visible in the 2016 Energy Agenda [277] and later in the 2019 Climate Agreement [278], in which the main theme in the electricity sector was production from large-scale offshore wind, solar, and hydrogen [transformational directionality failure] [230].

Aside from the downside of the 2013 Dutch Energy Agreement, it also stated that "To realise the energy transition, the legislation needs to be providing a consistent framework to provide investors with long-term security. In addition, legislation needs to facilitate innovation." This meant that legislation needed to provide sufficient space to enable desired new developments, in particular, when it comes to energy generated from RESs [276]. To this end, the Gas and Electricity Acts were to be revised. Consequently, the national government established a legislative agenda entitled "streamlining, optimising, and modernising" [279]. Eventually, this resulted in an executive order entitled "experiments decentralised, sustainable electricity production" (EDSEP) (2015). This allowed experiments contributing to the energy transition to deviate from certain stipulations regarding the specific electricity provision of the national Electricity Act 1998 [F2] [280].

EDSEP helped to develop and carry out so-called 'sandbox experiments' to resolve issues observed during the implementation of the IPIN demonstration pilots. Sandbox experiments are "tools" (i.e., small-scale demonstration pilots) for new socio-technical arrangements by providing regulatory exemptions for experimenters [281].

By introducing EDSEP, DSOs, the Netherlands Authority for Consumers and Markets (ACM), and tax authorities started to collaborate to facilitate experimentation. For example, Smart Grid Westland, Aardehuizen, Schoonschip, and Endona were approved under EDSEP (see [279] for details on the experiments in 2015-2019 period). Implementing EMS with dynamic tariffs and installing PV panels formed the main technical configuration within these experimental projects [280].

Legal exemptions were allowed for a maximum of ten years. EDSEP applies to specific articles of the Electricity Act; other regulations must be applicable. In general, exemptions are allowed for the projects that pursue increasing utilisation of renewable energy systems, enhancing the current energy infrastructure, and increasing the involvement of energy users in energy supply [271]. This meant that there had to be a lot of cooperation between agencies in order to decide if a project was eligible for an exemption. Although the programme was not finalised at the time of conducting this study, a number of issues emerged. The first issue encountered pertained to RVO not transparently explaining what the regulations entailed to DSOs and the ACM [279]. Moreover, compartmentalisation within DSOs and energy companies negatively influenced the progress of the sandbox projects because inconsistent decisions were made and in parallel [transformational policy coordination failure]. For example, a certain project could get approval for exemption from a DSO, although the ACM was not convinced (or the other way around) [281].

The case of 'Windpark Kloosterlanden' in the city of Deventer in 2015 illustrates this issue. The current electricity tariff code compelled newly constructed wind turbines to be connected to the nearest medium voltage substation. However, partners in the project, particularly energy providers, requested an exemption to connect the wind turbines to a specific medium voltage grid, which was not the nearest. The reason for such an exemption was to install wind turbines close to the energy demand in the smart grid with proper control of it. Local customers also supported this request, according to the energy supplier manager [282].

Nevertheless, the ACM did not grant the exemption on the grounds that exemption is only a temporary solution and precedents can arise. To support this argument, the ACM argued that this case was an opportunity for the grid operator to request an amendment to the electricity tariff code instead of asking for an exemption. In response, Liander (the responsible DSO) considered the rejection of the exemption as very unfortunate because it undermined the pilot project goals. Its manager believed that the project only needed a short-term solution for experimental purposes. Changing the code was considered a long-term process that should be done in consultation with other system operators and their federation 'Netbeheer Netherland' (interviewee #2) [transformational policy coordination failure] [282]. However, Liander took the decision of the ACM to heart and started a lobby to have this connection method adopted into legislation. This was eventually achieved in 2020 with the addition of Article 23 (2) in the Electricity Act [Structural system development as a revision of institutions] [283].

Related to these failures is the absence of lobby organisations and intermediaries to accelerate the law revision process. The efficiency of the experiments to make a long-term impact was undermined because RVO reports project progress to the Ministry of Economic Affairs and Climate Policy from its own perspective (interviewee #2). Experimenters are hardly asked to provide their inputs for revising regulations [transformational reflexivity failure]. Furthermore, RVO, the ACM, the DSOs, and the project developers were working in parallel worlds in which a shared vision regarding the goals and process was badly missed [236]. There was no communication channel supported by a lobbyist representative or intermediaries in different decision-making units. Nor was there any coordination of the activities [271]. "Energie Samen" was founded in 2018 as a national federation to resolve this issue for local community energy collectives. It is the successor to REScoopNL and a few other community energy federations. Its goal is to strengthen community energy initiatives and projects and to represent them in negotiations and lobbying vis-à-vis the government and, in particular, the regulatory authorities [F7] [279].

The analysis also reveals a lack of policy coordination between the EU and national government, particularly in terms of transposing EU directives into national legislation. For example, the EU obligates its Member States to provide the right for system users to access the electricity network indiscriminately (e.g., Directive 2009/72/EC of the European Parliament and the Council) [284]. This guarantees Third Party Access (TPA) for users that threaten the goals of experiments at the national level. Inasmuch as TPA implies that users have their own suppliers, the business models of experiments are undermined because their generation capacity will be constrained to the projected demand. Some parts of production cannot be used if users choose other energy suppliers than the energy provided by the energy suppliers involved in the experiment. In general, according to interviewee #5, the Ministry of Economic Affairs is too slow to transpose the EU packages [transformational policy coordination failure]. For example, the EU's Clean Energy Package [285], which includes the concept of energy sharing, should have already been transposed by the end of 2020 but is currently only expected to be transposed by 2024.

The opposite also happens when EU legislation tries to increase demand response, but national legislation deprives Dutch customers of the initial incentives. For example, the EU directive 2012/27/EU states that the network tariff should encourage demand response and promote system flexibility [239]. However, currently, the Dutch Electricity Act does not allow tariffs based on users' capacity and dynamic network tariffs. In addition, DSOs and aggregators could provide flexibility for the network by means of direct load control [286]. However, this option is also obstructed by Dutch national law. Applying direct load control by a DSO means rewarding a selective number of users for taking part in direct load control (i.e., implying a discount on their electricity bill). This can be considered as discrimination between customers because the DSO can only provide direct load control for consumers living in an area with grid constraints or congestion problems [287]. Obviously, this lack of coordination between the national and European levels limits experimenters' control over experimental projects [transformational policy coordination failure].

The implementation of DSM plans is also complicated by the regulatory setting that currently exists in the EU and the Netherlands [288]. The Electricity Act and EU Directives emphasise the importance of 'efficiency' in network management [289]. However, the DSOs' activities must be unbundled from the supply and production market as a result of liberalisation. Using DSM by DSOs can directly influence the electricity market. Furthermore, current methods for calculating the DSO's tariffs can discourage the end-user from adopting the DSM plans. End-users should be provided with transparent information about the financial value of the flexibility [288]. This is a challenging task for DSOs because the value of flexibility depends on the system condition at other electricity system levels and not only on the local condition. The current tariff setting is calculated based on the system connection level (e.g., 230/400 V) rather than on the customers' exact location [287].

Evaluating the current status of smart grid innovation indicates that the approach to running experiments has changed after the termination of the IPIN demonstration pilots in 2015 (interviewee #2). For instance, it was visible in the 'Uncertainty Reduction in Smart Energy Systems' research programme [F4] that ran from 2013 until 2018 [290]. The aim of this programme was to reduce uncertainties for actors in smart energy supply chains [291]. To this end, projects gained insight from social and behavioural sciences to analyse the cause and nature of uncertainties in smart grids [292]. Following the new approach for experimentation, as of September 2020, the Dutch government allows entrepreneurs to apply for financial support under the "Renewable Energy Transition" scheme in Dutch: "Hernieuwbare Energietransitie", HER+) [293]. Similarly, the national government subsidises projects contributing to the development of improved (self-learning) control systems for energy use and advanced control systems. This programme is called "Mission-driven Research, Development and Innovation" (in Dutch: "Missiegedreven Onderzoek, Ontwikkeling en Innovatie", MOOI) and it began in August of 2020 (interviewee #3) [F2, F4, F6] [250]. The national programmes were also backed by funding from EU frameworks programmes (e.g., Horizon 2020 and NER 300) (2013-2020) [F6] [294]. Over the same period, the number of energy cooperatives tripled (2017-2020). This was partially due to the available funding programmes [295]. Moreover, "Local Energy Monitor" [295] which monitors community energy sector performance annually shows that most of the energy firms, such as Alfen N.V. (an LLC), have been expanding their activities into EV charging product developments and upscaling of the energy storage since 2017 (interviewee #4) [F1, F5].

Rolling out the essential infrastructures and institutional changes indicate favourable developments that are promising for the future of smart grids in the Netherlands. In this regard, the Royal Netherlands Standardisation Institute (in Dutch: Nederlands Normalisatie Instituut) published its "Smart grid standardisation roadmap", "the IEC/TR 63097" in 2017. This document is used as a guiding principle for future smart grid experiments [F5] [296].

Another example of existing infrastructure is the high adoption rate of EVs in the Netherlands (reaching 34% of the market share in 2022) [297]. This is a result of the National Agreement (2019) commitment to electrification and the allocation of a 250 million euro stimulus to promote electric driving by the end of 2025 [298]. Provinces and municipalities have recently been active in setting-up extensive tenders to increase the number of charging stations. As a result, installing public charging infrastructure with open protocols, and smart charging without government investment is becoming the new norm [299].

In addition, for the first time in Europe, all Dutch DSOs and TSOs worked in partnership to create an online congestion management platform for the Dutch grid operators (GOPACS) [300]. This platform has been in operation since 2019 and successfully addresses the TSO-DSO coordination issue by requesting flexibility from the market to reduce congestion in the electricity grid. The platform considers DSOs' grid situation in coordination with the balance in the national electricity grid [301] [F5].

Furthermore, regarding smart meter installation, currently, the Netherlands can be considered one of the European frontrunners in rolling out smart meters despite having encountered initial setbacks (see Section 3.4). A 2021 study [240] shows the diffusion rate of the smart meter is at 85%, meeting the 2020 goal [developing structural system infrastructure]. Despite this rapid adoption, DSOs can hardly use data from smart meters for smart grid management purposes because of the current privacy legislation. To solve this problem, the Dutch DSOs developed a code of conduct approved in May 2022 by the Dutch data privacy authority [302].

The graphical summary of the events in Fig. 3.6 shows the absence of creation of legitimacy [-F7] and the existence of a substantial number of transformational failures (with six negative events). Lack of creation of legitimacy deprives the completion of a positive feedback loop because connections between creation of legitimacy [F7], guidance of the search [F4], and market formation [F5] are missing (interviewee #4). This resulted in a missing connection (network) between the government and interest groups to effectively establish the required institutions to support the whole smart grid innovation system. The failure to create legitimacy [-F7] indicates a systemic failure in networking between the smart grid supporters. Like the first period, knowledge diffusion is not developed [-F3] due to the absence of interactions between entrepreneurs, effective networks, and learning infrastructure. Similar to the second period, there are several failures and no positive feedback loop.

3.5. Discussion

The following findings are discussed in relation to the study's goal of identifying systemic and transformational failures in the development of smart grid innovation in the Netherlands in the 2001-2021 period by combining TIS and transformational perspectives. The analyses of the three periods show that in the first period a positive feedback loop could be observed in the form of a science and technology push motor. However, no positive feedback loop was observed in the second and third periods. In these two periods, systemic failures led to the weak fulfillment of some functions and the absence of certain linkages between functions. In all periods, the Dutch national

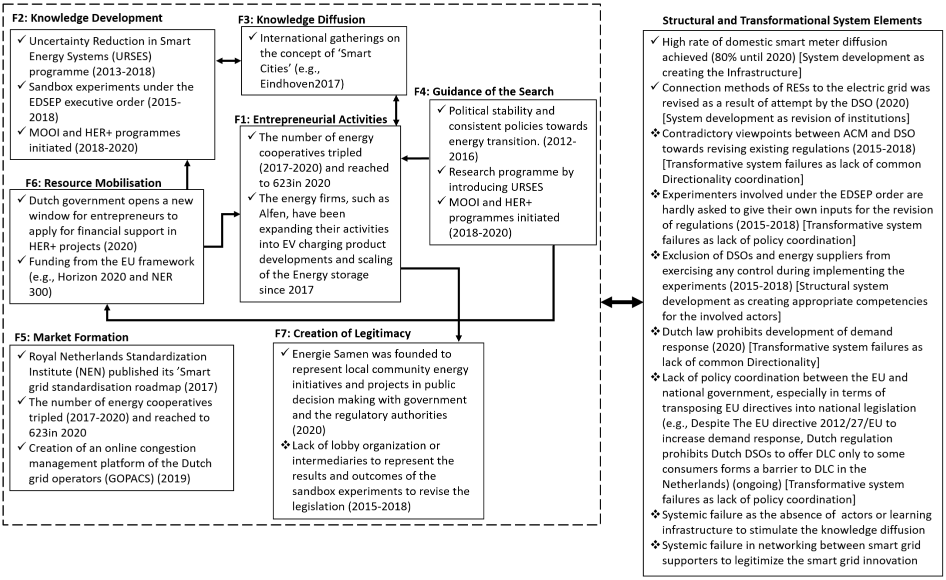


Figure 3.6: Overview of functions and failures in the third period (2016-2020).

government was motivated and intensified innovation activity in smart grid technology. The national government's adoption of the NMP4 in 2001 showed that smart grid-related technologies caught the attention of policymakers as promising technology. Supporting IPIN demonstration pilots in the second period revealed the same motivation. In the third period, this continued with support for socio-technical experimentation under EDSEP executive order.

In the first period, setting up support programmes like IOP-EMVT by the national government and investing in R&D projects facilitated the acceptance of the smart grid, at least, among a small network of scientists and early adopters (interviewee #3). Consequently, the number of involved firms and scientists working on the smart grid gradually increased. However, the small-sized network of entrepreneurs suffered from a lack of leadership and the near absence of learning platforms for the diffusion of smart grid knowledge (2001-2012). In general, entrepreneurs lacked a proactive mentality, and government and research institutes were in the lead of innovative projects, with firms taking more of a passive role (interviewee #5).

Similar trends characterised the second period (2012-2016), but it was somewhat more intensive than the first period in terms of fulfillment of entrepreneurial activities. Initiating the IPIN demonstration projects increased entrepreneurial activities in terms of the number of new entrants and established firms involved in the projects. The IPIN demonstration pilots could potentially work as a learning platform for entrepreneurs and end-users. However, this was not realised because designers predominately focused on technical improvement while ignoring end-users' preferences (interviewee #2). Demand-side support and standardisation were still underdeveloped. This meant that the created niche market could not significantly impact building the required infrastructure and institutions. As explained by Heyvelhof and Weijnen [196], building the infrastructures for market formation involves actors making a substantial investment in the market, which is risky because the return on investment depends on end-users' preferences and uncertain regulatory conditions.

Large-scale projects are considered necessary to influence the incumbent electricity system. This also requires a larger and more powerful actor-network to legitimise the smart grid TIS. This finding complements the findings by Van Summeren et al. [194] that energy cooperatives and other bottom-up initiatives in the Netherlands struggle to play their preferred role with respect to their needs and values because they have to comply with energy sector incumbents.

The third period started in response to the required structural changes (e.g., the need to remove regulatory barriers for proper experimentation). However, this had not been realised by 2021 due to a number of significant transformational failures. Experimentation in this period signalled that overcoming systemic failures is not only about the fulfillment of smart grid TIS functions but also about harmonising and alignment of activities outside the smart grid TIS. Here, a sound example concerns the contradictory viewpoint between the ACM and the DSO in revising the existing regulations in the Deventer wind park case. This is shown by Lammers and Heldeweg [152] who hold that decision-making in smart grid projects in the Netherlands is complex due to the diversity of stakeholders. Based on this study's results, this complexity also influences the collective action between regulatory authorities and system operators besides actors directly involved in the projects. Interviewee #5 elaborated on the market formation issue by stating that there is a lack of proactive mentality among business enterprises to adopt new business models like peer-to-peer trading. DSOs also experience a net capacity problem. Therefore, they have to improve the grid capacity, which leaves them with little financial capital to invest in smart grid innovation structurally.

In summary, legislation, technology and business did not work in tandem, with technological advancement. Projects and market development suffered from the slow adaption of legislation, and slow growth of business potential for smart grid innovation. What did not help either was the Dutch national government (unlike the European Union), lacking a vision and a structural innovation support programme (interviewee #5). The national government's approach to smart grid innovation was rather haphazard, lacking strategy, and changing suddenly between government administration terms, giving entrepreneurs, DSOs and research institutes little certainty on what to expect with regard to setting up the next smart grid innovation projects. Neither was there sufficient attention to scaling results of pilot demonstrations (interviewee #2).

Systemic failures resulting from a lack of networking between actors, interactions between entrepreneurs, and legitimising smart grid are crucial and must be addressed. Networking and interaction between actors can be improved by creating branch associations that impact policymakers and society [303]. This interaction can also influence the knowledge diffusion process. In addition, interactions between actors (both companies and consumers) dramatically increase by sharing knowledge during demonstration projects. However, it is recommended that the goals and strategic policies of the demonstration projects be defined before starting the projects. In designing strategic policies, specific attention should be paid to end-users and raising their awareness.

To legitimise the smart grid, it is recommended that involved companies take collective action to lobby and create legitimacy. This, in turn, can convince the government to emphasise the rule of the smart grid in the legislation. Then, more subsidies can be made available to support smart grid start-ups to survive the “valley of death”.

To address the identified policy coordination and demand articulation failures, the following should be considered. These failures are reflected in the Dutch energy agreements (2013) and Climate Agreement (2019), in which the Dutch government preferred to support centralised RESs. This is not surprising because the transition task forces and platforms are dominated by incumbents, which support centralised RESs. Support for RES innovations by incumbents means that they shape the public policy in a manner that is not disruptive to their business [187]. According to interviewee #2, this issue is rooted in the fact that there is no urgency among decision-makers or end-users to seriously consider adopting smart grid and related technologies, infrastructures, and services. Directionality and coordination transformational failures can be removed if support for the centralised RESs is downscaled and more focus is put on establishing local and regional, decentralised systems. This can lead to further smart grid legitimiSation. Consequently, the legitimiSed smart grid can improve the identified reflexivity failures because, if the smart grid is legitimiSed, the results of demonstration projects (such as IPIN) must be evaluated more thoroughly.

Although the results derive from a case study reflecting a single nation, there is reason to believe that similar results may also be found in other countries with similar characteristics, in particular in other North-Western European countries like Germany, Denmark, or Norway [304]. A comparable study in South Korea examined the development of the smart grid through a governance and innovation system lens [42]. Empirical studies from these countries have revealed similar failures hindering smart grid innovation system development. They pertain to knowledge sharing, acceptance issues, complexities in introducing suitable regulations, or a lack of legal definition, which harms practical operations and hinder the mainstreaming of a potentially mature smart grid innovation (i.e., energy storage; [305]).

These studies highlight the importance of designing a structured approach, tools to facilitate multidisciplinary knowledge exchange, and incentives to ensure a level playing field. The Dutch case complements results from studies in other countries by tracing issues to overarching transformational failures and showing how they occur in practice and impact innovation system development. Arguably, similar transformational failure might be found in fairly comparable countries with the government having the desire to stimulate and implement smart grid innovation (i.e., with similar institutions, technocratic visions, and socio-political conditions).

Table 4 provides various smart grid deployment metrics for the Netherlands and four other EU countries to complement this study’s qualitative findings. The selected metrics also serve as indicators of TIS functions. The overall deployment of the smart grid is reflected in metrics like CO_2 emission per capita and demand side flexibility market[2]. In terms of these metrics, the Netherlands’ adoption of the smart grid lags behind that of EU countries. Programmes focusing on physical infrastructures like the roll-out of

[2] Information on how to interpret ‘low’, ‘medium’, and ‘high’ rankings can be found in [214].

smart meters, the development of charging stations for EVs stations, and the storage capacity display encouraging numbers. The deployment of the smart grid, however, necessitates more than these infrastructures because each TIS depends on all institutions and actors working together [306]. Moreover, there are fewer patents, a key indicator for determining the development of knowledge. The number of collaborative interactions with other countries during the projects shows that knowledge sharing between the Netherlands and other countries is less than the interactions between other countries. Due to the less interaction, this may lead to fewer lobbying activities to legitimise the smart grid.

The level of concentration of DSOs [3] and the number of companies and organisations involved in the projects can be used to interpret the fulfillment of entrepreneurial activities. A medium concentration of DSOs in the Netherlands indicates average success in unbundling electricity networks and fulfilling entrepreneurial activities. This was observed during smart grid projects in the Netherlands (e.g., in IPIN), when a few DSOs played the dominant role. Moreover, the number of companies and organisations in smart grid projects also confirms the moderate speed of fulfillment of entrepreneurial activities. The comparative analysis also indicates that the Netherlands' total investment in smart grid projects is among the highest in the EU. This supports the qualitative analysis's conclusion that the Dutch government offers a variety of financial support schemes to run smart grid projects.

With a futuristic approach, the market's slow demand-side flexibility development can be problematic soon. Due to the increased percentage of renewable energy before 2050, the congestion problem in the Dutch power system will significantly increase [314]. More demand-side flexibility is necessary to solve this issue. Demand-orientation policies must take the place of supply-orientation, which is still the dominant policy in the Netherlands [315]. Policymakers can use the success of the adoption of EV innovations as an example to encourage the use of other smart grid technology [306]. To that purpose, the Dutch polder model's culture of collaboration in public decision-making and knowledge development between the government, private parties, and local government can be potentially used in other (energy) infrastructures [316].

Despite the merits of this study, two major shortcomings of the used integrated framework (see Fig. 3.3) compromise the accuracy of the analysis. First, the willingness, values, preferences, and position of end-users in the existing and future market are not thoroughly examined while looking for TIS development and transformational failures. Any transition in an electricity system cannot be realised by only providing comfortable and affordable technologies. To elaborate on this way of thinking, as Kemp and Van Lente argue [317], sustainability transitions through sustainable technology adoption require a dramatic change in the values and criteria of customers in addition to changes in technologies and infrastructure to accommodate these values and intentions. For instance, adopting smart grid technologies like installing solar panels by end-users can assist in reducing CO_2 emissions. However, more production at the end-user side means that DSOs have to cope with increasing net congestion problems. Taking electricity

[3]Low concentration means that they are mainly small, local DSOs and the three largest DSOs usually deliver less than 50 % of distributed power. Very high concentration means that there is only one DSO company [307].

Table 4: Comparing indicators of smart grid development in the Netherlands and four other EU countries until 2021.

Metric	The Netherlands	Germany	Norway	France	Denmark
Population (millions) [308]	17.53	83.13	5.40	67.5	5.85
Total investment in smart grid projects per capita (EUR/capita)	10	4.5	6	4	16
Total electricity power generation (GWh) [309]	117,440	250,385	39,412	530,418	32,793
Renewable generation percentage (%) [213]	34.8	41.80	98.80	23.25	78.14
PV penetration rate (%) [213]	11.8	10.9	0.1	3.6	5.0
Wind power capacity in relation to overall power capacity (%) [213]	14.7	25	7.49	6.76	39.1
Offshore capacity in relation to overall power capacity (%) [213]	5	3	0.01>	0.01>	12
Number of electric vehicles per 1,000 population [211]	21.7	15.7	117.3	11.6	24.7
Number of charging station per 1000 EV [211]	200	38	30	68	20
Absolute capacity of operational electrochemical storage (MW) [310]	37	570	6	19	2
Capacity of operational electrochemical storage by population (W/capita) [310]	2.11	9.02	1.19	0.28	0.341
Smart metering rolling out (%) [212]	85.2	15>	98	80-90	80
CO_2 emissions per capita (tonnes) [311]	8.06	8.09	7.57	4.74	5.05
Number of patents related to smart grid technologies per million population [312]	0.75	29.7	6.8	1.4	6.32
Electricity market potential for demand side flexibility [214]	low	medium	low	medium	low
DSOs level of concentration [307]	medium	low	low	very high	low
Number of participations in smart grid projects per capita [313]	18	8.1	18	6.1	28.7
Number of companies and organisations involved in the smart grid projects [313]	476	835	245	680	430
Number of collaborative interactions with other Eu countries during smart grid projects per 1000 population [313]	0.31	0.42	0.87	0.41	3.02

system operators, end-users are expected to accept the constraints of new technologies and start behaving and using electricity differently. However, this often does not match well with end-users' current behaviours, lifestyles, and social practices. It cannot be expected that end-users will change these overnight after adopting smart grid technology. It instead requires an adaptive process in which technology changes to accommodate behaviours and social practices. However, according to sociological and psychological research [304] minor changes in the latter can be achieved but are difficult to attain and maintain.

The second methodological problem occurred in identifying the transformational failures as there is no systematic way to retrieve all relevant transformational failures. Merely defining the transformational failures as a descriptive method is insufficient because sustainability is a complex normative problem that is rooted in actors' paradigms (i.e., basic beliefs) [318]. The paradigms of each actor determine what actions or practices are considered reasonable and legitimate. For example, a lack of coordination between different policy levels may happen because each level has a different vision regarding sustainability. This misunderstanding of the causes of transformational failures may result in poor policy design.

3.6. Conclusion

By using an integrated framework in which TIS structural elements, functions, and failures are combined with a transformational perspective, this study explains the development of the smart grid innovation system in the Netherlands. Results show that this went through a couple of stages of experimentation. Although knowledge development [F2], guidance of the search [F4], and entrepreneurial activities [F1] were found to have experienced the largest number of positive events, the functions of knowledge diffusion [F3] and creation of legitimacy [F7] had limited positive events. The weakly fulfilled functions are linked to systemic failures in terms of a lack of infrastructure to stimulate knowledge diffusion, failures in terms of the absence of interactions and actor networks to legitimise smart grid innovation, and failures in the absence of institutions (e.g., regulations) for experimentation purposes or market formation.

Moreover, market formation [F5] presents the potential for scaling up, for example, with the adopted standards and implemented infrastructures such as smart meters. However, systemic and transformational failures hinder smart grid innovation from developing into market concepts that can readily be commercialised. The implication is that resources [F6] for the projects still mainly come directly from the Dutch national government and from EU innovation investment funds, and the market plays a marginal role in feeding further experimentation.

The scientific novelty of this study lies in the combined analysis of TIS functions, systemic failures, and transformational failures. The results show that these three elements have influenced each other in the case of smart grids in the Netherlands. Transformation failures in the broader socio-technical system outside the TIS led to problems in TIS functions and to systemic failures. This study is also relevant to current debates on mission-oriented innovation policy [319]. In the case of smart grids in the Netherlands, it is shown that the influence of policy programmes and policy steering has been of considerable importance throughout all three studied periods. However, it is also shown that, in spite of stimulation programmes, misalignment between the actors involved, such as policymakers, entrepreneurs, energy cooperatives, business firms, and end-users, can lead to systemic failures and can severely slow down TIS growth.

Smart grid analysis shows why developing improved methods of analysis is necessary. The inability of TIS to reflect on the failures caused by the preferences and willingness of end-users is a major limitation of TIS functions and transformational failures. Therefore, it is essential that future research designs incorporate psychological considerations.

Moreover, methodological shortcomings hamper the reliability of recovered transformational failures when tracing the origins of these failures. This is due to the normative nature of transformational failures. As a result, studies should shift their focus to incorporating belief systems (paradigms) into innovation system analysis as the root causes of transformational failures.

Recently, studies took a first step in this direction by proposing policy interventions to overcome transformational failures [320]. Another interesting area of further research is the quantification of the qualitative results of this study in terms of the number of positive and negative events for modeling purposes, for example, to evaluate the impact of each function of the TIS on other functions in a system-dynamic manner.

4

Impact of Different Pricing Policies on Residential Smart Microgrids

This chapter is based on:
F. Norouzi, A. Shekhar, T. Hoppe, P. Bauer, "Analysing the Impact of the Different Pricing Policies on PV-Battery Systems: A Dutch Case Study of a Residential Smart Microgrid" Energy Policy, 2025, Vol 204, 114706.

This chapter investigates the techno-economic impacts of various pricing policies on a photovoltaic (PV) system combined with battery energy storage (BES) as a single integrated system within a Dutch residential building. With the increasing adoption of PV systems, managing bidirectional power flow and grid stability becomes crucial. The study evaluates different scenarios, including net metering, feed-in tariffs (FiT) with time-of-use (TOU), dynamic pricing, and subsidised BES. Using a multi-objective genetic algorithm, the optimal size and charging/discharging patterns of the PV-BES system were determined. The optimisation simultaneously minimises the Net Present Cost (NPC) and maximises the Self-Consumption Rate (SCR), leading to a non-zero BES capacity, as BES is necessary to achieve an optimal balance between economic and technical performance. Results indicate that dynamic pricing significantly enhances SCR. While the levelised cost of electricity (LCOE) and payback periods (PBP) are initially higher in the dynamic pricing scenario, subsidising BES can mitigate these disadvantages. Additionally, incorporating control variables into the energy management system (EMS) optimises the charging/discharging cycles, extending BES lifetimes and potentially increasing future revenues. These findings provide insights for policymakers to balance economic benefits and grid technical requirements through effective PV-BES integration.

4.1. Introduction

Recently, the adoption of photovoltaic (PV) systems has grown at an unprecedented rate worldwide. The International Energy Agency (IEA) projects that in 2050, solar and wind energy together could account for roughly 70% of global electricity generation [321]. However, the surge in PV adoption results in substantial bidirectional power flow into the grid, posing technical challenges for electricity systems. This includes congestion issues in distribution systems due to a mismatch between demand and the peak of PV generation [322].

A potential strategy to tackle these challenges is integrating battery energy storage (BES) with PV operations within the distribution systems [323]. If regulatory frameworks allow, Distribution System Operators (DSOs) can leverage the continued installation of PV-BES systems in residential microgrids. The benefits of these systems include peak demand shaving, power quality enhancement, and voltage and frequency stability improvements. Furthermore, the widespread adoption of PV-BES systems could delay the necessity for comprehensive power system reinforcement, thereby providing economic benefits and technical advantages [324].

From consumers' perspective, PV-BES systems can lower electricity bills and minimise PV curtailment. Despite this, the relatively high initial cost remains a significant barrier to the broader adoption of BES [325]. Nonetheless, the gradual decrease in BES prices makes installing PV-BES systems increasingly justifiable. Furthermore, the presence of subsidy schemes enhances the economic viability of BES [326].

From the perspective of DSOs, integrating Renewable Energy Sources (RESs) on a large scale imposes significant costs on distribution grids. Traditional distribution systems are not designed to handle substantial bidirectional power flows, necessitating major upgrades to distribution system assets, such as transformers and cables, to accommodate these changes [327]. Consequently, while consumers and DSOs recognise the value of deploying PV-BES systems, their objectives often diverge. Consumers focus on reducing electricity bills and increasing energy independence, while DSOs aim to maintain grid stability and minimise operational costs [328]. Therefore, achieving optimal performance from Energy Management Systems (EMSs) is crucial to ensure that economic benefits are maximised for all stakeholders, balancing the distinct goals of consumers and DSOs [322].

Effective EMS design depends on factors such as battery and PV system costs, system size, load consumption patterns, consumer selling tariffs, and electricity pricing regulations [329]. Additionally, for DSOs, the economic viability of EMS deployment hinges on the optimal use of BES for peak shaving, which can significantly reduce the need for distribution system reinforcement and associated costs [330].

The optimal design of EMSs for PV-BES has been extensively researched, with abundant literature addressing various aspects. Numerous studies, such as those by [331], have evaluated the economic value of PV-BES, focusing on enhancing self-consumption through optimal PV-BES sizing. [332] explored how pricing mechanisms influence BES sizing decisions. Since BES sizing is influenced by the formulation of the optimisation function and pricing policies, the findings in [333] suggest that BES is not an economically viable option when assessed solely based on financial metrics such as payback time and net present value (NPV).

In [334], optimal PV-BES sizing is integrated with a peak shaving control strategy to enhance system efficiency. Additionally, [335] examined the impact of meteorological conditions on PV-BES sizing, highlighting the influence of climate variability on system performance. In the realm of microgrids, [336] propose a novel optimisation technique aimed at maximising the utilisation of RESs while reducing reliance on fossil fuels. Shifting the focus to DSOs, [337] developed an algorithm for peak shaving using BES, incorporating varying investment costs to assess economic feasibility.

With respect to EMS design, the rule-based approach [338] is widely used due to its simplicity and suitability for industrial-scale applications [339] when compared to more complex techniques such as predictive control [340] and adaptive controls [341]. Rule-based methods offer clear and interpretable logic, making them practical for real-time implementation. However, rule-based EMSs may lack adaptability to dynamically changing grid conditions compared to more advanced approaches like ML-based EMSs [342].

To overcome this limitation, an optimisation approach can be combined with heuristic techniques such as tabu search [343], particle swarm optimisation (PSO) [344], and genetic algorithm (GA) [345] to enhance performance in specific applications. For instance, in [346], a rule-based EMS is integrated with demand response optimisation, considering energy import and export prices. Additionally, rule-based EMSs are applicable for power quality improvement. For example, reactive power support is incorporated into an EMS in [347].

Despite extensive literature on PV-BES systems, a significant gap remains in understanding the impact of changing pricing policies on primary stakeholders, namely consumers and DSOs. While DSOs view BES as a tool to reduce network utilisation and defer grid expansion costs, consumers focus on maximising economic benefits [348]. Bridging these differing objectives necessitates a well-structured and balanced pricing policy [324].

This study thoroughly examines the effects of various pricing policies on the optimal sizing and performance of a PV-BES using a rule-based EMS, chosen for its suitability in achieving the study‘s objectives of cost minimisation and increased self-consumption, while balancing the needs of both DSOs and consumers. This work provides a detailed comparison of pricing policies, highlighting their strengths and shortcomings. Additionally, the research investigates the impact of pricing structures on the lifecycle of BES. Specifically, unsuitable charging and discharging price limits can accelerate BES degradation, leading to higher replacement costs and reducing overall economic viability. Furthermore, this study explores the potential for subsidising BES to offset its high initial investment and replacement costs, integrating subsidies or financial incentives into the optimisation process. To achieve these objectives, a rule-based EMS is combined with an optimisation approach to solve a multi-objective problem. GA is applied to this optimisation problem due to its flexibility in handling multi-objective optimisation and adaptability to nonlinear and complex constraints, making it particularly effective in scenarios with multiple conflicting objectives [342].

This study addresses the question: "How will different pricing policies impact the techno-economic potential of PV-BES in the Netherlands?" To achieve this, the research analyses the optimal size and performance of EMSs within a designated smart microgrid under various policy scenarios. The primary focus is minimising the microgrid's annual net payment requirements and decreasing network utilisation. In comparison to prior research, this study provides the following contributions:

1. A multi-objective optimisation using a GA is conducted and integrated into a rule-based EMS to determine the optimal PV-BES sizing and BES charging/discharging patterns, aiming to minimise system costs and network utilisation by applying real-world data from the Netherlands to the assumed smart microgrid.

2. The designed integrated optimisation with a rule-based EMS is applied to the assumed pricing scenarios, and a comparative analysis is presented.

3. The impact of charging/discharging cycles on BES degradation is assessed by estimating the system's lifespan under each pricing scenario. Additionally, price constraints are incorporated into the optimisation to identify optimal pricing strategies that prevent excessive BES usage, thereby mitigating degradation and extending system longevity.

4. A sensitivity analysis is conducted to investigate the effects of variations in load demand, BES pricing, and electricity prices on each pricing scenario. Furthermore, a cash flow analysis is performed, accounting for both initial and replacement costs across all pricing scenarios.

5. An analysis is presented on the implications of future pricing policies for the efficient integration of BES, accompanied by recommendations for improved regulations.

The chapter is structured as follows: Section 4.2 defines the experimental system and the research scope and provides an overview of the real-world parameters associated with the case study. Section 4.3 presents the EMS and control strategy. Following this, Section 4.4 outlines the optimisation model. In Section 4.5, techno-economic findings are elaborated. Section 4.6 discusses the implications of various pricing scenarios. Finally, the general conclusion and policy implications are presented in Section 4.7.

4.2. System configuration and economic parameters

The focus of the study is a smart microgrid in a residential area in a given city in the Netherlands, given the significant increase in solar PV adoption in the country and the government's ongoing experiments with alternative energy pricing strategies [234]. Evaluating the implications of these pricing changes is vital, as similar techno-economic shifts are likely to occur in countries with comparable socio-technical characteristics [324]. Fig. 4.1 illustrates the assumed smart microgrid case study, consisting of a residential building with 20 households that share a single integrated PV-BES system for generation and storage. This assumption is based on the definition of a smart microgrid provided in [349] as "an intelligent electricity distribution system that interconnects loads, distributed energy resources, and storage within clearly defined electrical boundaries to

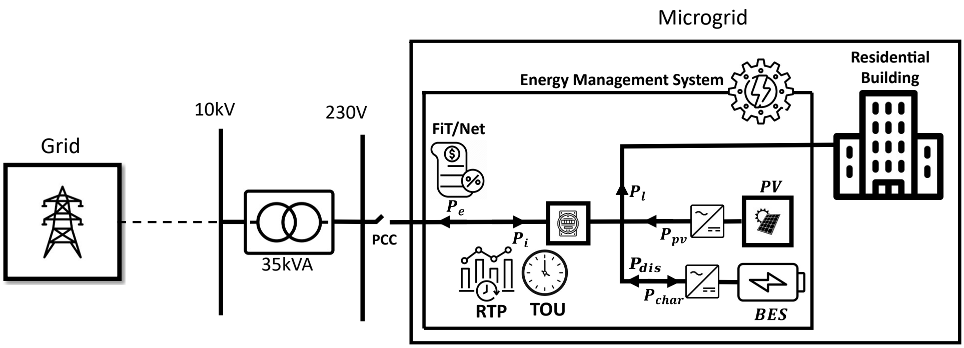


Figure 4.1: Smart microgrid architecture incorporating PV-BES system.

act as a single controllable entity with respect to the main grid" [12]. Smart microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and island modes.' In this setup, the electricity generated from PV primarily addresses the aggregated load. Any surplus PV generation can be sold back to the grid or stored in the BES. If the PV generation and battery discharging are insufficient to meet the demand, electricity must be purchased from the grid. The assumed system aims to be economically viable.

The EMS of the smart microgrid should ensure a balanced electrical energy while minimising operational costs. Optimal performance relies on pricing signals, real-time PV generation, load profiles, and the BES State of Charge (SOC) [350]. As BES lifetime is affected by charging/discharging cycles, the EMS should be designed to reduce BES replacement costs and enhance self-consumption. This is particularly crucial when analysing future regulatory scenarios, as the number of cycles can vary based on pricing signals [351].

4.2.1. PRICING POLICIES

Regulatory frameworks and business models should be considered when analysing the performance of PV-BES. Various settings can be assumed regarding the business model, including the location of BES, ownership and operation, value proposition, channels for selling the BES value based on the market environment, technology, and related costs of the BES [352].

This study assumes that end-users own the BES, which is installed behind the meter. Consequently, end-users cannot participate in the wholesale electricity market. Their revenue stream is generated through bilateral contracts with energy suppliers, who can participate in the wholesale market based on the products they wish to buy from end-users.

Various electricity pricing scenarios for the assumed smart microgrid can be considered in relation to the regulatory framework. The Dutch government plans to phase out the current net-metering policy starting in 2025 [353]. This decision is driven by the significant growth in installed PV capacity, which reached 6,900 MW by the end of

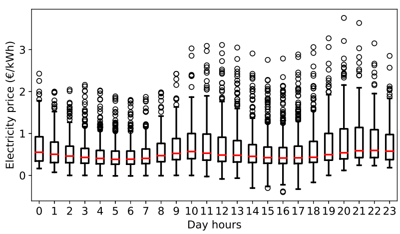
2019, marking a 51% increase [354]. This significant growth substantially threatens grid congestion [355]. The congestion issue is particularly severe in areas where the existing network capacity is insufficient. For instance, in the northern regions of the Netherlands, at certain points in time, the network capacity reaches its maximum [356]. Moreover, excessive export of PV power can lead to voltage regulation problems. These issues may cause frequent tripping of protective devices (e.g., voltage regulating devices), which reduces the lifespan of these devices. In addition, problems related to power quality, grid reliability, stability, and network protection have been widely reported [357, 358]. Currently, the net-metering system in the Netherlands calculates the annual difference between electricity consumption and generation, disregarding the time of consumption and generation. This undermines the Time-Of-Use (TOU) pricing scheme, differentiating price rates for peak and off-peak periods [352]. The Dutch government has outlined steps to transition to a feed-in tariff (FiT) scheme. Until 2025, end-users can sell back the energy produced from their PV systems at the same price. Starting in 2025, the allowable percentage for net metering will gradually be reduced, with complete elimination by 2031 [353]. The following factors are considered when defining regulatory scenarios in this study. By implementing a FiT policy instead of net metering, consumers lose the ability to sell excess energy at the purchasing price [234]. Additionally, the TOU scheme does not accurately reflect the true cost of electricity [359]. Hence, hourly adjustments of electricity prices based on actual costs could more effectively promote self-consumption among end-users and encourage BES adoption [360]. Finally, while supportive schemes for developing BES in the Netherlands exist, such as grants and funding for demonstration and R&D projects (e.g., [361]), no specific subsidies are available for residential customers [362]. Given the existing regulatory conditions, this study assumes four possible scenarios. Table 4.1 explains these policy scenarios. The first scenario is smart metering, which accounts for consumption and production times, addressing the current TOU's lack of incentives for self-consumption, which can enhance grid capacity and local power quality [363]. In the second scenario, net metering is fully phased out, but end-users with PV receive financial compensation for electricity supplied, assumed at 0.1 €/kWh for this study [364]. The third scenario considers dynamic pricing, anticipated for future implementation [365]. In this scenario, electricity prices can fluctuate hourly based on the wholesale market, enabling electricity users to manage their power consumption more flexibly and economically. Therefore, this scenario can be considered as real-time pricing (RTP), where the prices for upcoming hours are communicated to end-users in advance [366]. The final scenario combines the third scenario with BES subsidies to explore the necessity of such schemes for BES adoption [367].

Table 4.1: Overview of regulatory scenarios for the techno-economical analysis.

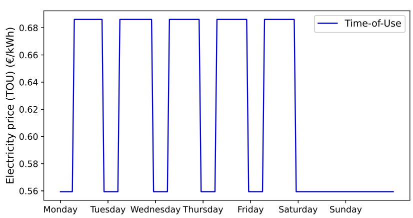
Scenario	Name	Explanation
A	Net metering	Under the net metering policy, customers can reduce their electricity costs by exporting surplus energy generated from their PV systems to the grid, with the exported energy credited against their grid consumption to lower their overall electricity bill [368]. This study extends the analysis by considering not only the net metering scheme but also the timing of energy production and consumption, which influences the financial and operational effectiveness of the system.
B	FiT with TOU	Under the FiT policy, consumers can export surplus electricity generated from PV systems to the grid and receive compensation from their energy supplier. The compensation rate is typically predetermined and guaranteed for a specific duration [234]. This study assumes the abolition of net metering in 2021, with prosumers compensated at 0.10 €/kWh for surplus power fed back into the grid, and consumption prices based on TOU rates.
C	RTP	Under RTP, consumers are invoiced or compensated based on hourly day-ahead prices, which are typically published 24 hours in advance. This dynamic pricing model aligns retail electricity rates with wholesale market fluctuations, encouraging consumers to adjust their energy usage in response to price signals. [324].
D	Subsidised BES	Due to high investment costs, BES is currently not profitable [369]. Therefore, a scenario is considered to implement a 30% investment subsidy for BES combined with RTP.

4

4.2.2. ECONOMIC PARAMETERS



(a) Box plot of dynamic pricing.



(b) TOU pricing for weekdays and weekends.

Figure 4.2: Real-time and Time-of-use electricity prices.

In the Netherlands, energy suppliers offer varying prices for dynamic pricing and TOU schemes [370]. Fig. 4.2a presents a box plot of hourly dynamic pricing for 2021, with an average value of 0.62 €/kWh used to ensure consistent comparisons with TOU. Dynamic pricing data, sourced from [371], may include negative values during periods of high renewable energy generation. As shown in Fig. 4.2b, TOU pricing exhibits higher electricity prices during peak hours (7:00 to 23:00), while lower prices are applied during off-peak hours and weekends. Table 4.2 details the pricing signals and other economic parameters used in the analysis.

Table 4.2: PV-BES economic parameters

	Details	Value
PV module [372] [373]	Capital & mounting costs	400 €/kWp
	Maintenance cost	40 €/kW/year
BES [374] [375]	Capital cost	700 €/kWh
	BES inverter cost	75 €/kWh
	Replacement cost	400 €/kWh
	Operation & maintenance costs	0.5% of capital cost/year
Electricity rates and financing [376] [377]	TOU (average)	0.62 €/kWh
	TOU (peak)	0.69 €/kWh
	TOU (off-peak)	0.56 €/kWh
	Dynamic pricing (average)	0.62 €/kWh
	Dynamic pricing (max)	3.75 €/kWh
	Dynamic pricing (min)	-0.4 €/kWh
	FiT	0.2 €/kWh
	Annual interest rate	2.8%
	Project lifetime	20 years

4.2.3. Load profile

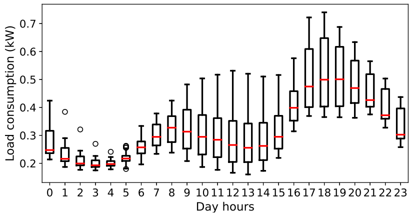
The electricity load profile for an assumed smart microgrid with a sizable residential building in Delft, Netherlands, is derived from [378]. Fig. 4.3a illustrates the daily load consumption of 20 households throughout the year. The peak power is 14.8 kW, with an average load consumption of 6.62 kW. The daily mean energy consumption is 158.88 kWh, resulting in an annual energy consumption of 57,999.97 kWh.

4.2.4. PV profile simulation

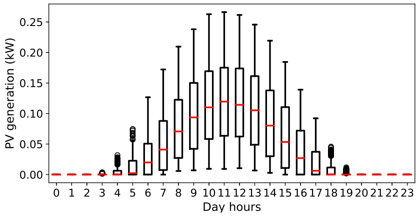
To estimate the annual PV profile, hourly data was retrieved from [379]. In 2021, the ambient temperature in Delft ($T^{amb}(t)$) was 10.02 °C, and the daily average solar insolation was 2.95 kWh/m^2/day. Using this data, a mathematical model was deployed to generate the power output of a given PV module (P_{pv}) as described in [380].

$$P_{pv}(t) = N_{pv} \times P^{r}_{pv}(G(t)/G^{ref})[1 + T^{cof}(T^{c}(t) - T^{ref})] \tag{4.1}$$

$$T^{c}(t) = T^{amb}(t) + ((T^{noct} - 20)/800 \times G(t)) \tag{4.2}$$



a: Load box plot for the residential building.



b: PV generation box plot for a single PV module.

Figure 4.3: Daily load and PV generation in the assumed smart microgrid for 2021.

In Eq. (4.1), N_{pv} denotes the total number of PV modules used in the building, while P^{r}_{pv} represents the rated power output. Solar insolation is denoted by G and expressed in (W/m^2). The solar insolation reference, G^{ref}, has a value of 1000 (W/m^2). For this study, the temperature coefficient T^{cof} is given a value of -3.8×10^{-3} $(1/°C)$. T^{ref} represents the standard temperature for solar cells, set at 25 °C [381].

In Eq. (4.2), T^{c} is a function of ambient temperature (T^{amb}), solar insolation, and nominal operating cell temperature (T^{noct}). To simulate PV power output, The IM72CB-330 photovoltaic module was selected for this study due to its affordability and suitability for home application [372]. This module comprises 72 multi-crystalline solar cells connected in series, generating a maximum power of 330 Wp. The daily average electricity generation from a single IM72CB-330 module is 0.96 kWh. Fig. 4.3b illustrates the daily PV generation in Delft city for the assumed smart microgrid.

4.3. ENERGY MANAGEMENT SYSTEM

The proposed smart microgrid in Fig. 4.1 aims to maximise economic and technical benefits. An Energy Management System (EMS) combined with an optimisation method is proposed to meet system requirements. Power can be sold to or purchased from the grid based on PV generation $P_v(t)$ and load power $P_l(t)$. When $P_v(t)$ exceeds $P_l(t)$, the BES will be charged at the rate of $P_{char}(t)$ within SOC limit, and any excess power will be sold to the grid. However, the export power is limited by the grid's maximum export capacity $P_{e,max}$. Conversely, the BES will be discharged at the rate of $P_{dis}(t)$ within the SOC limit if PV generation is less than load power. If a power deficit persists, additional power will be imported from the grid. In addition, pricing conditions are incorporated through the use of $X1$ and $X2$ price limit values to ensure the economic feasibility of charging and discharging the BES. These variables are outlined in Section 4.4.3. The export power $P_e(t)$ and import power $P_i(t)$ can be calculated using Eqs. (4.3) and (4.4).

$$P_e(t) = \begin{cases} \min\{P_{e,\max}, P_{pv}(t) - P_l(t) - P_{char}(t)\} & \text{if } P_{pv}(t) \geq P_l(t) \\ & \quad \text{and } P_{pv}(t) - P_l(t) \geq P_{b,\text{in}}(t) \\ & \quad \text{and Price}(t) \geq X_2 \\ 0 & \text{otherwise} \end{cases} \tag{4.3}$$

$$P_i(t) = \begin{cases} P_l(t) - P_{pv}(t) - P_{dis}(t) & \text{if } P_l(t) \geq P_{pv}(t) \\ & \quad \text{and } P_l(t) - P_{pv}(t) \geq P_{b,\text{out}}(t) \\ & \quad \text{and Price}(t) \leq X_1 \\ 0 & \text{otherwise} \end{cases} \tag{4.4}$$

The available output power $P_{b,out}$ and input power $P_{b,in}$ of the BES for each timestep Δt can be calculated using Eq. (4.5) and (4.6). Here, $P_{b,max}$ represents the maximum allowable power of BES and C_{bat} denotes the BES capacity [382].

$$P_{b,out}(t) = \min\{P_{b,max}, (C_{bat}/\Delta t) \cdot (SOC(t) - SOC_{\min})\} \tag{4.5}$$

$$P_{b,in}(t) = \min\{P_{b,max}, (C_{bat}/\Delta t) \cdot (SOC_{\max} - SOC(t))\} \tag{4.6}$$

The SOC of the battery in each hour is calculated using Eq. (4.7).

$$SOC(t+1) = SOC(t) + \frac{P_{char}(t) \cdot \eta_{char} - P_{dis}(t)/\eta_{dis}}{C_{bat}/\Delta t} \tag{4.7}$$

Where the efficiencies of the charging and discharging processes are denoted by η_{char} and η_{dis}, respectively [383].

4.4. OPTIMISATION PROCESS

This study employs a multi-objective genetic algorithm, an evolutionary algorithm based on the principle of survival of the fittest [384]. The optimisation model aims to minimise the net present cost (NPC) and maximise self-consumption. Fig. 4.4 illustrates the optimisation process, where the proposed EMS integrates with the algorithm to determine the optimal size of the PV-BES in different regulatory scenarios. To ensure an optimal global solution, the population size is set to 200 and the number of generations to 500. The mutation rate is 0.1, with a tournament size of 3 for selection and a simple average method used for crossover [345].

4.4.1. OBJECTIVE FUNCTION

The goal of optimisation is to minimise the net present cost (NPC) of the smart microgrid, which includes the NPC of electricity cost (NPC_e) and the NPC of all components, represented as the sum of the NPC of each component ($\sum_j NPC_{\text{c}_\text{j}}$). Additionally, import from and imports to the grid should be minimised to maximise self-consumption. Therefore, the objective function, denoted by J, is calculated as

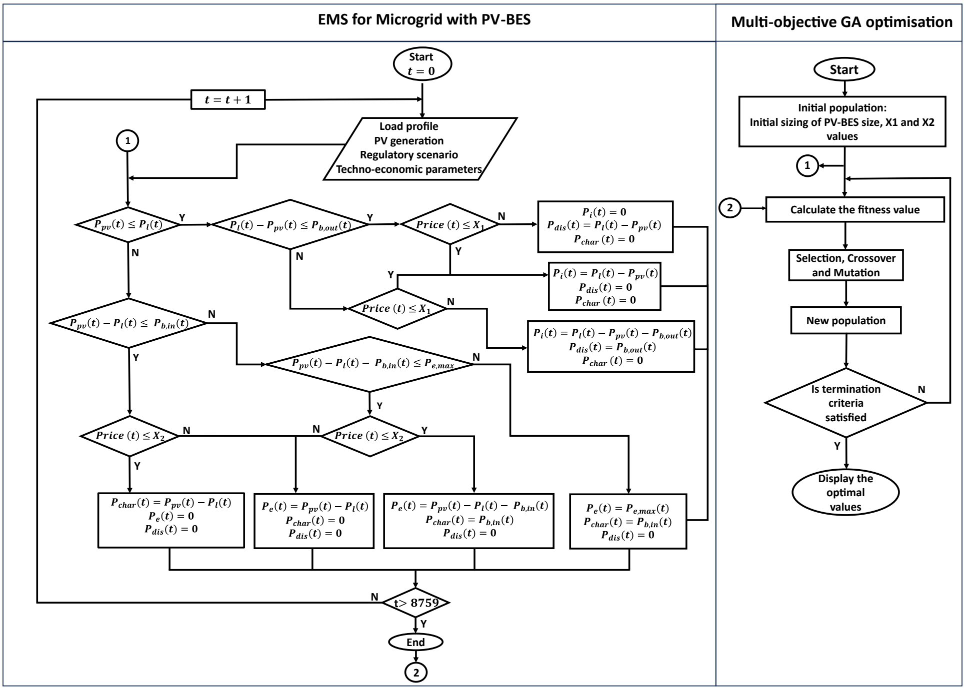


Figure 4.4: Integrated EMS-optimisation model.

$$J = \min \sum_{t=0}^{8759} \left(NPC_e(t) + \sum_j NPC_{c_j}(t) \right) + \min \sum_{t=0}^{8759} (P_i(t) + P_e(t)) \tag{4.8}$$

The system's NPC_e is calculated by

$$NPC_e(t) = C_e(t).\frac{(1+i)^y - 1}{i(1+i)^y} \tag{4.9}$$

where i denotes the interest rate and y represents the project lifetime in years [385], while $C_e(t)$ is the annual cost of electricity, calculated using Eq. (4.10).

$$C_e(t) = \sum_{t=0}^{8759} B(t).P_i(t).\Delta t - \sum_{t=0}^{8759} S(t).P_e(t).\Delta t \tag{4.10}$$

where $B(t)$ and $S(t)$ represent the buying and selling price at each timestep [386]. The NPC_{c_j} encompasses capital costs, maintenance expenses, and replacement costs of components as [387]

$$NPC_{c_j}(t) = NPC_{cap_j} + NPC_{m_j}(t) + NPC_{r_j}(t) \tag{4.11}$$

where the subscript j represents each component. The subscripts cap, m, and r denote capital, maintenance, and replacement costs, respectively [385]. The maintenance cost of a component during the lifetime of the system is calculated by

$$NPC_{m_j} = Cm_j.\frac{(1+i)^{(M_j)}-1}{i(1+i)^{(M_j)}} \tag{4.12}$$

where Cm_j is annual maintenance cost of the component j ,and M_j denotes the lifetime of the component j in years [388].

The replacement costs of a component over the system's lifetime is calculated as [389]

$$NPC_{r_j} = C_{r_j}.\sum_{t=0}^{N_j}\frac{1}{(1+i)^{t.M_j}} \tag{4.13}$$

4

where C_{r_j} denotes the replacement cost of component j, and N_j represents the number of times component j is replaced over the system's lifetime , calculated as [351]

$$N_j = \left\lfloor \frac{y}{M_j} \right\rfloor \tag{4.14}$$

4.4.2. BES lifetime

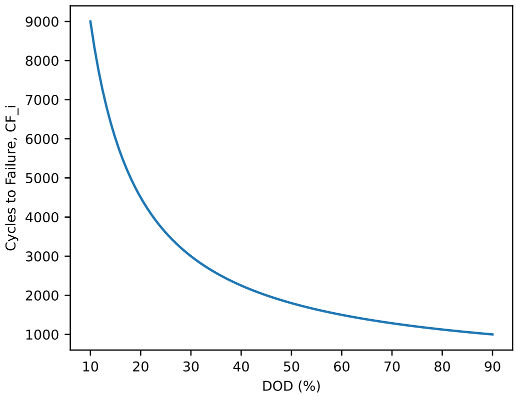


Figure 4.5: Cycles to failure vs. DOD for a typical battery.

The replacement cost for PV-BES systems is primarily influenced by the BES lifetime. The lifetime of the BES is indirectly determined since it depends on the number of charging cycles, which vary based on the BES application and the designed EMS [390]. Although factors such as operational temperature and corrosion are included in battery aging models, the most significant factor is degradation due to the energy cycle [391].

This study applies the cycle counting method to estimate the battery's lifetime. This method counts the number of charging cycles N_i per year. The cycle numbers are calculated based on the SOC data for the entire year [392]. Additionally, each cycle's Depth of Discharge (DOD) is tracked, ranging from 10% to 90%. Based on the DOD range, the corresponding Cycles to Failure (CFi) can be determined using the CFi vs.

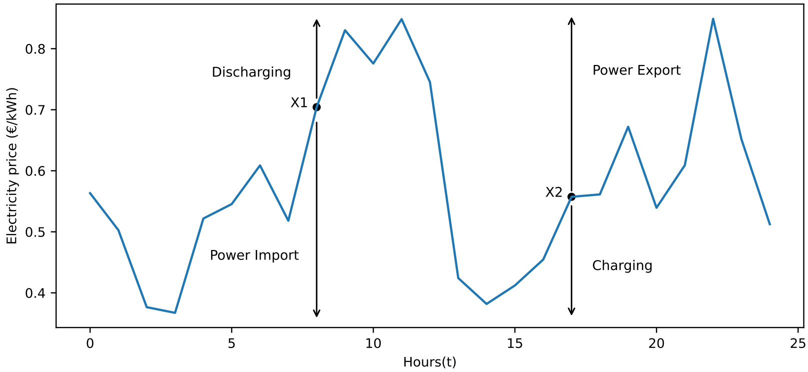


Figure 4.6: Exemplifying the application of X_1 andX_2 price limits on a daily basis

DOD curve provided by the battery manufacturer [393]. Fig. 4.5 illustrates a typical battery's CFi vs. DOD relationship. The battery duration is calculated using Eq. (4.15) when the DOD is divided into m ranges [351].

$$Life_{BES} = \sum_{t=i}^{m} \frac{N_i}{CF_i} \tag{4.15}$$

4.4.3. CHARGING AND DISCHARGING PRICE LIMITS

Given the significant impact of the battery's capital and replacement costs on the NPC, it is crucial to consider the effect of pricing on BES aging under various scenarios. Therefore, the optimisation process incorporates the sizing and optimal timing for charging and discharging the BES. To optimise BES operation, the limits X_1 and X_2 are introduced into the EMS, representing the charging price limit and discharging price limit, respectively. Fig. 4.6 illustrates these limits.

In dynamic pricing scenarios, electricity prices change hourly, leading to multiple charging cycles and a reduced battery lifetime [394]. To mitigate this, the charging and discharging price limits are set to balance the reduction in annual charging cycles while maximising arbitrage benefits. The charging price limit (X_1) determines that discharging is preferred when prices exceed this threshold, while power is imported from the grid when prices fall below it. Conversely, the discharging price limit (X_2) suggests that charging is economically advantageous when prices fall below this threshold, and exporting power to the grid is preferred when prices exceed it.

4.4.4. SYSTEM CONSTRAINTS

The objective function in Eq. (4.8) is subject to the following constraints [395].

$$P_{pv}(t) + P_{dis}(t) - P_{char}(t) - P_e(t) + P_i(t) = P_l(t) \tag{4.16}$$

$$0 \leq P_e(t) \leq P_{e,max} \tag{4.17}$$

$$0 \leq P_{pv}(t) \leq P_{pv,max} \tag{4.18}$$

$$0 \leq P_{cha}(t) \leq P_{cha,max} \tag{4.19}$$

$$-P_{dis,max} \leq P_{dis}(t) \leq 0 \tag{4.20}$$

$$SOC_{min} \leq SOC \leq SOC_{max} \tag{4.21}$$

$$Price_{min} \leq X_1, X_2 \leq Price_{max} \tag{4.22}$$

The power balance constraint is expressed in Eq. (4.16), and (4.17) is the constraint of the exported power to the grid. Output power constraints of the PV-BES system are represented in Eq. (4.18), (4.19), and (4.20). Eq. (4.21) shows the SOC constraint of the BES. Eq. (4.22) presents the X_1 and X_2 price limits for charging and discharging.

4.4.5. Evaluation criteria

Considering the optimisation goals, the levelised cost of electricity (LCOE) and payback period (PBP) can be used as metrics to measure end-user benefits [396]. The LCOE is calculated as the system's net present cost (NPC) divided by the total annual energy consumed over the project's lifetime [397].

$$LCOE = \frac{NPC}{\left(\sum_{t=0}^{8759} P_l(t)\right) \cdot y} \tag{4.23}$$

The PBP metric indicates the time required to recover the initial investment and is calculated by dividing the initial investment cost by the annual cash flow [398].

$$PBP = \frac{I}{CF_t} \tag{4.24}$$

In Eq. (4.24), I is the initial investment. The CF_t represents the cash flow for the year t. It is defined as the difference between the energy savings resulting from the PV-BES and the associated maintenance and replacement costs as [398]

$$CF_t = C_{e,without,t} - C_{e,t} - C_{m\&r,t} \tag{4.25}$$

Where $C_{e,\text{without}}$ and C_e denote the electricity costs incurred without and with the PV-BES system, respectively. The $C_{m\&r}$ represents the maintenance and replacement costs associated with the PV-BES system.

The final metric, the self-consumption rate (SCR), is crucial for reflecting the system operator's benefit and can be calculated annually as [399]

$$SCR = \sum_{t=0}^{8759} \frac{(P_{dis}(t) + P_{pv,dir}(t)).\eta_{dis}}{P_{pv}(t)} \tag{4.26}$$

Eq. (4.26) implies that the Self-Consumption Ratio (SCR) represents the ratio of energy generated by the PV-BES system and consumed directly or indirectly within the smart microgrid to the annual energy produced by the PV system. Therefore, $P_{pv,dir}(t)$ denotes the PV generation utilised directly within the smart microgrid, excluding any energy exported to the grid or used for charging the BES.

4.5. RESULTS

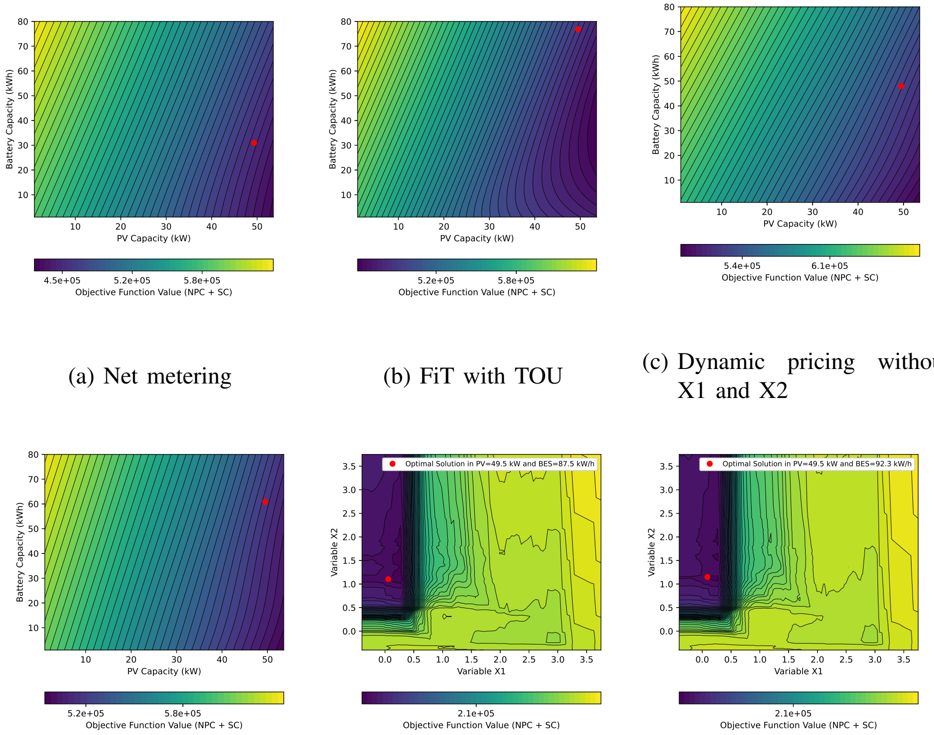
Table 4.3: Optimisation results for PV-BES system in the assumed smart microgrid.

Scenario	PV (kWp)	BES (kWh)	X_1 (€)	X_2 (€)	$Life_{BES}$ (year)	LCOE (€/kWh)	PBP (year)	SCR (%)
Net metering	49.5	30.9	-	-	7.5	0.12	2.8	36
FiT with TOU	49.5	76.8	-	-	8.5	0.41	3.6	62
Dynamic pricing without X_1 and X_2 price limits	49.5	49.6	-	-	5.2	0.36	3.5	57
Subsidised BES without X_1 and X_2 price limits	49.5	61.3	-	-	5.5	0.29	3.4	58
Dynamic pricing with X_1 and X_2 price limits	49.5	87.5	1.21	0.23	9.3	0.38	5.3	71
Subsidised BES with X_1 and X_2 price limits	49.5	92.3	1.22	0.24	10.5	0.34	4.1	72

The optimisation results for the proposed EMS under the considered scenarios are summarised in Table 4.3. To evaluate the effectiveness of the proposed X_1 and X_2 price limits, the analysis includes results without these limitis for both the dynamic pricing and subsidised BES scenarios. Fig. 4.10a-4.7d illustrate the variation in the objective function relative to the size of the PV-BES. Fig. 4.7e-4.7f depict the changes in the objective function concerning variations in X_1 and X_2. The available roof space can accommodate up to 150 PV modules, resulting in a PV production capacity of 49.5 kWp across all scenarios. This makes further PV adoption economically viable. The results show that net metering offers a lower LCOE of 0.12 €/kWh and a shorter PBP of 2.8 years, with a relatively small BES size of 30.9 kWh. However, this scenario also yields a lower SCR of 36%. Conversely, the FiT with TOU scenario necessitates a larger BES size of 76.8 kWh and results in a higher LCOE of 0.41 €/kWh and a longer PBP of 3.6 years, yet achieves a considerably higher SCR of 62%.

Regarding the optimal BES size, previous studies have indicated that when only NPC optimisation is considered, net metering results in an optimal BES size of zero, as the grid effectively acts as a cost-free form of storage [333]. However, minimisation of grid utilisation in Eq. (4.8) leads to non-zero BES values for the policy scenarios. For comparison purposes across different policy scenarios, it is assumed that 1 kWh of grid utilisation is equivalent to 1 € in Eq. (4.8). However, different weighting factors can be applied to reflect various trade-offs between NPC and SCR in the objective function, depending on the specific system settings. The results indicate moderate BES sizes and SCR values for scenarios involving dynamic pricing and subsidised BES without X_1 and X_2 price limits. The dynamic pricing scenario without X_1 and X_2 price limits shows a BES size of 49.6 kWh, a LCOE of 0.36 €/kWh, and a PBP of 3.5 years, with an SCR of 57%. The subsidised BES scenario without X_1 and X_2 price limits improves slightly with a BES size of 61.3 kWh, a LCOE of 0.29 €/kWh, and a PBP of 3.4 years, achieving an SCR of 58%.

In scenarios incorporating X_1 and X_2 price limits, dynamic pricing and subsidised BES show substantial improvements in SCR, reaching 71% and 72%, respectively. These scenarios require the largest BES sizes of 87.5 kWh and 92.3 kWh, respectively, and demonstrate extended battery lifetimes of up to 10.5 years. The higher initial investment is reflected in higher LCOE values (0.38 €/kWh for dynamic pricing with X_1 and X_2 and 0.34 €/kWh for subsidised BES with X_1 and X_2), along with longer PBPs of 5.3 and 4.1 years, respectively.



(a) Net metering

(b) FiT with TOU

(c) Dynamic pricing without X1 and X2

(d) Subsidised BES without X1 and X2

(e) Dynamic pricing with X1 and X2

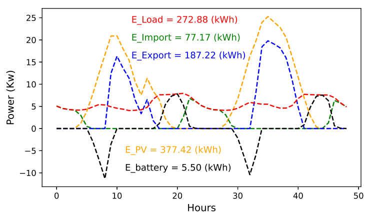
(f) Subsidised BES with X1 and X2

Figure 4.7: Objective function values for each scenario. The red dots indicate the optimal solutions.

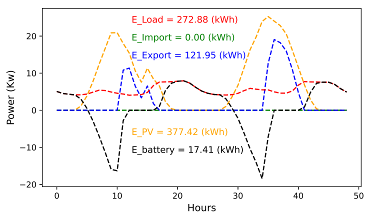
4.5.1. DAILY POWER FLOW

Power flow analysis provides valuable insights into system performance across different scenarios. Fig. 4.8 presents the power flow for each scenario over two consecutive days in April, selected for their temperature and solar irradiation values closely matching the annual average[1]. The power flow patterns in the subsidising scenarios resemble those in the dynamic pricing scenario. Therefore, only the dynamic pricing scenarios are depicted, with and without the X_1 and X_2 price limits.

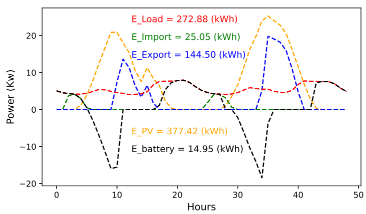
In the net metering scenario (Fig. 4.8a), the system exports a significant amount of generated energy (187.22 kWh) to the grid and imports 77.17 kWh, highlighting a low SCR despite high PV generation of 377.42 kWh. The BES's contribution is minimal, discharging only 5.50 kWh. Conversely, the system achieves zero import from the grid in the FiT with the TOU scenario (Fig. 4.8b), and BES discharges 17.41 kWh to meet the load demand of 272.88 kWh. This scenario also shows reduced power exports (121.95 kWh), reflecting a higher SCR. Comparing the dynamic pricing scenarios without and with X_1 and X_2 price limits (Fig. 4.8c - Fig. 4.8d), it is evident that the introduction of price limits reduces the exported energy from 144.5 kWh to 128.84 kWh. Notably, this reduction is achieved while maintaining the same discharging energy from the BES at 14.95 kWh.



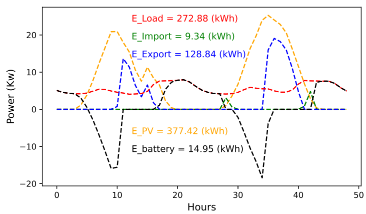
(a) Net metering



(b) FiT with TOU



(c) Dynamic pricing without X_1 and X_2 price limits



(d) Dynamic pricing with X_1 and X_2 price limits

Figure 4.8: Power flow for the considered scenarios in two consecutive days in April 2021.

[1]The full-year power flow illustration is visually complex and difficult to interpret. Interested readers are encouraged to contact the authors for access to the complete power flow dataset. Furthermore, the yearly energy values are presented in Table 4.4 in the discussion section.

4.5.2. Annual cash flow

The cash flow analysis of end-users in smart microgrid provides a detailed overview of the annual payments throughout the project's lifetime, taking into account the interest rate and replacement costs of system components [400]. Fig. 4.9 presents a comparative cash flow analysis for the considered scenarios over a 20-year period. The total benefit for each scenario is determined by summing the annual benefits. Under the net metering scenario, the BES is expected to be replaced up to three times, resulting in an overall revenue of 853,354.6 €. In contrast, despite having lower replacement costs, the FiT and TOU scenario incurs higher energy costs for end-users. Consequently, this scenario yields the lowest total benefit, amounting to 506,187.87 €.

Under the dynamic pricing scenario without X_1 and X_2 price limits, the BES requires replacement every 5 years, resulting in substantial costs and consequently yielding a low total benefit of 558,899.25 €. Introducing a subsidy to the dynamic pricing scenario increases the total benefit to 571,814.86 €. When X_1 and X_2 price limits are incorporated into the dynamic pricing and subsidised BES scenarios, the total benefits rise to 643,552.43 € and 647,185.07 €, respectively.

4

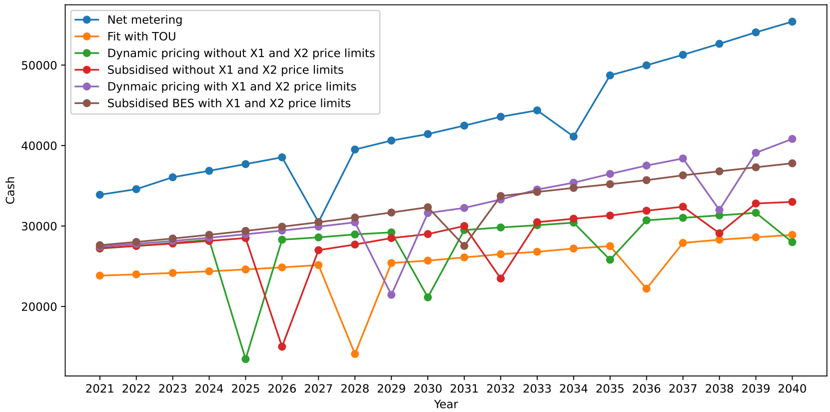
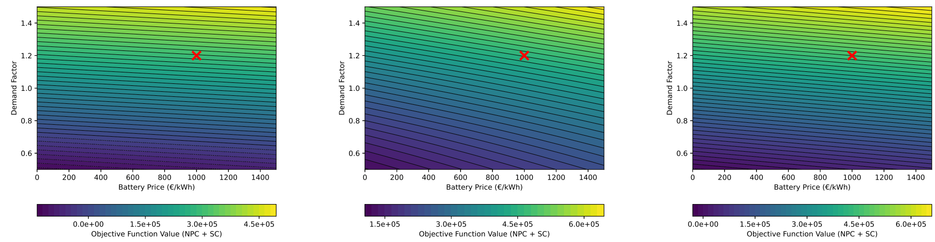


Figure 4.9: Cash flow comparison among scenarios over the project lifetime.

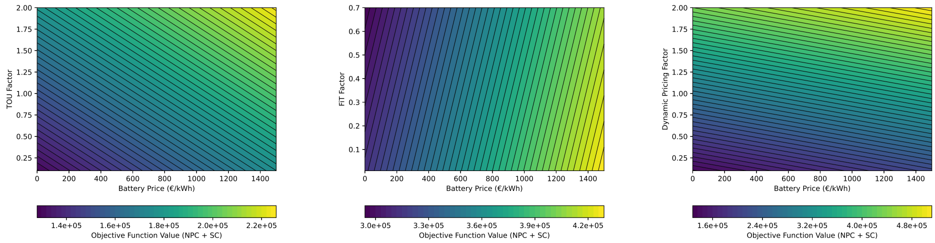
4.5.3. Sensitivity analysis

The sensitivity analysis presented in Fig. 4.10 highlights the impact of BES price, demand changes, and electricity price change on the objective function value across the scenarios. The subsidised scenario is not illustrated due to its similar results to the dynamic pricing scenario. To discuss the sensitivity of scenarios with changing BES price and electricity demand, a point is specified with a red cross where the battery price is 1000 €/kWh, and the demand factor is 1.2. The FiT with TOU scenario (Fig. 4.10b) exhibits the highest objective function value at this point, approximately 4.54×10^5, indicating significant sensitivity to parameter changes and sharp steps in the contour lines. Net metering (Fig. 4.10a) shows a more horizontal contour pattern, suggesting greater sensitivity to battery price than to demand factor, with an objective function value of around 2.96×10^5. Dynamic pricing (Fig. 4.10c) is similarly more sensitive to battery price, with an objective function value of 4.51×10^5 at the specified point, considerably higher than the net metering scenario.

In addition, the sensitivity of scenarios concerning the impact of electricity price changes and battery price changes on the objective function is considered. Fig. 4.10d shows a relatively uniform spacing of the contour lines, indicating a consistent rate of increase in the objective function value concerning both parameters. Fig. 4.10e reveals that the objective function decreases as the FiT factor increases. Fig. 4.10f demonstrates that the objective function is less sensitive to price changes in dynamic pricing, suggesting more stability in this scenario.



(a) Net metering (b) FiT with TOU (c) Dynamic pricing



(d) Net metering (e) FiT with TOU (f) Dynamic pricing

Figure 4.10: Sensitivity analysis for different scenarios. (a), (b) and (c) show the effect of BES price and demand change on the objective function value. (d), (e) and (f) show the effect of BES price and electricity price changes on the objective function value.

4.6. Discussion

Tables 4.4 and 4.5 summarise the quantitative and qualitative comparisons of the policy scenarios. The energy values represent annual totals, while the revenue is presented as an average over the duration of the project. The following points are discussed to evaluate the impact of each policy scenario on the techno-economic performance of PV-BES systems in the Netherlands.

Table 4.4: Quantitative comparison of pricing policy scenarios, with $P_l = 57999.98$ kWh and $P_{pv} = 52782.81$ kWh fixed for all scenarios.

Scenario	P_i (kWh)	P_e (kWh)	$P_{battery}$ (kWh)	Revenue (€/year)	Sensitivity		
					BES Price	Electricity Price	Demand
Net Metering	30500.69	26029.86	746.33	42667.73	High	Moderate	Low
FiT with TOU	22525.27	18870.33	1562.23	25309.39	High	High	High
Dynamic Pricing	26671.69	22591.24	1136.71	27944.96	High	Low	Low
Subsidised BES	24494.04	20636.03	1359.15	28590.74	-	-	-
Dynamic Pricing with X1 & X2	23434.16	1969.62	1475.62	32177.62	-	-	-
Subsidised BES with X1 & X2	23295.12	19569.4	1491.45	32359.25	-	-	-

Table 4.5: Qualitative comparison of the assumed pricing policies.

Scenario	Advantages	Disadvantages
Net metering	Financially attractive for end-users due to low LCOE and short payback period.	Leads to low self-consumption rate (SCR) and high grid congestion, which are not ideal for grid stability.
FiT with TOU	Encourages better self-consumption than net metering.	Requires higher BES capacity, increasing costs and LCOE, discouraging widespread adoption.
Dynamic pricing without X_1 and X_2	Balances costs and SCR better than FiT, offering moderate SCR and financial benefits.	Suffers from shorter BES lifetimes and higher replacement needs.
Subsidised BES without X_1 and X_2	Improves SCR slightly with subsidies reducing costs.	BES replacements are frequent, limiting long-term cost efficiency.
Dynamic pricing with X_1 and X_2	Significantly enhances SCR and BES lifetime.	Requires larger BES capacity, increasing initial investment and extending payback period.
Subsidised BES with X_1 and X_2	Optimal for SCR and BES lifetime; subsidies and control variables reduce costs and replacement frequency.	

In the net metering scenario, the results demonstrate a significant reliance on the grid for energy transactions, with the highest export values among all scenarios. This scenario benefits from a lower LCOE, a short PBP, and the maximum total revenue over the project's lifetime, making it financially attractive for end-users. However, the SCR is relatively low, leading to higher grid congestion and making it less attractive to DSOs. This result supports the current policy of the Dutch government in terminating the net metering scheme [267].

A larger BES is required in the FiT with TOU scenario, resulting in a relatively higher LCOE for end-users. This scenario achieves a higher SCR than net metering despite the increased cost. Therefore, the higher costs can discourage the wider adoption of PV-BES systems [401].

Under the dynamic pricing scenario, although SCR is slightly reduced, the LCOE and PBP are less than in the FiT with TOU scenario. The total revenue in this scenario is more than in the FiT with TOU scenario, indicating a more balanced solution for end-users and system operators. In addition, dynamic pricing offers more stable financial outcomes despite market fluctuations, making it a more viable future policy. However, the optimisation assumes perfect foresight, whereas real-world price forecasts are uncertain, affecting its effectiveness. Furthermore, introducing a subsidy scheme for dynamic pricing significantly reduces both the PBP and the LCOE, making it a more attractive and feasible option for end-users.

Analysis results show that the net metering scenario is unfavorable when realising the energy transition due to the low SCR. The alternative solutions of the FiT with TOU and dynamic pricing can potentially promote energy transition, but both scenarios require additional support to reduce LCOE for end-users. However, subsidy schemes can hardly be realised under the current regulatory framework in the Netherlands, in which BES is not defined as a renewable energy resource [352]. Therefore, any modifications to pricing policies should be supported by corresponding amendments to the regulatory framework.

In general, changing the regulatory framework is a very complex and time-consuming process [402]. The alternative solution is to focus on changing business models. Business model frameworks can be seen as interrelated components (e.g., customers, value stream, and value proposition) working together to create and deliver value [403]. For the BES case, the cost structure is a determining factor, and while the regulatory structure does not provide enough freedom to increase revenue, lowering the cost can mitigate this unfavorable regulatory condition. Therefore, incorporating the X_1 and X_2 price limits into the EMS results in postponing the replacement time of the BES and enhancing future economic benefits, as reflected in the cash flow analysis. This also leads to a larger BES capacity and an increased SCR. Although this new EMS design extends the PBP due to a larger BES, it is advantageous for microgrids and aggregated BES systems, where larger BES capacities are used. This benefit arises from the economies of scale, as the price per kWh decreases with higher BES capacities [404].

4.6.1. Limitations

The study is based on several critical assumptions that could influence the interpretation of the results. First, the EMS is assumed to be rule-based, employing predefined rules and algorithms for system components [405]. For future comparative analyses, more advanced EMSs, such as adaptive and learning-based techniques like reinforcement learning [406], can be considered. These methods can more effectively capture and respond to diverse pricing data.

Secondly, this study assumes perfect foresight in dynamic pricing scenarios, meaning future electricity prices are known in advance. While this is common in optimisation studies, real-world conditions involve uncertainties and forecasting errors, which may reduce the actual effectiveness of dynamic pricing strategies. Future research could explore integrating forecasting methods to account for real-time price variability and enhance the robustness of the approach.

Additionally, the study assumes that BES is located at the end-user's site, limiting its value to self-consumption and energy arbitrage. Future research could explore BES installations at the transmission and/or distribution levels, where it could provide additional services such as voltage and frequency regulation and investment deferral support. Future studies could also assess various BES locations within relevant regulatory frameworks and business models. Furthermore, this study examines the benefits DSOs gain from PV-BES systems and the increase in SCR. However, more precise criteria, such as investment deferral potential, could provide deeper insights into PV-BES adoption. It is also essential to consider regulatory challenges, as current regulations in the Netherlands prohibit DSOs from owning BES systems, preventing them from directly benefiting from the services these systems provide.

4.7. Conclusion and policy implications

This study employs an integrated EMS-optimisation model and applies various evaluation criteria to explore the question: "How will different pricing policies impact the techno-economic potential of PV-BES in the Netherlands?" The findings suggest that while net metering is advantageous for end-users due to its lower costs, it leads to a low SCR. In contrast, the FiT with TOU pricing policy results in a higher LCOE and SCR, making it more favorable for DSOs.

Based on the study's findings, dynamic pricing combined with subsidies proves to be a highly effective strategy. Dynamic pricing motivates end-users to adjust their energy consumption in response to real-time electricity prices, thereby promoting more efficient energy use. However, the high initial costs associated with BES installations can be a significant barrier to adoption. To overcome this, introducing subsidies to offset these upfront costs would enhance the economic attractiveness of PV-BES systems for residential users. These subsidies can be offered as direct financial incentives or tax rebates [407].

However, the provision of subsidies faces critical challenges. Current regulatory frameworks do not classify BES as a renewable energy resource, limiting the potential for subsidies and other supportive measures. Regulatory amendments should be pursued to recognise BES as part of the renewable energy ecosystem[352]. Moreover, the current Dutch electricity market design does not adequately reward the benefits provided by BES. For instance, market mechanisms fail to compensate for the critical services BES offers, such as voltage and frequency regulation. Without appropriate market incentives, the viability of BES is restricted primarily to congestion management [408]. As a result, the potential contribution of BES to broader economic and societal objectives remains uncertain to the Dutch government, leading to limited investment in BES [409].

The study highlights that larger BES installations significantly enhance self-consumption rates and overall system efficiency. Policymakers may consider implementing incentive programs tailored to encourage the deployment of larger BES capacities. Such incentives can include higher subsidy rates for larger systems. Moreover, establishing a framework for aggregated BES systems, where multiple households or communities can share a large BES, would optimise economies of scale and further lower costs per kWh [410]. Additionally, installing larger BES units can overcome a key market barrier in the Netherlands, where minimum bid requirements for participating in the electricity market cannot be met by small-scale BES systems [352].

The study results indicate that adopting advanced EMS with optimisation techniques for BES operation is crucial for maximising the benefits of PV-BES systems. Policies should encourage the use of smart EMS technologies that optimise BES charging and discharging cycles. By utilising predictive algorithms and real-time data, these EMS can dynamically adjust energy flows, reduce discharge frequency and depth, and extend BES lifespan, thereby lowering replacement costs and enhancing return on investment for consumers.

5

Reinforcement Learning for Energy Management

This chapter is based on:
F. Norouzi, A. Shekhar, T. Hoppe, P. Bauer, "Energy Management in a Residential Smart Microgrid Using Reinforcement Learning Under Different Pricing Policies", *submitted in International Journal of Electrical Power & Energy Systems*

With the growing complexity of energy systems due to the adoption of distributed energy resources, real-time pricing policies, and high variability in load demand, traditional optimisation-based energy management systems (EMS) struggle to adapt to changing conditions. To address these challenges, this chapter proposes a Reinforcement Learning-based Energy Management System (RL-EMS) for residential smart microgrids equipped with photovoltaic (PV) and energy storage systems (ESS). The RL-EMS employs a model-free approach using Deep Q-Networks (DQN) and integrates Long Short-Term Memory (LSTM) for accurate forecasting of electricity prices, loads, and PV generation, enabling dynamic optimisation of energy arbitrage and self-consumption under diverse operational and policy scenarios.

The performance of the RL-EMS is compared against a Genetic Algorithm (GA)-based EMS, demonstrating superior financial outcomes for the RL model while maintaining comparable Self-Consumption Ratios (SCR). The RL-EMS showcases advanced decision-making capabilities, including strategic ESS utilisation during high-price periods and adaptability to dynamic pricing conditions, even when trained under a different pricing scheme.

5.1. Introduction

The power system landscape has been significantly transformed by advancements in control technologies, digital sensors, sophisticated communication systems, and information management tools [411]. These innovations have accelerated the shift from traditional centralised power systems, reliant on centralised energy resources, to modern paradigms that integrate distributed energy resources (DER) [36]. The deployment of DERs, energy storage systems (ESSs), advanced distribution automation, and energy management systems (EMSs) in smart microgrids facilitates this transition [412]. In smart microgrids, power grid operators and consumers generate and utilise vast amounts of data [413]. However, existing control techniques and optimisation methods struggle to process the high-dimensional data generated by the grid [414]. This complexity arises from factors such as the unprecedented growth in load demand, the rapid adoption of renewable energy resources, the deployment of electric vehicles (EVs), and the increasing popularity of ESSs [415]. Therefore, the increasing volume of data requires the development of solutions capable of scaling to handle larger information flows and interactions between agents [416].

To meet the demands of the energy transition, improvements are necessary in domains such as load forecasting, system stability, and power grid security. Artificial intelligence (AI) applications are increasingly being employed to assist in system operation processes [373]. From the perspective of system operators, AI enhances renewable energy generation forecasting, supports power grid stability assessments, enables fault detection, and increases grid security [417].

From the customer's perspective, significant opportunities are emerging to pursue benefits through the adoption of innovative solutions, such as energy storage systems (ESS) combined with renewable energy resources [418]. In addition to providing technical advantages for system operators, such as peak shaving and frequency regulation, ESS empowers consumers to engage in energy arbitrage [419].

Electric power arbitrage has been further incentivised through supportive schemes, subsidies, and real-time pricing policies [420]. Furthermore, advancements in metering infrastructure and information and communication technologies (ICT) enable access to real-time data on electricity prices, demand, and generation. These developments incentivise consumers to participate in demand-side response in smart grids [421].

A major challenge in energy management systems (EMSs) lies in their incompatibility with varying objectives. Conventional EMS approaches, such as deterministic rule-based methods and abstract models like mixed-integer linear programming (MILP), often result in suboptimal solutions when input variables change [422]. Additionally, traditional EMSs lack scalability for large-scale systems with a high number of variables [423].

The incompatibility issue becomes even more critical when policy scenarios change. For instance, many countries are transitioning from time-of-use (TOU) pricing to real-time pricing (RTP) to reflect actual energy costs and facilitate the energy transition [424]. This shift poses significant challenges for consumers in adapting their energy consumption behaviours. Similarly, system operators struggle to forecast the long-term effects on consumption patterns and electricity prices, leading to inaccuracies in key input data, such as price, load, and generation forecasts. These inaccuracies directly affect the benefits of both consumers and system operators [425]. Therefore, in the design of an EMS, its scalability in terms of replication across different contexts, such as varying legal and policy settings, should be considered [426].

To address these challenges, EMS strategies must be upgraded by incorporating advanced forecasting techniques to enhance adaptability and accuracy [427]. Recent efforts have increasingly focused on energy scheduling through the design of EMSs aimed at maximising system efficiency and optimising the dispatch of renewable energy resources [428].

EMS design approaches are broadly classified into three categories: rule-based, optimisation-based, and model-free strategies [429]. Model-free methods rely on data about the system's current condition to make decisions dynamically [430]. In contrast, rule-based and optimisation-based methods typically rely on predefined algorithms or structured optimisation frameworks. For instance, in [431], a rule-based EMS was modeled as a mixed-integer linear programming (MILP) optimisation problem to schedule power flows within a microgrid comprising electric vehicles (EVs), controllable loads, and energy storage systems (ESSs). Similarly, an EMS designed using particle swarm optimisation was proposed in [432] to operate in both grid-connected and autonomous modes.

Other studies have considered additional objectives in EMS design. For example, [433] and [434] explored EMS frameworks that optimise fuel costs while meeting thermal comfort requirements in microgrids. These varied approaches underscore the evolving nature of EMS design and are developed to address specific operational challenges and objectives.

In contrast to model-based and optimisation- based EMSs, model-free EMSs leverage the decision-making capabilities of reinforcement learning (RL) agents, enabling them to operate without prior information about the environment [435]. The application of model-free EMSs has been analysed for managing controllable loads in microgrids [436] and reducing peak load in smart homes [435]. Additionally, the role of RL in optimising the EV charging process has been reviewed in [437].

From a pricing policy perspective, time-of-use (TOU) pricing has been explored in [430] for enhancing demand response. Furthermore, a distributed RL algorithm integrated with real-time pricing (RTP) is proposed in [438]. These studies, however, assume that pricing policies are predetermined [437].

Despite these advancements, the current literature has significant limitations. Notably, it lacks comprehensive evaluations of the performance of model-free EMSs under diverse pricing scenarios. Additionally, accurate forecasting of input data for future scenarios, including RTP, is crucial to ensure the effectiveness of EMS implementations [439].

This study addresses the following research question: "How does the RL-EMS perform compared to conventional EMS under different pricing policies?" To answer this, the study proposes an RL-EMS aimed at optimising energy arbitrage and increasing self-consumption in an assumed smart microgrid. RL provides the advantage of finding optimal solutions without requiring prior knowledge while also offering scalability for deployment in microgrids with diverse objectives and policy scenarios.

To tackle uncertainties in power generation, load, and price fluctuations, the RL-EMS integrates a long short-term memory (LSTM) forecasting algorithm to ensure accurate predictions of future conditions. The system's performance is evaluated using real-world data under both RTP and TOU pricing policies. The results are benchmarked against an optimisation-based EMS to evaluate its effectiveness.

The major contributions of this study are summarised as follows:

- A comprehensive, model-free EMS is proposed, integrated with a deep-learning forecasting algorithm to schedule the ESS without requiring prior knowledge.
- A comparison is presented between the performance of the RL-EMS and an optimisation-based EMS.
- The effectiveness of the RL-EMS is evaluated under both RTP and TOU pricing scenarios.

The remainder of the chapter is organised as follows: Section 5.2 presents the model of the assumed smart microgrid and the EMS mechanism. Section 5.3 elaborates on the reinforcement learning process and the applied forecasting algorithm. Section 5.4 details the application of RL to the assumed PV-ESS system and offers a comprehensive overview of the proposed algorithm architecture. Section 5.5 outlines the parameters of the case study and presents the obtained results of the proposed EMS. The results are further discussed in Section 5.6, and finally, Section 5.7 provides the conclusions.

5.2. Model architecture

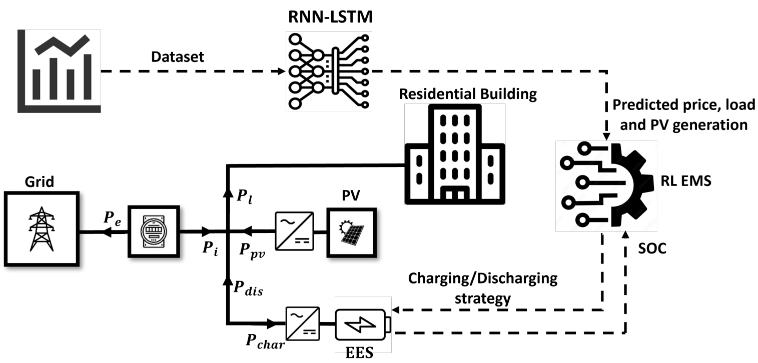


Figure 5.1: Proposed Microgrid Structure with RL-EMS.

Fig. 5.1 illustrates the proposed system in this study. The system represents a microgrid located in the Netherlands, consisting of a residential building equipped with a PV-ESS system. Operating in grid-connected mode, the microgrid exchanges energy with the utility grid as required [440]. The EMS optimises decisions to manage energy from the PV, ESS, and utility grid to meet load demand. These decisions are based on the Q-learning algorithm [441], which is implemented in the RL model [442]. The RL-EMS employs hour-ahead forecasted values for electricity price, load, and PV generation to optimally control the operation of the ESS.

5.2.1. Load, PV generation and price data

For the forecasting and decision-making process, adequate historical data should be used to accurately reflect annual trends, peak values, and seasonality for training and testing the model [188]. Details of load, electricity price, and PV generation in 2021 are summarised in Table 5.1. To obtain the input data for the assumed microgrid, the hourly power consumption data from [378] is used as the load dataset, while electricity price data is sourced from the wholesale electricity market in [371]. The dataset consists of hourly data from the beginning of 2016 to the end of 2021. The PV generation data is calculated using Eq. (5.1) as follows:

$$P_{pv}(t) = N_{pv} \times P_{pv}^{r}(G(t)/G^{ref})[1 + T^{cof}(T^{c}(t) - T^{ref})] \tag{5.1}$$

$$T^{c}(t) = T^{amb}(t) + ((T^{noct} - 20)/800 \times G(t)) \tag{5.2}$$

The generated power (P_{pv}) is a function of several factors, including the number of PV panels used (N_{pv}), the rated power output of each PV panel (P_{pv}^{r}), solar irradiance (G), solar irradiance under standard test conditions (G^{ref}), the temperature coefficient (T^{cof}), and the standard reference temperature for solar cells (T^{ref}). This relationship is expressed in Eq. (5.1). The cell temperature ($T^{c}(t)$), which influences P_{pv}, can be calculated using Eq. (5.2). It is determined by the ambient temperature (T^{amb}) and the nominal operating cell temperature (T^{noct}) of the PV panels.

5

5.2.2. ENERGY STORAGE SYSTEM MODEL

To determine the charging and discharging power of the ESS in each time slot, the SOC is taken into account [443]. As shown in Eq. (5.3), the SOC at time slot $t+1$ is calculated based on the SOC value at time slot t, along with the charge power (P_{char}) or discharge power (P_{dis}) during time slot t.

$$SOC(t+1) = SOC(t) + \frac{P_{char}(t) \cdot \eta_{char} - P_{dis}(t)/\eta_{dis}}{C_{ESS}/\Delta t} \tag{5.3}$$

where C_{ESS} represents the capacity of the ESS, and η_{char} and η_{dis} denote the charging and discharging efficiency coefficients, respectively.

The performance of the ESS is subject to several limitations. The SOC at each time slot is constrained within upper and lower boundaries, as shown in Eq. (5.4). This constraint ensures the durability and longevity of the ESS [444].

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{5.4}$$

As shown in Eq. (5.5) and Eq. (5.6), the ESS cannot be charged beyond its maximum charging power $P_{cha,max}$ or discharged beyond its maximum discharging power $P_{dis,max}$ [395].

$$0 \leq P_{cha}(t) \leq P_{cha,max} \tag{5.5}$$

$$-P_{dis,max} \leq P_{dis}(t) \leq 0 \tag{5.6}$$

Additionally, the ESS cannot charge and discharge simultaneously. To enforce this condition, Eq. (5.7) must be satisfied in each time slot [444].

$$P_{cha}(t) \cdot P_{dis}(t) = 0 \tag{5.7}$$

Table 5.1: Key parameters for load, pricing, PV generation, and ESS configuration in 2021.

Parameter	Details	Value
Load Parameters [378]		
E_{daily}	Daily average energy consumption	158.88 kWh
P_{peak}	Peak power demand	14.8 kW
E_{yearly}	Yearly energy consumption	58,000 kWh
Electricity Price Parameters [371]		
$Price_{avg}$	Average RTP pricing	0.62 €/kWh
$Price_{max}$	Maximum RTP pricing	3.75 €/kWh
$Price_{min}$	Minimum RTP pricing	-0.4 €/kWh
$Price_{TOU}$	TOU pricing (peak, off-peak)	0.69 €/kWh (peak), 0.56 €/kWh (off-peak)
PV Generation [372, 379]		
E_{PV}	Daily average generation per PV module	0.96 kWh
G	Daily average solar insolation	2.95 kWh/m^2/day
T^{amb}	Daily average ambient temperature	10.02 °C
N_{pv}	Number of PV modules	150
G^{ref}	Solar insolation reference	$1000\ (W/m^2)$
T^{cof}	Temperature coefficient	$-3.8 \times 10^{-3}\ (1/°C)$
T^{ref}	Standard temperature for solar cells	25 °C
Energy Storage System (ESS) Parameters [393]		
C_{ESS}	Capacity for RTP and TOU pricing policies	50 kWh (RTP), 31 kWh (TOU)
η_{char}	Charging efficiency	0.95
η_{dis}	Discharging efficiency	0.90
SOC_{max}	Maximum state of charge (SOC)	90%
SOC_{min}	Minimum state of charge (SOC)	10%

The optimal sizing of PV-ESS systems has been extensively studied in the literature [445]. In this study, the optimal sizing is determined using a Genetic Algorithm (GA) as described in [446]. Additionally, maximising self-consumption is incorporated into the objective function, as detailed in Section 5.2.4. The optimisation is performed for both TOU and RTP scenarios. The number of PV modules is determined to be 150, which corresponds to the maximum available assumed rooftop space [447]. The ESS capacities are found to be 50 kWh and 31 kWh for the TOU and RTP scenarios, respectively.

5.2.3. Power balancing

To maintain power balance in the microgrid, the total power supply must equal the total power demand, as expressed in Eq. (5.8):

$$P_{pv}(t) + P_{dis}(t) - P_{char}(t) - P_e(t) + P_i(t) = P_l(t) \tag{5.8}$$

where $P_{pv}(t)$ represents the power generated by the PV system, $P_i(t)$ denotes the power imported from the grid, $P_l(t)$ is the load power, and $P_e(t)$ refers to the power exported back to the grid.

5.2.4. OBJECTIVE FUNCTION

This study aims, first, to minimise energy costs (C_{cost}) through optimal power trading for end users over the considered time duration. Second, it seeks to maximise self-consumption to support system operators in congestion management. Maximising self-consumption can be interpreted as minimising both (P_i) and (P_e). Therefore, the objective function can be expressed as:

$$\min C = \min C_{cost} + \min \left(P_i(t) + P_e(t)\right) \tag{5.9}$$

The energy cost (C_{cost}) is defined as:

$$C_{cost} = \sum_{t=0}^{T} B(t) \cdot P_i(t) \cdot \Delta t - \sum_{t=0}^{T} S(t) \cdot P_e(t) \cdot \Delta t \tag{5.10}$$

where $B(t)$ and $S(t)$ are the purchasing and selling prices at time t, respectively. These values depend on the pricing policies.

5.3. METHODOLOGY

This section begins with an introduction to the Markov Decision Process (MDP) framework, followed by a comprehensive explanation of the Deep Q-Networks (DQN) method, which is used to estimate the Q-values associated with the MDP. The theoretical concepts are subsequently complemented by the implementation details of the DQN, specifically tailored for the ESS scheduling problem within the assumed microgrid. Finally, the integration of the LSTM and DQN models into a unified LSTM-DQN framework is presented.

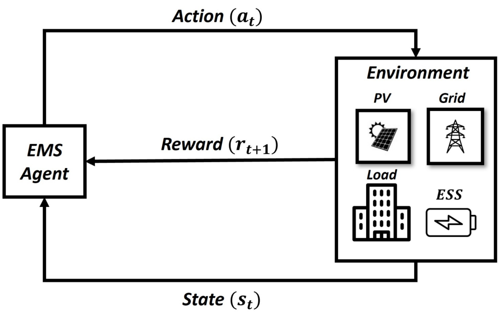


Figure 5.2: Markov decision process in reinforcement learning.

5.3.1. OVERVIEW OF MARKOV DECISION PROCESS

The objective function defined in Section 5.2.4 is formulated as a Markov Decision Process (MDP) to determine the optimal scheduling actions for the ESS. The MDP is a mathematical framework that models decision-making processes. The objective of this process is to maximise the expected cumulative reward over time [448]. Fig. 5.2

illustrates the framework for MDP, which is defined by a set of states S, a set of actions A, a transition model P, a reward function R, and a policy π. The state $s \in S$ represents the environment's current situation. The action $a \in A$ is a choice made by the agent that affects the state. The transition model $P(s'|s,a)$ defines the probability of transitioning to a state s' given that the agent is in state s and takes action a. The reward function $R(s,a,s')$ specifies the immediate reward received after transitioning from state s to state s' due to action a [449].

A policy $\pi(a|s)$ is a strategy that specifies the action a to be taken when in state s. The value function $V^{\pi}(s)$ measures the expected cumulative reward from state s following policy π, and the action-value function $Q^{\pi}(s,a)$ measures the expected cumulative reward from state s taking action a and then following policy π. The Bellman equations are fundamental to these formulations. The Bellman expectation equation for the value function is given in Eq. (5.11):

$$V^{\pi}(s) = \sum_{a} \pi(a|s) \sum_{s'} P(s'|s,a)[R(s,a,s') + \gamma V^{\pi}(s')] \tag{5.11}$$

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Similarly, the Bellman expectation equation for the action-value function is given in Eq. (5.12):

$$Q^{\pi}(s,a) = \sum_{s'} P(s'|s,a)[R(s,a,s') + \gamma \sum_{a'} \pi(a'|s') Q^{\pi}(s',a')] \tag{5.12}$$

where γ is the discount factor.

The objective in reinforcement learning is to find the optimal value function $V^*(s)$ and the optimal action-value function $Q^*(s,a)$, which correspond to the maximum expected cumulative reward achievable from any state and state-action pair, respectively [450]. The optimal functions satisfy the Bellman optimality equations, as expressed in Eq. (5.13) and Eq. (5.14):

$$V^*(s) = \max_{a} \sum_{s'} P(s'|s,a)[R(s,a,s') + \gamma V^*(s')] \tag{5.13}$$

$$Q^*(s,a) = \sum_{s'} P(s'|s,a)[R(s,a,s') + \gamma \max_{a'} Q^*(s',a')] \tag{5.14}$$

The optimal policy π^* can be derived from the optimal action-value function Q^*. The optimal policy is the policy that selects the action that maximises the Q-value for each state. Therefore, the optimal policy can be expressed as shown in Eq. (5.15):

$$\pi^*(s) = \arg\max_{a} Q^*(s,a) \tag{5.15}$$

By addressing the Bellman equations directly or through iterative techniques such as Q-learning or policy iteration, the agent can derive the optimal policy π^*, enabling effective decision-making within the environment. Basic Q-learning employs a lookup table to associate each state-action pair with a value. However, in environments with large or continuous state spaces, maintaining such a table becomes impractical [441]. To address this, Deep Q-Networks (DQN) use neural networks to approximate the Q-value function, leveraging deep reinforcement learning [451, 452].

In DQN, the Q-value function is parameterised as $Q(s,a;\theta)$, where θ represents the neural network's parameters. The network takes the state s as input and outputs Q-values for all possible actions a. The parameters θ are updated using gradient descent to minimise the loss function based on the Bellman equation. The loss function is defined as shown in Eq. (5.16):

$$L(\theta) = \mathbb{E}_{(s,a,r,s')\sim\mathcal{D}}\left[\left(r + \gamma \max_{a'} Q(s',a';\theta^-) - Q(s,a;\theta)\right)^2\right] \tag{5.16}$$

where (s,a,r,s') is a transition sampled from the replay buffer $\mathcal{D}$, γ is the discount factor, and θ^- are the parameters of the target network. The target network $Q(s',a';\theta^-)$ is a copy of the Q-network $Q(s,a;\theta)$, updated periodically to stabilise training [453].

To enhance stability and efficiency, DQN incorporates two key techniques: experience replay and a target network. Experience replay stores transitions (s,a,r,s') in a replay buffer $\mathcal{D}$. During training, mini-batches of transitions are sampled randomly from $\mathcal{D}$, breaking the correlation between consecutive updates and improving data efficiency [454]. The target network, with parameters θ^-, generates stable target values and is updated less frequently to avoid instability caused by rapid parameter changes [450].

5

5.4. Application of RL for EMS

Following the conceptual explanation, the main components of the MDP are described, specifically as they are designed for the proposed microgrid illustrated in Fig. 5.1.

5.4.1. Agent

The EMS is modeled as an agent with learning capabilities, utilising observations from states and the rewards obtained. The EMS agent determines and executes actions related to ESS scheduling in each time slot. It learns from offline data and applies the acquired knowledge to the real environment.

5.4.2. Environment and states

In the assumed microgrid, the environment is represented by hourly data on electricity prices, load, PV generation, and the SOC of the ESS. The agent observes the states of these parameters at each time slot. These states serve as inputs to the neural network in the DQN for each time interval. The states consist of forecasted values for electricity price ($\hat{e}_{(t)}$), PV generation ($\hat{p}_{pv(t)}$), and load ($\hat{p}_{l(t)}$) for the next hour, along with the current SOC. For the subsequent hour, the SOC value is updated based on the action taken. Therefore, the state of the environment at time t is given in Eq. (5.17):

$$s_t = [\hat{e}_{(t)}, \hat{p}_{pv(t)}, \hat{p}_{l(t)}, \hat{soc}_{(t)}] \tag{5.17}$$

5.4.3. Action

The output layer of the neural network determines the action taken by the agent to charge, discharge, or hold. The chosen action leads to a transition to a new SOC state, which subsequently serves as input to the neural network in the next time step. The action value is positive for discharging, negative for charging, and zero for holding, as shown in Eq. (5.18). These actions are constrained by the maximum charging and discharging power of the ESS, as expressed in Eq. (5.19).

$$a_t = [P_{cha(t)}, P_{dis(t)}, 0] \tag{5.18}$$

$$a_t \in [P_{dis,max}, P_{cha,max}] \tag{5.19}$$

5.4.4. Rewards

The action taken from the output layer determines the rewards associated with the agent's decisions. These rewards are used to compute the target Q-value and minimise the loss function between the predicted Q-values and the target Q-values, as defined in Eq. (5.14). The value function in this study is based on Eq. (5.9), which specifies that the optimal policy for the agent is to minimise electricity costs while maximising self-consumption, thereby earning higher rewards.

At the same time, the agent should avoid actions that result in punishments, which are treated as negative rewards. The total reward obtained in the next time hour is calculated by aggregating both positive and negative rewards, as expressed in Eq. (5.20).

$$r_{t+1} = r_{t+1}^{cost} + r_{t+1}^{SOC} + r_{t+1}^{balance} + r_{t+1}^{local} \tag{5.20}$$

In Eq. (5.20), r_{t+1}^{cost} represents the reward resulting from power arbitrage, as defined in Eq. (5.10). The reward r_{t+1}^{SOC} ensures that the SOC remains within the boundaries specified in Eq. (5.4). $r_{t+1}^{balance}$ represents the reward for maintaining power balance, while r_{t+1}^{local} incentivises local consumption of power generated from PV.

The weighting factor ζ_1 in Eq. (5.21) is used to enhance r_{t+1}^{cost}. To define r_{t+1}^{SOC}, the weighting factor ζ_2 is set to a positive value, while ζ_3 is assigned a large negative value to ensure that the SOC remains within the acceptable range, as shown in Eq. (5.22). Power balance is enforced by assigning a large negative value to the weighting factor ζ_4 in Eq. (5.23). Finally, the reward r_{t+1}^{local} is calculated using a negative weighting factor ζ_5 to stimulate local consumption, as shown in Eq. (5.24).

$$r_{t+1}^{cost} = \zeta_1 C_{cost} \tag{5.21}$$

$$r_{t+1}^{\mathrm{SOC}} = \begin{cases} \zeta_2 & (SOC_{min} < SOC(t) < SOC_{max}) \\ \zeta_3 & (SOC(t) \leq SOC_{min} \ or \ SOC(t) \geq SOC_{max}) \end{cases} \tag{5.22}$$

$$r_{t+1}^{balance} = \zeta_4 P_{total}(t) \tag{5.23}$$

$$r_{t+1}^{local} = \zeta_5 \left(P_i(t) + P_e(t)\right) \tag{5.24}$$

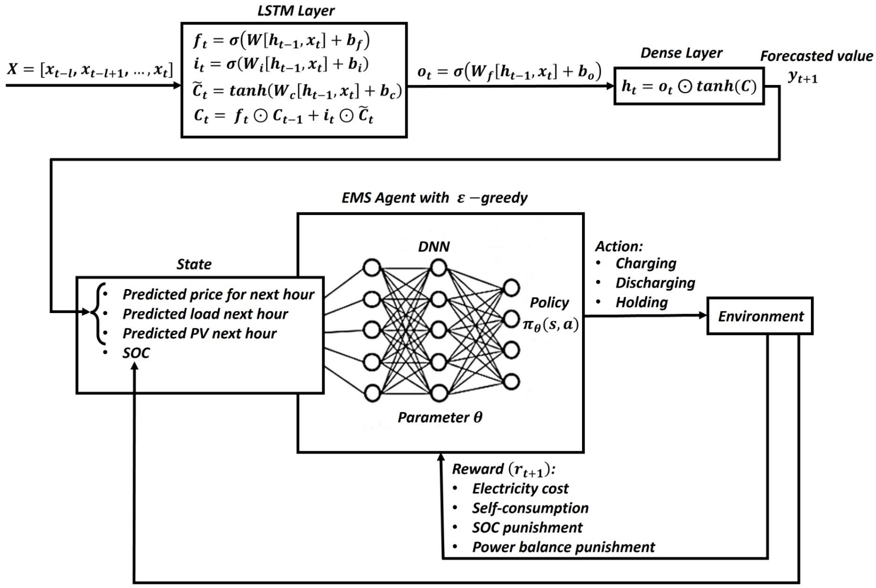


Figure 5.3: Proposed LSTM-DQN framework to optimise the performance of EMS.

5.4.5. Combining LSTM with DQN

This study employs an LSTM neural network to forecast PV generation, load, and electricity prices [455]. LSTM is well suited for time series forecasting due to its ability to capture long-term dependencies [456]. Fig. 5.3 shows the overall framework of LSTM-DQN. The procedure begins with preprocessing the historical data and updating the input vector for the LSTM model. The LSTM-based model forecasts electricity prices, load, and PV generation for the next hour using historical data spanning the past five years.

The input to the LSTM model is structured as overlapping windows of size l, representing the look-back period, or the number of previous time steps used as input features for forecasting. Each input sequence is represented in Eq. (5.25):

$$X = [x_{t-l}, x_{t-l+1}, \dots, x_t] \tag{5.25}$$

where x_t represents the past values at time t, and the corresponding output is y_{t+1}, which denotes the forecasted values for the next hour.

The LSTM layers process the input sequences using gates to control the flow of information. The forget gate is shown in Eq. (5.26):

$$f_t = \sigma(W_f[h_{t-1}, x_t] + b_f), \tag{5.26}$$

where f_t is the forget gate vector, σ is the sigmoid activation function, W_f and b_f are the weight matrix and bias vector, h_{t-1} is the hidden state, and x_t is the input. The input gate adds new information to the cell state, as in Eq. (5.27):

$$i_t = \sigma(W_i[h_{t-1}, x_t] + b_i), \tag{5.27}$$

and the candidate cell state is calculated by Eq. (5.28):

$$\tilde{C}_t = \tanh(W_C[h_{t-1}, x_t] + b_C). \tag{5.28}$$

The cell state updates as in Eq. (5.29):

$$C_t = f_t \odot C_{t-1} + i_t \odot \tilde{C}_t, \tag{5.29}$$

where $\odot$ denotes the element-wise product. The output gate computes the hidden state using Eq. (5.30):

$$o_t = \sigma(W_o[h_{t-1}, x_t] + b_o), \tag{5.30}$$

The hidden state is calculated using Eq. (5.31):

5

$$h_t = o_t \odot \tanh(C_t). \tag{5.31}$$

After obtaining forecasted and SOC values as the current state, the EMS agent computes optimal ESS scheduling decisions iteratively using an ε-greedy policy. This policy balances exploration and exploitation. The action a_t at time t is selected using Eq. (5.32):

$$a_t = \begin{cases} \text{random action from } \mathcal{A}, & \text{with probability } \varepsilon, \\ \arg\max_a Q(s_t, a; \theta), & \text{with probability } 1-\varepsilon, \end{cases} \tag{5.32}$$

The exploration probability ε decays over time using Eq. (5.33):

$$\varepsilon_t = \max(\varepsilon_{\min}, \varepsilon_{\text{start}} \cdot e^{-k \cdot t}), \tag{5.33}$$

where $\varepsilon_{\text{start}}$ is the initial exploration rate, $\varepsilon_{\min}$ is the minimum exploration rate and k is the decay rate.

After deciding on ESS actions using the ε-greedy policy, the EMS agent receives rewards and updates its state based on Sections 5.4.4 and 5.4.2. This process repeats at each time step, forming a single episode. The procedure continues until the total number of episodes (N) is completed. At the end of each episode, the EMS agent determines the optimal actions for the remaining hours $H-h$ and executes the optimal action for the current hour h. The algorithm progresses hour by hour until the final hour H is reached.

5.5. Results

The historical dataset, consisting of hourly time series measurements, was preprocessed to address missing values and normalised using a standard scaler [459]. The forecasting performance of the LSTM model was evaluated separately, and its predictions were subsequently input into the RL model. The hyperparameters for the LSTM and DQN models are summarised in Tables 5.2 and 5.3.

Table 5.2: LSTM hyperparameters [457].

Hyperparameter	Value
Number of hidden layers	3
Number of neurons per layer	50
Dropout ratio	0.2
Optimiser	Adam
Loss function	Mean Squared Error
Epochs	100
Input sequence length	Look-back period

Table 5.3: RL hyperparameters [458].

Hyperparameter	Value
Episodes N	200
Learning Rate α	0.001
Discount Rate γ	0.95
Initial exploration $\varepsilon_{\text{start}}$	1
Minimum exploration ε_{min}	0.001
Decay Rate	0.995

5.5.1. LSTM MODEL FORECASTING RESULT

The dataset was divided into training, validation, and test sets in proportions of 70%, 20%, and 10%, respectively [460]. Model performance was evaluated against actual values using the Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and R^2 Score, as defined in Eqs. (5.34)–(5.36) [461].

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \tag{5.34}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{5.35}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{5.36}$$

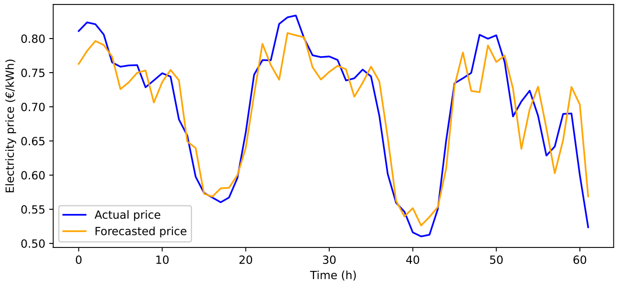
Here, n represents the number of data points, y_i denotes the actual value at data point i, $\hat{y}_i$ is the corresponding forecasted value, and $\bar{y}$ is the mean of the actual values. Fig. 5.4 illustrates the forecasted and actual values for electricity price, load, and PV generation over three days in June 2021.

Table 5.4: Performance evaluation of the LSTM model for forecasting.

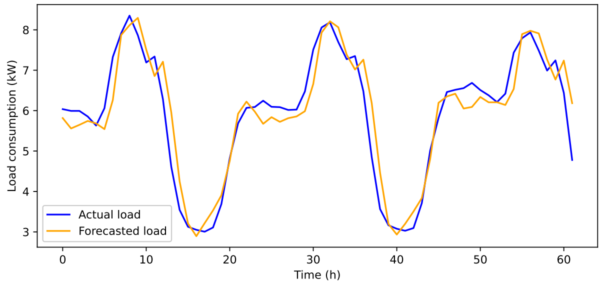
Metric	RMSE	MAE	R^2
Electricity price forecasting	0.12	0.21	0.88
Load forecasting	1.11	0.81	0.97
PV generation forecasting	1.3	0.5	0.87

The results indicate that the forecasted values exhibit a similar trend to the actual values. Quantitative comparisons are presented in Table 5.4. The LSTM model for electricity price forecasting achieves the lowest RMSE (0.12), indicating minimal overall error magnitude; however, its R^2 is the lowest (0.88), reflecting the complexity of price data and slightly reduced accuracy in capturing trends compared to load and PV generation data.

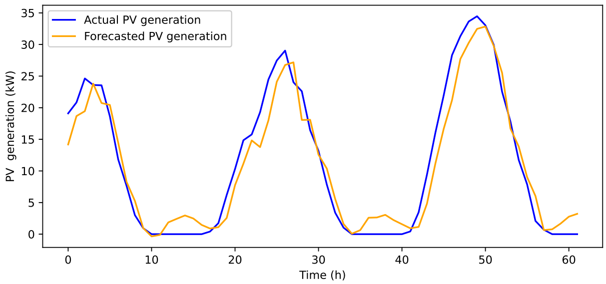
Meanwhile, load forecasting demonstrates a substantially larger RMSE (1.11) and MAE (0.81), but the highest R^2 (0.97), implying that despite experiencing larger errors,



(a)



(b)



(c)

Figure 5.4: LSTM model forecasting results for June 14-16, 2021: (a) electricity price, (b) load, (c) PV generation.

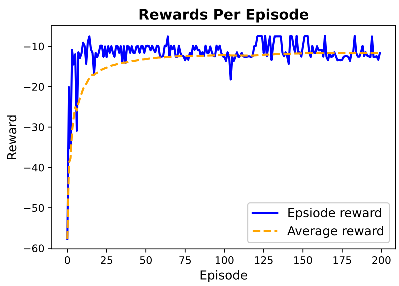
the model reflects most of the variance in the dataset. PV generation falls between these two, with an RMSE of 1.3, a moderate MAE (0.5), and an R^2 of 0.87, reflecting a balance between capturing variance and controlling error magnitude.

5.5.2. PERFORMANCE OF RL

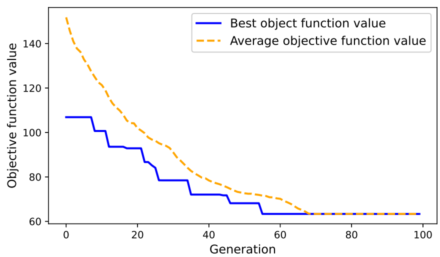
The DQN agent was trained using data from July 13, 2021, chosen due to its high standard deviation (STD) values 0.42 for load and 15.752 for PV generation. These elevated STD values signify substantial variability, providing a challenging and dynamic environment for the agent's training. This selection was intended to facilitate the development of a robust policy capable of effectively adapting to significant fluctuations in the system.

Fig. 5.5a illustrates the learning process based on the defined reward structure. The RL algorithm successfully identifies an optimal policy and achieves convergence after approximately 100 episodes. In the early episodes, the rewards are highly negative due to penalties associated with exceeding SOC limits or violating power balance constraints. As the training progresses, the agent learns to minimise these penalties by optimising actions, resulting in a steady improvement in rewards and eventual policy stability. Due to the minimum exploration rate $\varepsilon_{\min}$, rewards may deviate from the optimal value even in the final episodes. However, the average reward maintains a steady value.

To evaluate the performance of the trained RL agents, the model was applied to three consecutive days in July 2021, from the 14th to the 16th, providing an opportunity to assess its effectiveness in online decision-making. The RL model was initially trained using a TOU pricing scheme with peak and off-peak levels, while testing was conducted under an RTP scheme with hourly varying prices. This setup enabled the evaluation of the model's adaptability to different pricing environments.



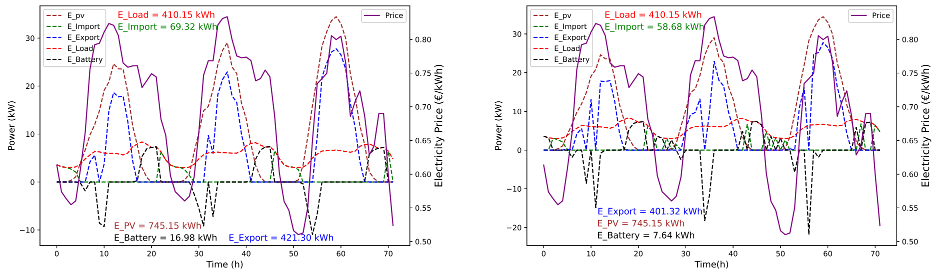
(a) RL-based EMS.



(b) GA-based optimisation EMS.

Figure 5.5: Convergence process of RL-based and GA-based EMS methods.

For benchmarking, the performance of the RL-based approach was compared to a genetic algorithm (GA)-based solution, as detailed in [462, 463]. The convergence process of the GA, illustrating its optimisation trajectory, is shown in Fig. 5.5b. Both approaches were evaluated using the same objective function outlined in Eq. (5.9), which aims to minimise electricity costs while maximising renewable energy self-consumption.



(a) RL-based EMS. (b) GA-based optimisation EMS.

Figure 5.6: Power flow analysis of EMS under real-time pricing scheme for RL-based and GA-based methods.

As a standard metric for comparing the two EMSs, the Self-Consumption Ratio (SCR) was calculated using Eq. (5.37). The SCR is defined as the proportion of PV-BES energy consumed within the microgrid either directly ($P_{pv,dir}(t)$) or for charging the ESS to the total annual PV energy generation [399, 464].

$$SCR = \sum_{t=0}^{T} \frac{(P_{dis}(t) + P_{pv,dir}(t)).\eta_{dis}}{P_{pv}(t)} \tag{5.37}$$

Table 5.5 summarises the performance of the two EMS approaches. The training of the DQN algorithm in RL is computationally intensive compared to the faster convergence of the GA model. On average, each RL episode lasts approximately 6 minutes, whereas each GA generation takes around 1 minute. The results highlight the financial advantages of the RL-based EMS compared to the GA-based EMS under both TOU and RTP pricing schemes. Specifically, the RL-based EMS demonstrates superior performance, yielding net financial benefits of 261.52 € under TOU and 289.90 € under RTP. In contrast, the GA-based EMS achieves lower net benefits of 241.51 € under TOU and 265.62 € under RTP. These findings indicate the potential of the RL-based approach for improving financial outcomes in both pricing scenarios. An interesting observation is the RL agent's ability to adapt to previously unseen conditions. While the RL model was trained exclusively under the TOU pricing scheme, it was subsequently tested under the RTP scheme to explore its capacity to operate in dynamically changing environments. The results suggest that, even without prior training in RTP, the RL-based EMS showed promising performance compared with the GA-based EMS, pointing to its possible applicability in diverse and dynamic settings.

The SCR results for both EMS models are within 2% of each other in all scenarios. Under TOU, the GA-based EMS achieves an SCR of 88.57%, slightly higher than the RL-based EMS at 86.24%. Under RTP, the RL-based EMS achieves 83.62%, comparable to the GA-based EMS at 84.23%. While SCR performance is similar, the RL-based EMS delivers significantly better financial outcomes.

Comparison of performance between GA and RL based solely on electricity cost

Table 5.5: Comparison of EMSs under TOU and RTP pricing schemes.

EMS	Computation Time (min)	TOU		RTP	
		Electricity Cost (€)	SCR (%)	Electricity Cost (€)	SCR (%)
RL	Training: 1200 Testing: 15	-261.52	86.24	-289.9	83.62
Genetic Algorithm	90	-241.51	88.57	-265.62	84.23

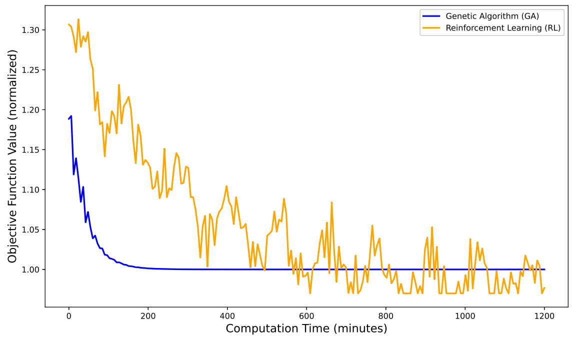


Figure 5.7: Comparison of normalised objective function values for GA and RL.

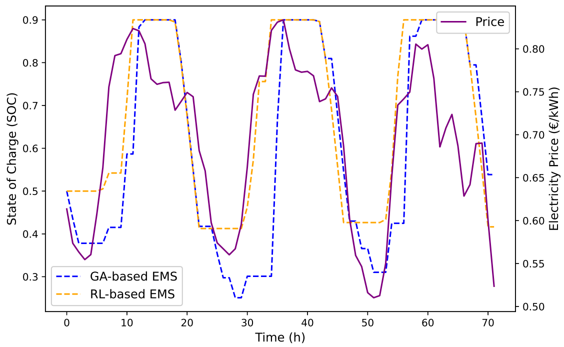


Figure 5.8: Comparison of SOC for GA-based and RL-based EMSs in relation to electricity price.

and SCR values is insufficient because these values are not directly comparable. Additionally, the current assumption in the objective function in Eq. 5.10 is that SCR and electricity cost have the same impact on the optimisation. To enable a more comprehensive comparison between RL and GA, their overall performance can be assessed by comparing the values of their objective functions. Fig. 5.7 illustrates how the objective function values for GA and RL evolve during the computation time. Since SCR and electricity cost have different units, these two values are first normalised, and the objective function values are presented based on the normalised aggregated values of

SCR and electricity cost. As shown in Fig. 5.7, although the convergence time for RL is slower than that of GA, RL achieves lower objective function values.

The power flow analysis, illustrated in Figs. 5.6a and 5.6b, highlights the RL-EMS's superior responsiveness to pricing signals. Notably, during peak pricing periods, the RL agent consistently maximises energy exports. In contrast, the GA-based EMS often opts to charge the ESS during these periods, as observed in specific intervals (e.g., hours 10-15). Furthermore, the RL-based EMS demonstrates more intelligent utilisation of the ESS, particularly during periods of insufficient PV production (e.g., hours 42-52). The RL model strategically opts to continuously use the ESS to avoid importing power during high-price periods. In contrast, the GA model behaves differently, leading to unnecessary battery discharge at low prices (e.g., hour 50) instead of importing cheaper power from the grid. This results in the RL agent, overall, discharging 4 kWh more than the GA model, particularly during periods when prices remain high.

The SOC of the ESS provides deeper insights into how the RL-based and GA-based models manage ESS utilisation, as shown in Fig. 5.8. While the GA-based EMS performs slightly better at avoiding charging during periods of very high prices, it exhibits poor performance in discharging at very low prices. In contrast, the RL-based EMS effectively avoids deep discharges at low prices, preserving the stored energy for higher arbitrage opportunities during periods of higher prices (e.g., hours 08 and 22-30).

5.6. Discussion

In addressing the research question, "How does the RL-EMS perform compared to conventional EMS under different pricing policies?", the analysis suggests that reinforcement learning offers potential for optimising energy management. Using real-time pricing (RTP) and time-of-use (TOU) data, the RL-EMS demonstrated the ability to efficiently adjust the charging pattern of the BES, providing an improvement over the GA algorithm. Unlike GA, which operates on fixed optimisation rules, RL-EMS can update its strategy in response to variations in energy prices, load demands, and renewable generation. Such adaptability could be valuable for smart microgrids, where high variability in input parameters requires more responsive decision-making [465]. Observed behaviours, such as prioritising energy export during higher price periods and delaying ESS charging when costs are high, indicate that RL-EMS has the potential to enable more dynamic operational strategies [405]. However, these observations are based on a limited test period of 72 hours, and further extended experiments across a broader range of scenarios are necessary to confirm the consistency and generalisability of these findings.

Despite these potentials, its reliance on accurate forecasting algorithms, such as the integrated LSTM model, adds complexity and dependency on data quality. The training time for RL models, often extending to hours for convergence, may limit their application in systems requiring rapid deployment or frequent reconfiguration. Furthermore, while the RL-EMS outperforms GA in terms of economic efficiency and energy utilisation, its computational demands during training suggest the need for optimised algorithms or hybrid approaches to balance computational efficiency with operational performance. These findings indicate that RL-EMS is a transformative approach for energy management but necessitates further refinement to address its drawbacks in practical implementations.

5.7. CONCLUSION AND FUTURE WORK

This study introduces an RL-EMS for residential smart microgrids equipped with PV-ESS. It utilises a Markov Decision Process framework, integrating the LSTM algorithm to forecast electricity prices, loads, and PV generation. By employing Deep Q-Networks, the RL-EMS dynamically optimises energy arbitrage and self-consumption without requiring prior knowledge of the system environment. This model-free approach ensures scalability and adaptability to varying operational conditions and pricing policies, such as TOU and RTP.

The results demonstrate that the RL-EMS outperforms the GA-based EMS in financial performance under both TOU and RTP schemes, while maintaining a comparable Self-Consumption Ratio (SCR). The RL-EMS exhibits greater adaptability and efficiency in dynamic and complex energy pricing scenarios. Notably, even though the RL-EMS was trained under TOU, it successfully adapts to RTP, demonstrating its robustness and capacity to handle diverse pricing conditions effectively.

The study highlights directions for future research, including the integration of demand response mechanisms and the consideration of ESS degradation to enhance real-world applicability. These improvements would align energy management strategies with user preferences and promote long-term sustainability. Additionally, efforts to optimise the computational efficiency of the RL model and explore hybrid approaches could address challenges related to training time, enabling broader application in dynamic microgrid environments.

6

Conclusion

This thesis sets out to examine the development and implementation of smart grids as a central transition pathway, with smart microgrids serving as foundational building blocks, analysed from a socio-technical perspective. The motivation stems from the recognition that prior research has often treated the technical, social, political, and regulatory aspects of SMG innovation in isolation. Yet, smart grids are not solely technological systems, but are embedded within broader institutional, economic, and social contexts. They reshape how electricity is generated, distributed, and consumed, and thus require a holistic framework to understand their potential and limitations within an evolving energy regime.

Grounded in the understanding that the pace and success of energy transitions depend on dynamic interactions among technical capabilities, institutional support, actor configurations, and market mechanisms, this thesis aimed to:

- Untangle the interactions among various aspects of the transition towards smart grids;
- Provide policy implication insight for future designs to accelerate the adoption of smart grids.

A literature review in Chapter 2 aimed to examine the complexities involved in the transition toward smart grids. When necessary, the focus shifted to smart microgrids, with real-world projects analysed to identify practical barriers. The findings indicate that a major challenge lies in the gap between technological capabilities and existing regulatory and market frameworks. Although pilot projects demonstrate that smart grids can operate flexibly and efficiently, they are often constrained by interconnection rules and market structures designed for centralised systems. Restrictions on exporting renewable energy or participating in peer-to-peer trading reduce economic viability and hinder the development of community-based models, thereby preventing full utilisation of smart grid functionality.

Institutional and social factors further complicate implementation. Governance is often fragmented, with multiple stakeholders such as technology providers, utilities, regulators, and communities operating under unclear roles. This fragmentation slows coordination and creates friction. Trust is also a critical issue, as communities may be cautious of new technologies while utilities fear loss of control. Addressing these challenges requires not only technical innovation but also institutional adaptation, active community engagement, and transparent, collaborative decision-making that aligns incentives among all actors. The review highlights that current policies primarily focus on individual prosumers' consumption and generation, often overlooking broader community engagement. To foster collective action and shared benefits, consumers should be incentivised not only to optimise their energy behaviours but also to participate in collaborative efforts that improve smart microgrid performance and resilience. Such incentives are particularly important for the adoption of innovations like storage devices, and pricing mechanisms strongly influence consumer uptake. This issue is further explored in Chapter 4.

To provide context-based insights into the development of smart grids, a Technological Innovation System (TIS) framework was applied in Chapter 3 to examine smart grids both as an innovation and from a transition studies perspective. The analysis identifies three distinct phases in the evolution of smart grid innovation in the Netherlands. The Initiation Phase (2000–2010) was characterised by the emergence of smart grid concepts, with pilot projects and early research demonstrating technical feasibility and potential benefits. The Development Phase (2010–2020) focused on scaling up initiatives and integrating diverse technologies to enable more efficient and flexible energy networks, although regulatory and market barriers became increasingly evident. The Consolidation Phase (2020–present) centered on refining and optimising smart grid systems by addressing earlier shortcomings, aligning policies, strengthening stakeholder engagement, and improving technology integration.

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In Chapter 4, building on the findings of Chapter 2, which emphasise the importance of incentivising the adoption of smart grid–related technologies, and aligning with the insights from Chapter 3 on legitimising policies for market formation, further analysis is conducted to assess the economic viability and market acceptance of sustainable components within smart microgrids.

The study in Chapter 4 demonstrates that pricing structures directly influence both the operational performance and the economic feasibility of residential PV-battery systems, shaping their potential role within smart microgrids. Real-time pricing emerges as a powerful lever for improving the flexibility and self-sufficiency of residential PV-battery setups. However, to keep systems affordable, policymakers should look at offering subsidies or financial support to help cover the high upfront costs. Additionally, embedding advanced EMS controls, such as price-limit features, can significantly enhance both technical performance and system resilience.

In Chapter 3, the importance of scalability for future smart grid projects in the Netherlands was highlighted. In this context, scalability refers not only to physical expansion but also to the capacity of solutions to adapt and perform effectively under different regulatory and policy environments. Building on this, Chapter 5 introduces a Reinforcement Learning (RL)-based Energy Management System (EMS) integrated with LSTM forecasting to optimise the operation of a PV-BES residential smart microgrid. The RL-EMS was benchmarked against a traditional Genetic Algorithm (GA)-based optimisation system. Results indicate that the RL-EMS shows slightly better performance in terms of the overall objective function under both Time-of-Use (TOU) and Real-Time

Pricing (RTP) scenarios. These findings suggest that RL-EMS can provide scalable and adaptable solutions for residential smart microgrids across varying regulatory and policy environments. Even when trained under TOU conditions, the RL-EMS performs comparably under RTP pricing, suggesting potential scalability across different market and policy settings. While self-consumption rates are largely similar between the RL and GA approaches, the RL-EMS shows a tendency toward slightly better financial outcomes and may respond more effectively to price signals during peak periods, indicating its potential for improving operational flexibility in residential smart microgrids.

6.1. ANSWERING THE RESEARCH QUESTIONS

1. What socio-technical factors hinder the adoption and diffusion of smart grids (SGs) in electric systems?

This question was addressed in Chapter 2 with the following main findings. A significant barrier is the lack of a shared vision and common goals among stakeholders, including utilities, regulators, technology providers, and communities. This fragmentation leads to misaligned incentives, where each actor pursues objectives that may conflict with the collective interest, slowing down collaborative efforts essential for SMG development. Additionally, the absence of standardised protocols and interoperability among different technologies and systems complicates integration and scalability, making it challenging to expand SGs beyond pilot projects. The chapter also highlights that policy uncertainty and inconsistent regulatory support create an unstable environment, deterring investment and innovation in SGs. Furthermore, social acceptance and trust issues arise when communities perceive SGs as complex or intrusive, leading to resistance against adoption. Addressing these socio-technical barriers requires fostering a unified vision, establishing clear and consistent policies, promoting technological standardisation, and building trust through community engagement and transparent communication.

2. What systemic and transformational failures are identified in developing smart grid innovation in the Netherlands?

The TIS analysis in Chapter 3 shows that, although entrepreneurial activities and knowledge development are relatively well-supported, significant shortcomings remain in legitimacy creation, actor alignment, and market formation. Institutional misalignments—such as fragmented responsibilities between DSOs, policymakers, and energy cooperatives—undermine coordinated experimentation and hinder the scaling of smart grid systems. In addition, the absence of regulatory frameworks that accommodate new business models, coupled with limited support for risk-sharing mechanisms, restricts the development of robust smart grid markets. Addressing these challenges will require coherent policy interventions, stronger cross-sector collaboration, and targeted measures to build societal trust in smart grid technologies.

3. How will different pricing policies impact the techno-economic potential of PV-BES in the Netherlands?

In Chapter 4, the findings indicate that net metering, while financially beneficial for end-users, results in low self-consumption rates and provides limited value at the system level. In contrast, combining Feed-in Tariffs (FiT) with Time-of-Use (TOU)

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pricing increases self-consumption and better supports grid management objectives, although it raises the levelised cost of energy (LCOE). Dynamic pricing, when paired with subsidies, further enhances flexibility and responsiveness, but requires substantial initial investment in battery systems. Regulatory reforms are needed to classify batteries as renewable energy components to enable subsidy access and to allow aggregation and community-scale storage solutions, which can improve cost-efficiency and market participation. **4. How does the machine learning-based EMS perform compared to conventional EMS under different pricing policies?**

Applying a model-free energy management system integrated with a deep-learning forecasting algorithm in Chapter 5 allows scheduling of the PV-battery system without requiring prior knowledge. Unlike genetic algorithms, which rely on fixed optimisation rules, RL-based energy management systems (RL-EMS) can potentially adjust their strategies in response to changes in energy prices, load demand, and renewable generation. This flexibility may be particularly useful for smart microgrids, where rapidly changing conditions call for more adaptive decision-making. Observed behaviors, such as prioritising energy export during periods of higher prices and delaying energy storage system charging when costs are elevated, suggest that RL-EMS could support more dynamic and responsive operational strategies.

6.2. LIMITATIONS

The TIS and transformational failure frameworks used in Chapter 3 offer valuable diagnostic tools, but their qualitative nature introduces subjectivity and limits comparative generalisability. Moreover, they do not explicitly incorporate behavioural economics or social psychology, which are critical to understanding end-user adoption.

The pricing policy simulations in Chapter 4 are based on specific regulatory assumptions. While realistic within the Dutch context, different policies or market evolutions could significantly alter outcomes.

In Chapter 5, the RL-based EMS was tested over only three days due to computational limitations, specifically hardware constraints and limited memory storage. While the initial findings appear promising, further validation over longer periods and a wider range of scenarios is needed to assess the generalisability of the results.

6.3. FUTURE WORK

As a continuation of the findings in Chapter 2 and Chapter 4, regulatory frameworks that support energy storage and community-based energy governance should be explored to fully realise the potential of storage devices in smart microgrids. Business models that promote coordination among users, aggregators, and distribution system operators will be important for further developing storage solutions while maintaining system reliability.

To complement the work in Equation (5.3), further work is also needed to quantify innovation system functions using dynamic modeling techniques, translating qualitative TIS insights into simulation-based tools that can inform policy design. In parallel, deeper integration of behavioural and institutional theories would help better capture how users and organisations respond to SG-related incentives and risks.

To verify the findings presented in Chapter 5, it is important to expand the scope of RL-EMS studies to encompass longer timeframes and real-world deployment conditions. Such studies could consider factors including system degradation, user variability, and multi-agent interactions. It would also be useful to test the performance of RL-EMS under different pricing mechanisms to better understand its applicability across varying market conditions.

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A

Appendix A

Table A1.: List of experts for validation interviews

Experts	Position and Expertise	Organisation
1	Assistant Professor with expertise in International and European Law and Multidisciplinary Approaches	University of Groningen
2	Former manager in IPIN demonstration pilots, and advisor with expertise in energy transition	Energy consultancy
3	Assistant Professor with expertise in end-user practices and Sustainable Urban Development	University of Amsterdam
4	Associate Professor with expertise in Modelling of Innovation Systems, innovation management and entrepreneurship	Eindhoven University of Technology
5	Former Chief Technology Officer with expertise in energy transition on the local, national and international level	Energy consultancy and DSO Stedin

A

Table A2.: A semi-structured interview guide

Main Theme	**Open-ended questions**	**No. of resolved discrepancies**
Events	Is there any moment identified during the analysis that cannot be considered an event? Do you confirm the causality between events?	7
Functions	Do you agree with the method of mapping events to functions? Is there any event mapped to the wrong function? Is there any need for amending the functions' relationships?	10
Systemic failure	Do you confirm the identified unsatisfied system functions? Do you confirm the identified system failures?	5
Transformational failures	Do you confirm the identified transformational failures? Do you agree with the method of mapping events to transformational failures?	6
Missing event or data	Is there any event that is not included in the analysis? Do you add any events to the ones that have already been identified? Do you add more explanations to the events? Do you recommend any resources for retrieving more events?	14

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List of Publications

Journal Papers

1. F. Norouzi, T. Hoppe, L. Ramírez-Elizondo, P. Bauer, "review of socio-technical barriers to Smart Microgrid development", *Renewable and Sustainable Energy Reviews*, 2022, vol 167, 112674.

2. F. Norouzi, T. Hoppe, L.M. Kamp, C. Manktelow, P. Bauer, "Diagnosis of the implementation of smart grid innovation in The Netherlands and corrective actions", *Renewable and Sustainable Energy Reviews*, 2023, vol 175, 113185.

3. F. Norouzi, A. Shekhar, T. Hoppe, P. Bauer, "Analysing the Impact of the Different Pricing Policies on PV-Battery Systems: A Dutch Case Study of a Residential Microgrid", *Energy Policy, 2025, vol 204, 114706*.

4. F. Norouzi, A. Shekhar, T. Hoppe, P. Bauer, "Energy Management in a Residential Microgrid Using Reinforcement Learning Under Different Pricing Policies", *submitted in International Journal of Electrical Power & Energy Systems (JEPE)* .

Conference Papers

1. F. Norouzi, L. Ramírez Elizondo, T. Hoppe, P, P. Bauer, "An Adaptive Control Strategy for Dynamic Response of an Autonomous DC system", *2021 56th International Universities Power Engineering Conference (UPEC)*, 2021, pp. 1-6.

2. F. Norouzi, A. Shekhar, T. Hoppe, P. Bauer, "Economic Impact of New Pricing Policies on Solar PV Households in the Netherlands", *2023 IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)* , 2023, pp. 1-6.

3. K. Deivamani F. Norouzi, A. Shekhar, P. Bauer, "A Comparison of Various Deep Learning Methods for Household Load Forecasting ", *2023 IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, 2023, pp. 1-6.

Journal Paper (COLLABORATIVE Study)

1. S. Aghaeian, F. Norouzi, W.G. Sloof, J.M.C. Mol, A.J. Botter , "Predicting the parabolic growth rate constant for high-temperature oxidation of steels using machine learning moldes", *Corrosion Science*, 2023, pp. vol 221.

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