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Role of Energy Community Microgrids in Energy Transition

A Case Study from a Technological Innovation Systems Perspective

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Acknowledgements

I would like to thank my family for their constant encouragement, understanding, and support throughout my studies. In many ways, my family has been my own “microgrid” — a small but resilient system that connects me to the wider world while providing a space for growth and renewal. It may not be the most powerful system, but it has given me the most essential capacity: resilience.

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ABSTRACT:

Energy transitions have evolved from linear shifts in dominant energy sources to complex processes requiring fundamental restructuring of socio-technical systems. Contemporary transitions are driven by climate imperatives, efficiency demands, justice concerns, and security risks to achieve sustainability goals. They necessitate coordinated evolution across technological, institutional, and social dimensions. Such coordination is increasingly realized at local and regional levels through new technological and organizational configurations. Energy communities and microgrids have emerged as regional solutions for decentralizing and localizing energy systems. Microgrids integrate distributed energy resources, energy storage systems, and flexible loads within local energy community's power system capable of both grid-connected and islanded operation. They facilitate renewable energy integration, enhance system flexibility and accessibility, and improve local resilience and efficiency. However, their transformative potential extends beyond technical capabilities.

This study examines how energy community microgrids contribute to the energy transition. Employing a qualitative single-case study and functional analysis, the research analyzes an implementation: LEMENE—Lempäälä Energy Community (Finland). The analytical framework draws on the Technological Innovation System approach from innovation policy studies, systematically exploring how microgrids in communities reconfigure local energy systems across technological deployment, institutional embedding, and social participation dimensions. Through functional analysis of system dynamics, this research identifies key drivers, institutional constraints, and challenges shaping microgrid development. Findings reveal that microgrids function not as standalone technical solutions but as socio-technical assemblages whose transformative capacity emerges through interactions with regulatory frameworks, market mechanisms, ownership models, and community engagement patterns.

The study contributes theoretically by extending the application of the Technological Innovation System framework by integrating functional analysis with technological, institutional, and social structural dimensions. Empirically, the case study demonstrates that such systems develop through experimentation-driven innovation processes characterized by knowledge development and resource mobilization. At the same time, their broader development and deployment remain constrained by institutional conditions. These findings highlight the importance of policy environments that combine regulatory adaptability, experimental spaces for innovation, and stable long-term policy signals to enable the wider role of energy community microgrids in energy transition processes.

KEYWORDS: Energy transition; Microgrids; Energy communities; Socio-technical systems; Technological Innovation Systems; Decentralization; Flexibility

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Abbreviations

CHP	Combined Heat and Power
DER	Distributed Energy Resource
EMS	Energy Management System
ESS	Energy Storage System
EU	European Union
FCR	Frequency Containment Reserve
LEMENE	Lempäälä Energy Community
PCC	Point of Common Coupling
PV	Photovoltaic
TIS	Technological Innovation System

1 Introduction

This chapter introduces the research topic and establishes the scope for the study. It first outlines the broader background of the energy transition and the increasing importance of decentralized and locally coordinated energy systems. It then identifies the research gap and presents the main and sub- research questions guiding this study. Finally, the research approach and the structure of the thesis are briefly introduced.

1.1 Research background

Multiple factors, such as climate change, increasing energy demand, inequality, and energy dependence, are calling for a rapid transformation of the global energy system. The “next” energy transition has become increasingly necessary, as current energy systems are environmentally, socially, and economically unsustainable (Grubler, 2012). Addressing these challenges requires several key strategies, including reducing energy consumption, decarbonizing energy systems, and electrifying end-use sectors such as heating and transportation. Decarbonization has become a central objective in international climate policies, with renewable electricity playing a crucial role in this process. At the same time, the transformation of energy systems increasingly requires decentralization and flexibility to accommodate both existing and emerging actors within the energy system. In addition, resilience has become an essential feature of future energy systems, as energy infrastructures must adapt to climate-related disruptions while supporting long-term sustainability. Moreover, a fundamental shift in mindset is underway, where ordinary consumers can simultaneously become energy producers called prosumers. However, the complexity of this transition has led many scholars to argue that incremental technological change alone is insufficient. Instead, a deeper structural transformation of energy systems is required, involving changes in technologies, institutions, and social practices. Achieving a just energy transition requires a fundamental shift in the “rules of the game” governing energy systems (McCauley & Heffron, 2018; Sovacool, 2016; Wallsgrove et al., 2021).

According to this background, a distributed and localized energy system is emerging in view of the future direction. Small-scale energy systems may act as a "game changer" in the large-scale energy revolution. Numerous scientists and businesspeople are working to create an environment for the development and integration of renewable energy sources in decentralized power systems, and microgrids are emerging as one of the promising solutions in the transition. Microgrids are power distribution systems with loads, distributed energy resources, and energy storage, which can be controlled and coordinated in operation, whether islanded or connected to the main power grid (Hatziargyriou, 2014; Ton & Smith, 2012). They can reduce transmission losses, improve system reliability, and enable locally coordinated energy management. However, the significance of microgrids extends beyond their technical capabilities. Their development increasingly involves new forms of governance, market participation, and prosumer engagement within local energy systems (Hatziargyriou, 2014; Hirsch et al., 2018; Uddin et al., 2023). In this context, the concept of energy communities has gained increasing attention in both policy and research discussions. Energy communities refer to locally organized energy initiatives in which citizens, businesses, or local institutions collectively participate in energy production, consumption, and management (European Commission. Joint Research Centre., 2020). When combined with microgrid technologies and the social structure of energy communities, it integrates distributed energy technologies with new institutional arrangements and social participation. Such configurations have the potential to play an important role in shaping structural transformations of energy systems.

1.2 Research gap and research questions

Existing research has produced substantial knowledge on both microgrids and energy communities. Studies on microgrids have mainly focused on technological design, control architectures, optimization, energy storage integration, and economic performance (Hatziargyriou, 2014; Hirsch et al., 2018; Uddin et al., 2023). Research on energy communities has emphasized governance, prosumer participation, regulatory frameworks, and market roles (European Commission. Joint Research Centre., 2020; Gianaroli et al., 2024). While these studies have significantly advanced understanding of decentralized energy systems, less attention has been paid to energy community microgrids as integrated socio-technical configurations within broader energy transitions.

In particular, existing studies have rarely examined how technological infrastructures, institutional arrangements, and social participation interact in shaping the development of energy community microgrids and their potential contribution to the broader energy transition. Understanding these interactions is important for explaining how decentralized energy configurations can influence structural changes in energy systems. To address this gap, this study examines the mechanisms through which energy community microgrids shape the broader energy transition. The study is guided by the following research questions, which collectively examine the innovation dynamics, socio-technical interactions, and broader transition implications of energy community microgrids.

Main research question

How do energy community microgrids contribute to the broader energy transition?

Sub-questions

RQ1: What innovation dynamics shape the development of energy community microgrids during the energy transition?

RQ2: How do technological, institutional, and social dimensions interact in shaping the development of energy community microgrids?

RQ3: What opportunities and constraints do energy community microgrids create for broader energy transition?

These questions provide a structured framework for analysing how energy community microgrids develop and influence the broader energy transition.

1.3 Research approach and structure of the thesis

To address the research questions, this study adopts a qualitative case study approach focusing on the development of an energy community microgrid. The empirical analysis examines the LEMENE energy community microgrid located in Lempäälä, Finland. The project represents an early example of an industrial and business-oriented local energy community integrating distributed energy technologies, sector coupling, and market participation within a microgrid configuration (Nordic Energy Research, 2023). As a real-world implementation of decentralized energy infrastructure, the case provides an opportunity to examine how technological systems, institutional arrangements, and social actors interact in the development of energy community microgrids.

The analysis is guided by the Technological Innovation System (TIS) framework, which examines how emerging technologies develop through interactions among technological, institutional, and social elements within broader socio-technical transition processes. In particular, the study analyses the development of energy community microgrids through the seven key functions of innovation systems: knowledge development and diffusion, influence on the direction of search, entrepreneurial experimentation, market formation, legitimation, resource mobilization, and the development of positive externalities (Bergek et al., 2008). The analysis interprets these functions across three analytical dimensions: technological, institutional, and social (T-I-S). This perspective provides a structured view for examining the mechanisms through which energy community microgrids evolve within the broader energy transition.

The remainder of this thesis is structured as follows. Chapter 2 reviews the literature on energy transition, microgrids, and energy communities and introduces the socio-technical transition perspective and the Technological Innovation System (TIS) framework. It also outlines the seven TIS functions and the technological, institutional, and social (T-I-S) dimensions that guide the analysis. Chapter 3 describes the research methodology, including the case study design, case selection criteria, data collection process, and analytical framework used in the study. Chapter 4 presents the case study of the LEMENE energy community microgrid and the results of the functional analysis. The findings and their implications for understanding the role of energy community microgrids in broader energy transition are discussed in Chapter 5. Finally, Chapter 6 concludes the thesis by summarizing the main findings and outlining potential directions for future research.

2 Literature Review & Theoretical Framework

This chapter develops the theoretical foundation for analyzing how energy community microgrid technologies contribute to broader energy system transitions. The analysis proceeds through four interconnected steps: first, examining microgrids as both technical solutions and system-level arrangements; second, situating these developments within the broader framework of socio-technical transitions; third, introducing the Technological Innovation System (TIS) as an analytical approach for understanding innovation dynamics; and finally, proposing a multi-dimensional framework that embeds TIS functions within Technology, Institution, and Society dimensions to address identified analytical gaps.

2.1 Microgrids in the energy transition

To understand microgrids' significance in contemporary energy transitions, it is necessary to first establish what characterizes the current transition and why it differs from historical energy shifts. This section begins by examining energy transition as a socio-technical transformation, then introduces microgrids as technical systems and analyzes their roles, challenges, and future trends.

2.1.1 Energy transition as a socio-technical transformation

Learning to use fire was a significant event in human civilization and a major milestone in energy utilization. The sources of energy and the ways of using energy have shifted throughout human history. These processes are still continuous now and will undoubtedly have no ending in the future (Cherp et al., 2018). We are now in an era where there is an urgent need for a change in energy. These long-term processes, which are called energy transitions, are influenced by a number of variables, including technical innovation, regulations, environment, policies, economy, culture, etc. This complexity is a major challenge in researching and explaining the energy transition.

As shown in Table 1, a single, widely accepted definition of the energy transition does not exist in the literature. This reflects the inherently complex and multi-dimensional nature of energy transition processes, which involve not only technological change but also institutional and social transformations. However, these definitions still share a common core: an energy transition is commonly understood as a change in an energy system, typically involving a shift in energy sources, technologies, or prime movers (Sovacool, 2016). At the same time, due to the ongoing evolution of technology, policy, society, and so on, examining the current energy transition must be done from a broader perspective while retaining its core meaning. The current energy transition differs from earlier transitions in that it requires deeper systemic changes across multiple dimensions. Cherp (2018) argued that the current energy transition requires deeper system changes, incorporating numerous technologies and covering national and global scales, would be necessary to mitigate the dangers of climate change and address other sustainability concerns.

Table 1. Five definitions of energy transitions (Sovacool, 2016).

Definition	Source
A change in fuels (e.g., from wood to coal or coal to oil) and their associated technologies (e.g., from steam engines to internal combustion engines)	Hirsh and Jones (2014)
Shifts in the fuel source for energy production and the technologies used to exploit that fuel	Miller et al. (2015)
A particularly significant set of changes to the patterns of energy use in a society, potentially affecting resources, carriers, converters, and services	O’Connor (2010)

The switch from an economic system dependent on one or a series of energy sources and technologies to another	Fouquet and Pearson
The time that elapses between the introduction of a new primary energy source, or prime mover, and its rise to claiming a substantial share of the overall market	Smil (2010)

It is particularly important to clarify that the starting point for the energy transition we are currently experiencing is very different from that of the past. The current energy transition is driven by several key external factors, including climate change, increasing energy demand, Inequality, and energy dependence, each of which shapes the transition in different ways and is discussed in the following sections.

The global energy system must change quickly in order to address the global climate crisis. This is not simply an environmental initiative or a set of values, it is a major common challenge facing human society. The speed of human action is the key point, as the carbon emission should reach net zero by 2050 to limit global warming to 1.5 °C (Wallsgrove et al., 2021). The energy sector must contribute the most of reductions. Sovacool(2016) emphasized that it can be too late if a transition is not made rapidly. He introduced the "climate paradox," which states that humanity would have passed the point of no return by the time they fully understand how much they need to switch to low-carbon energy sources. Historical experience shows that energy transitions are always delayed or even reversed (Grubler, 2012), but this time we don't have much room to pay for such phenomena, and we can't rely solely on the progress of the free market to advance the transition. The energy system should run into sustainability fast.

Without an energy transition, energy demand will experience explosive growth that the current energy system cannot support. Nallolla (2023) anticipated that global energy consumption would rise by 53% by 2035. Simultaneously, the prices of the main energy sources in the current energy system are continuously increasing; this is made much more noticeable when the system's external costs are taken into account (Grubler, 2012). Artificial Intelligence (AI) is an emerging technology with the potential to become a general-purpose technology, deeply permeating every corner of society. It cannot be ignored in the energy transition, playing a dual role of energy consumer and improver. By 2030, AI-related energy consumption is expected to triple, making up around 1.3% of all electricity used worldwide (Senyapar & Bayindir, 2025). Energy demand cannot and should not grow indefinitely without considering efficiency. Even if all energy sources were renewable (obviously impossible, just as burning wood has never disappeared from human life), it still cannot be considered sustainable. The energy transition at this time cannot focus solely on changing energy sources; it must be considered holistically in conjunction with the demand side to jointly improve energy efficiency.

Approximately two billion people are still not benefiting from previous energy transitions, which have significantly increased society's access to modern (Grubler, 2012). A broader shift that radically transforms energy systems to solve inequality has been advocated by a number of academics, activists, and politicians (Wallsgrove et al., 2021). Energy justice is being called for incorporating into the energy transition, and academic research on energy justice has increased significantly . Figure 1 illustrates the three core tenets of energy justice: procedural justice, distributive justice, and restorative justice (McCauley & Heffron, 2018). Wallsgrove (2021) claimed that decision-making processes must: (i) equitably and adequately take into account marginalized perspectives and communities (procedural justice); (ii) distribute the advantages and disadvantages of generation, transmission, distribution, consumption, and other aspects of energy systems (distributive justice); and (iii) make amends for past and present injuries resulting from energy systems (restorative justice). He also emphasized that the principles are rarely implemented in practice at present, and there is a lot of work to be done. Energy justice is still on the way.

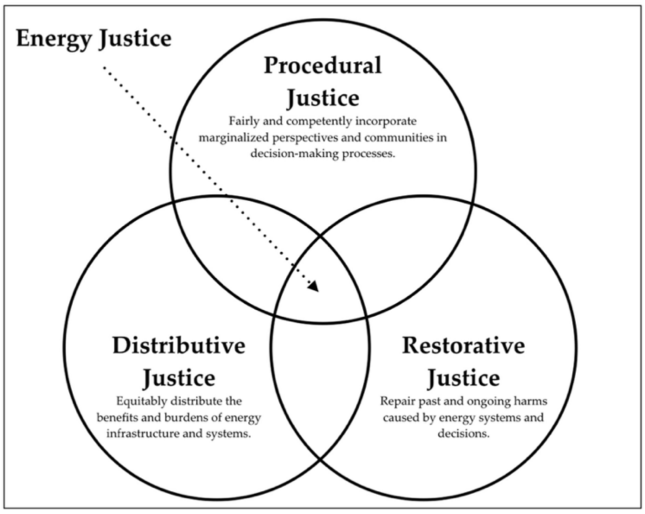

Figure 1. Three core energy justice principles (Wallsgrove et al., 2021).

In modern society, the demand for energy permeates every corner of society, making it more important than ever to ensure energy supply; this is known as energy security. According to Cherp & Jewell , energy security is defined as low vulnerability of vital energy systems (VES). They also mentioned an important system for categorizing concerns related to energy security, which included availability, accessibility, affordability, and acceptability. Extreme weather, war, political policies, global pandemic, and other unstable factors all threaten energy security at any time. The 2025 Iberian Peninsula blackout is a recent illustrative example of the vulnerability of the current energy system. A power drop of approximately 15 GW occurred in just five seconds, leaving millions in Spain and Portugal without power, disrupting critical infrastructures such as transportation, communications, and healthcare services, and even causing eight people to die (Cherp & Jewell, 2014; LaboniyAngel, 2025). Without energy security, we will not only be unable to make an energy transition, but we will have no energy at all.

These driving forces are propelling deeper and broader system changes, considered a socio-technological transformation. They promise us a future that can ‘ensure access to affordable, reliable, sustainable, and modern energy for all (Department of Economic and Social Affairs, n.d.). However, the bright future has not yet arrived; **the energy transition is not progressing smoothly.**

According to Smil (2010), an energy transition is the period of time between the launch of a new fuel and its ascent to a quarter of the national or international market share. Based on historical major energy transitions, this process is widely considered to be lengthy, taking decades or even more than a century (Grubler, 2012; Sovacool, 2016). There is currently no authoritative theoretical model to explain this phenomenon, but we can still find some insights to discuss it. Grubler(2012) points out that the expansion of technology is what promotes the energy transition, and that technological systems have clear patterns that prevent, or should be avoided, from taking bold actions. There are distinct "phases" required a significant amount of time and are sequenced rather than simultaneous, determining the decades-long processes during the transition. Moreover, Training professionals, upgrading technology, and building infrastructure in energy systems all require high investment and long timeframes, which leads to strong lock-in and inertia in the system to resist change (Knox-Hayes, 2012; Lund, 2006; Unruh, 2000). The strategic capturing, manipulation, or "overthrow" of a novel energy system or concept may also be a contributing cause to path dependence (Sovacool, 2016). The incumbent utilizes their enormous influence to control the energy transition, with huge, vested interests. The energy system is like a sophisticated and complex machine running at high speed, making it difficult to change direction.

Change is always slow, but it is not static or impossible to accelerate. Scholars suggested that **real evolutionary shifts must come from all levels of the system concurrently to overcome lock-in, inertia, and path dependence** (Sovacool, 2016). Sovacool (2016) noted that innovation, climate change, and scarcity are the key factors to accelerate future transition. He also emphasized that technological innovation has the potential for exponential growth. According to Professor Leah Stokes (2020), the speed and scope of cleaning up the electricity system are not secondary problems but a primary task in the energy transiton. According to Grubler (2012), end-use has a significant influence on driving energy transitions. Bottom-up, decentralized demand-side shifts are faster than traditional top-down supply-side shifts. However, the energy transition did not match the end-use shift, such as the rapid spread of electric cars. A bridge between the end-use and supply sides is needed to accelerate progress. Wagemans (2019) emphasized the importance of local energy coordination. Decentralization does not lead to an atomized society, and coordination mechanisms are still needed. The importance of coordinating end-use and energy supply in the energy transition is often overlooked, but its bridging role is key to facilitating a rapid transition.

2.1.2 What are microgrids? From technical concept to system solution

In the digital age, electricity has become a vital resource and has drastically changed modern civilization. The electrical network, which facilitates the transmission and distribution of power and connects more entities than ever acknowledged in history, is the most integrated physical system ever constructed by humans (Falvo et al., 2013). However, the electrical network of today is not a static entity. It is on a historic arc that started with Thomas Edison's small-scale distributed generation (known as the first DC microgrids) in the late 19th century, experienced centralization and consolidation due to rising demand, and is now beginning to revert to decentralization (Hirsch et al., 2018). Environmental protection, improved energy efficiency, energy security, reduced and deferred investment, and lower electricity costs all point to decentralized solutions. A widely accepted power grid architecture solution has emerged, known as “Microgrid”.

In the technical literature, the idea of a microgrid was first presented as a way to reliably integrate Distributed Energy Resources (DERs), including Energy Storage Systems (ESSs), with controlled loads. The main grid would view such a microgrid as a single component reacting to the proper control signals (Lasseter, 2001). This idea was later formalized in the U.S. context by the Department of Energy, which emphasizes clearly defined electrical boundaries and the capability of both grid-connected and islanded (Ton & Smith, 2012). In the European research context, the concept of a microgrid has a stronger focus on low-voltage distribution systems and coordinated operation. According to Hatziargyriou (2014, pp.24):

Microgrids comprise LV distribution systems with distributed energy resources (DER) (microturbines, fuel cells, photovoltaic (PV), etc.) together with storage devices (flywheels, energy capacitors and batteries) and flexible loads. Such systems can be operated in a non-autonomous way, if interconnected to the grid, or in an autonomous way, if disconnected from the main grid. The operation of microsources in the network can provide distinct benefits to the overall system performance if managed and coordinated efficiently.

Although these definitions come from different institutions and in different contexts, each with its own emphasis, they are highly consistent in their core requirements: The part of the distribution system that forms a microgrid can be distinguished from other parts of the system. The resources linked to a microgrid are managed cooperatively rather than independently. The microgrid can operate whether or not it has access to the main grid (Hirsch et al., 2018). These shared characteristics indicate that a microgrid is not merely a technical configuration, but a structured system in which generation, storage, loads, and control are organized.

Figure 2 illustrates a typical microgrid architecture. There are five basic components in a Microgrid system, including generation, Energy storage system (ESS), loads, Energy management system (EMS)& controller, and Point of Common Coupling (PCC).

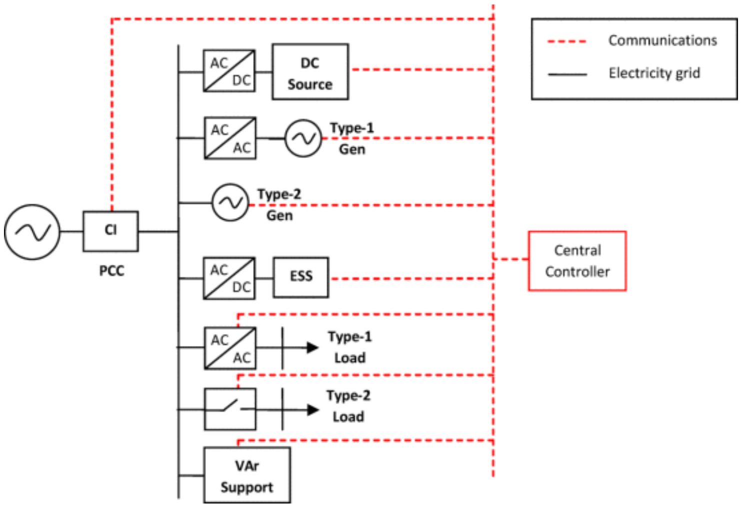

Figure 2. Microgrid general components (Olivares et al., 2014).

Generation: In terms of energy sources, two types of generation technologies can be used in microgrids, such as non-renewable distribution generation (internal combustion, engine, Microturbines, etc.), and renewable distribution generation (photovoltaic (PV), wind, biomass, hydro, etc.). Due to the intermittent nature of renewable energy resources, a fully renewable energy power system faces significant challenges in terms of controllability and reliability (Hossain et al., 2014; Lidula & Rajapakse, 2011). Categorizing generation solely by energy source is insufficient to understand the microgrid operation of flexibility and resilience. Therefore, an additional and analytically more relevant distinction is between dispatchable (biogas generators, combined heat and power (CHP), etc.) and non-dispatchable (solar, wind, etc.) generation (Uddin et al., 2023). This distinction is closely related to reliability and controllability, particularly in microgrids where supply-demand balance and islanded operation are critical. Centralized electricity generation is not suitable for the new energy system due to the requirement of sustainability, efficiency, reliability, flexibility, and accessibility. Many countries are actively promoting distributed and renewable power generation, and the share of efficient and sustainable power generation is growing rapidly. It is essential to point out that heat and power (CHP), also referred to as cogeneration, which concurrently generates electricity and heat, and wind power generation have demonstrated significant advancements in technology and application, establishing a robust case for use in microgrids (Lidula & Rajapakse, 2011).

Energy Storage System (ESS): Energy storage in microgrids can be classified according to the form in which energy is stored and released. As shown in Figure 3, storage technologies can be broadly grouped into electrical, electrochemical, thermal, mechanical, and electrochemical systems (Kolokotsa et al., 2019). Due to the fact that the majority of microgrid generation sources lack both the inertia characteristic of big synchronous generators and the load variability found in more expansive geographical areas, energy storage devices are vital components for the effective running of a microgrid (Hirsch et al., 2018; Lidula & Rajapakse, 2011). Depending on the specific project requirements and budget, energy storage is not mandatory, but introducing energy storage systems will greatly improve the operating efficiency and reliability of microgrids (Abu-Sharkh et al., 2006). The energy storage system (ESS) serves various purposes in microgrids (MGs), including maintaining energy supply continuity, ensuring power quality, peak load shaving, frequency management, time and peak shifting, and stabilizing the output of renewable energy sources (RESs) (Hossain et al., 2014; Kolokotsa et al., 2019; Lidula & Rajapakse, 2011; Uddin et al., 2023). The most typical scenario for energy storage systems is to support seamless switching between grid-connected and islanded operation of microgrids in order to maintain the important characteristic of resilience (Lidula & Rajapakse, 2011). It should be mentioned that a distributed energy resources (DER) unit may also be a hybrid, meaning that it has a storage component in addition to its primary energy source (Laaksonen, 2011). The development of energy storage technologies has been rapid over the past few decades. Batteries, flywheels, and super-capacitors are the energy storage technologies that are most suitable for microgrid systems among those that are currently available (Abu-Sharkh et al., 2006; Laaksonen, 2011; Lidula & Rajapakse, 2011).

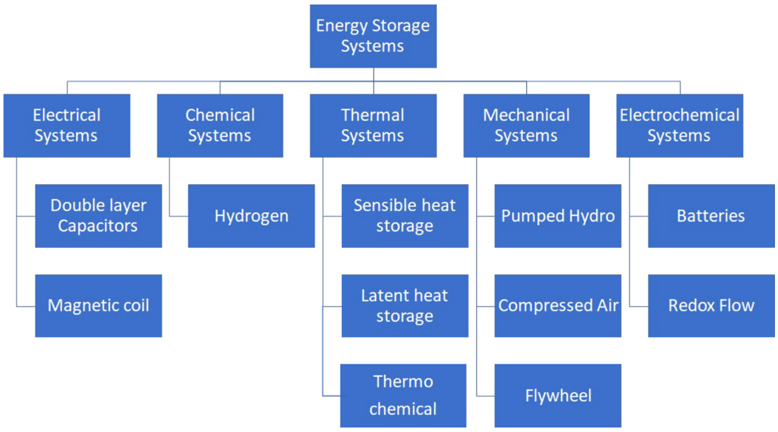

Figure 3. The energy storage systems categories (Kolokotsa et al., 2019).

Loads: In order to achieve the most economical power generation, microgrids have two main types of loads: (i) critical loads that must be served in all circumstances, and (ii) deferrable loads that can be modified for microgrid load balancing. (Lidula & Rajapakse, 2011; Mariam et al., 2013; Uddin et al., 2023). Critical loads are considered sensitive, which require high power reliability and quality (Lidula & Rajapakse, 2011). In the microgrid configuration, this load classification is crucial to achieving the desired operation: Improvement of power quality and reliability in crucial loads; Optimization of DER ratings by reducing the peak load; Stabilization of voltage and frequency in island condition; Satisfaction of net import/export electricity in grid-tied mode (Hossain et al., 2014; Lidula & Rajapakse, 2011).

Energy Management System (EMS) & Control: The Energy Management System (EMS) and control units together constitute the operational core of a microgrid. With the aid of energy meters and communication devices, EMS guarantees the microgrid's smart operation. The EMS is responsible for decision-making and optimization, such as scheduling generation, storage, and loads based on economic, reliability, and operational criteria (Uddin et al., 2023). The system's real-time operation is supervised by the microgrid controller. The controller ensures the real-time execution by regulating voltage, frequency, and power flows under different operating modes, including grid-connected and islanded operation (Lidula & Rajapakse, 2011; Uddin et al., 2023).

Point of Common Coupling (PCC): Since it serves as the physical link between the microgrid and the main grid, the point of common coupling (PCC) is a vital component. This comprises parts like protection relays, synchronization devices, and circuit breakers (Uddin et al., 2023). Beyond acting only as a physical connection point, the PCC plays a key role in enabling controlled power exchange, safe islanding, and secure reconnection between the microgrid and the utility grid. From a system perspective, the PCC defines the electrical boundary of the microgrid, allowing it to be treated as a single controllable entity from the viewpoint of the main grid (Hirsch et al., 2018). Microgrids without a PCC are isolated microgrids. Isolated microgrids run continuously in stand-alone mode in remote locations where connecting to the main grid is difficult due to technical or financial limitations (Olivares et al., 2014).

The new structure design of microgrids brings many operational challenges, especially in control and protection, that need to be overcome to realize its potential and not put the existing system in danger. The main obstacles are bidirectional power flows, stability problems, updating modeling, low inertia, and uncertainty (Olivares et al., 2014). There are two very different methods that may be distinguished when it comes to the control architecture of a power system: centralized and decentralized (Hatziargyriou, 2014). The centralized control system uses data collected in a specialized central controller, demanding close contact between the central controller and the units under control (Hossain et al., 2014). The decentralized control only receives local input and is not completely aware of system-wide variables or other controllers' actions. It allows a system in which any device can regulate itself independently (Khajeh et al., 2020; Olivares et al., 2014). The power system spans a vast geographical area, and some internal units are strongly coupled, making it impossible to achieve expection by either centralized or decentralized control. Olivares et al. (2014) proposed a compromise, a hierarchical control scheme with three control levels: primary, secondary, and tertiary. The hierarchical architecture, shown in Figure 4, illustrates the relationships between different control levels. Primary control, also called local control, has the quickest reaction without communicating demand. Secondary control, also known as EMS, is responsible for the optimization of microgrid operation. Tertiary control can coordinate several micrograms at the highest level, being considered as a portion of the main grid.

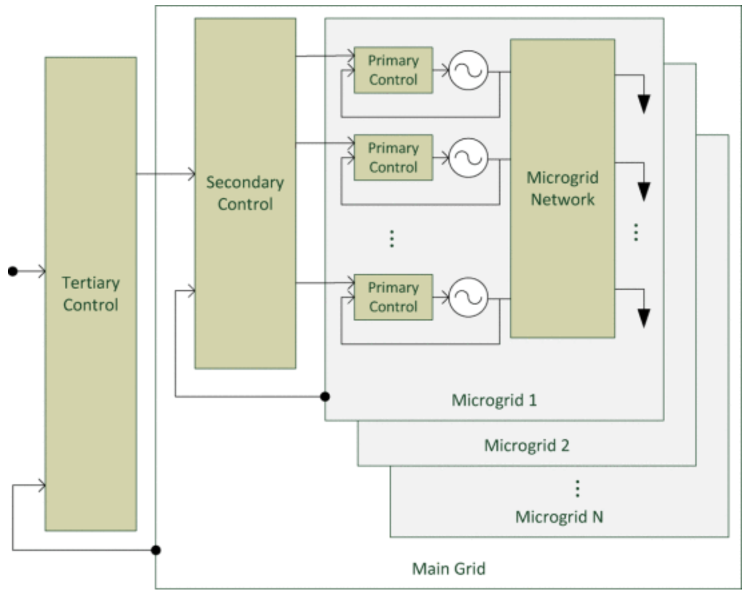

Figure 4. Hierarchical control levels: primary control, secondary control, and tertiary control (Olivares et al., 2014).

Figure 5 illustrates the multiple classification dimensions of microgrids, showing how they can be differentiated by control architecture, size, power supply type, energy sources, operating scenarios, geographical location, and application contexts. Selecting the ideal microgrid could be challenging because they are available in a wide variety of configurations. It becomes particularly crucial to fully understand the goal and application context (Wood, 2018).

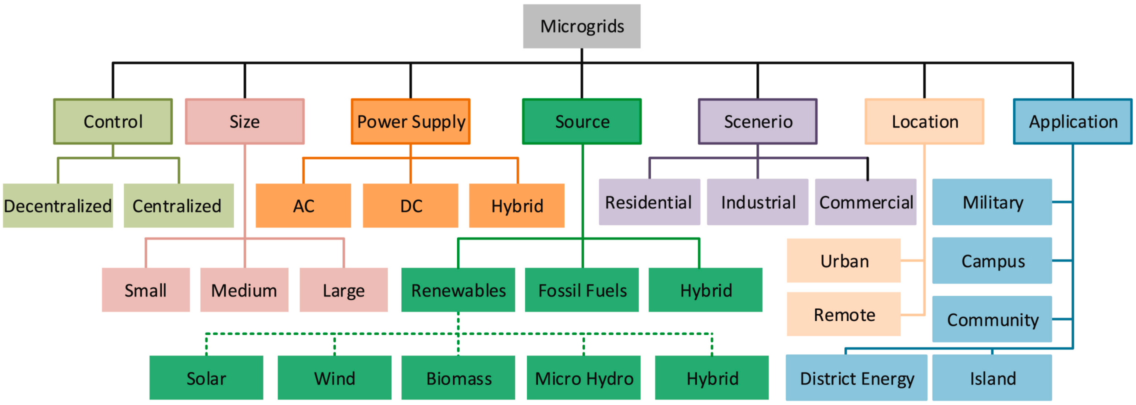

Figure 5. Classification of microgrids (Uddin et al., 2023).

A microgrid's final design and operating plans are determined by the possibly competing interests of several parties involved in the supply of electricity, including network executives, distributed generation (DG) owners and operators, providers of energy, consumers, and regulatory agencies (Hatziargyriou, 2014). As shown in Figure 6, Technical, economic, or environmental aspects decide the optimal operation plan in microgrids (Hatziargyriou, 2014; Laaksonen, 2011). Recent research emphasizes that infrastructure systems are increasingly expected to serve broader system-level objectives, including equity and public value, which cannot be fully captured by purely technical, environmental, or economic criteria (Sovacool et al., 2016). Microgrids also need to carry more diversified goals in the larger social transformation.

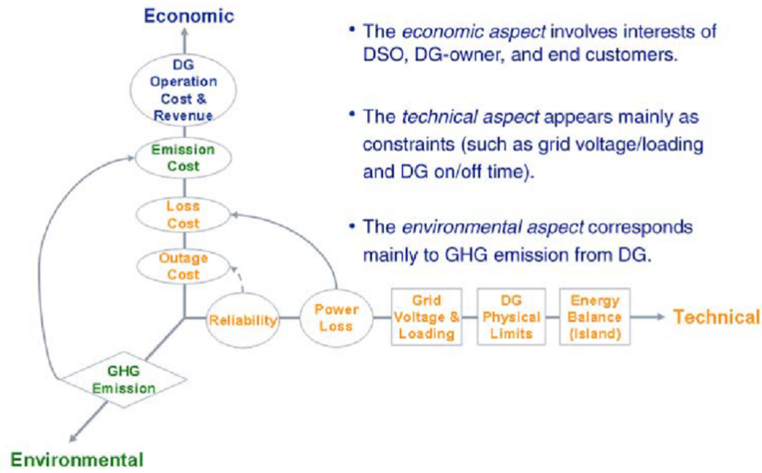

Figure 6. Microgrid operation strategies (Hatziargyriou, 2014).

2.1.3 Roles of microgrids in the energy transition

From the viewpoint of the energy transition, microgrids are crucial not only because of their technical advantages but also their ability to address a variety of interconnected system-level demands in energy transition brought on by climate change, rising energy demand, inequality, and energy dependence. They make it possible for important transition processes that are challenging to carry out in the centralized energy systems of today. According to Hirsch et al. (2018), three factors—energy security, economic benefits, and clean energy integration—are driving microgrid development in areas with existing grid architecture. While these drivers help explain the diffusion of microgrids, they also point toward a broader analytical question regarding the role of microgrids within the ongoing energy transition. Rather than focusing solely on their individual advantages, microgrids can be viewed as system-level arrangements whose structural features influence the restructuring of energy supply configurations, the transformation of demand-side dynamics, and the increasing significance of social and institutional requirements in energy system design.

Reconfiguring energy supply structures: decarbonization, renewable integration, and distribution. Decarbonizing generation is an important means of achieving the goal of zero emissions, but it also faces the greatest inertia of the energy system (Sovacool, 2016). Recent global energy statistics show that fossil fuels still provide over 80 % of the world’s primary energy consumption (Energy Institute, 2024). Microgrids do not mandate a specific generation and may integrate both low-carbon and fossil-based energy sources. However, in real-world cases and studies, microgrids have demonstrated a significant effect on emissions reduction. According to most of these studies, microgrids, especially with an energy storage system, cause much fewer climate change impacts than other power generation technologies (Papageorgiou et al., 2020; Wallsgrove et al., 2021)

A higher proportion of renewable energy is an important indicator of energy transition. The intermittent nature of renewable energy sources such as solar and wind power makes their output uncertain, hindering their large-scale use (Us Salam et al., 2024). Yu (2018) noted that massive PV integration creates new problems for the electrical system, such as sub-optimization and grid management. To overcome this hurdle, microgrids can work as a system-level integration mechanism, rather than treating renewable generation as isolated injections into a centralized grid, providing a bounded operational environment in which distributed renewable sources, energy storage, and controllable loads can be jointly managed (Hirsch et al., 2018; Olivares et al., 2014).

Distributed energy generation and transmission are an important direction for High-efficiency and economical energy. Utility investments in new generating capacity are referred to as "lumpy" because the ideal size for additions of generating stations under the conventional central generating plant model is quite substantial (Van Nostrand, 2015). Numerous imbalances may result from this mismatch between resource upgrades or reductions and growing or reducing load. It also happens in the transmission capacity additions, for instance, a “North American Supergrid” has obstacles to the installation of large transmission infrastructure (Klass, 2019). Microgrids offer a flexible solution by implementing distributed generation closer to the load, in accordance with a grid operator's local demands (Wallsgrove et al., 2021). The characteristic of distribution in microgrids is the system-level contribution to the energy supply side. In terms of energy resources, generation scale, and transmission configuration, microgrids have significant potential to change the supply-side structure.

Responding to demand-side transformation: electrification, flexibility, and efficiency. Electrification enables energy transitions by shifting final energy demand toward electricity, which can be supplied by low-carbon or renewable sources. Remote areas or underdeveloped areas are a major challenge for electrification. Microgrids are a feasible approach to address this issue with the ability of integration of distributed generation and energy storage systems (Hatziargyriou, 2014; Wallsgrove et al., 2021). Drawing on three cases from Southeast Asia, Brown et al. (2024) show that microgrids provide a scalable and context-sensitive solution for electrification where centralized grid extension is economically or technically infeasible. Moreover, Electrification does not necessarily lead to a transition toward renewable or clean energy sources. In this context, microgrids can function as an intermediate bridge that links end-use electrification with low-carbon electricity supply, with the capacity to integrate renewable energy resources (Hirsch et al., 2018). Electrification also presents challenges to the power system. For example, a large number of electric vehicles can significantly impact grid stability (Laaksonen, 2011). Microgrids have the ability that can offer flexibility to proactively manage electric vehicle charging and even utilize bidirectional flow capabilities of grids to draw power from electric vehicles to assist grid operation (Wallsgrove et al., 2021; Woo et al., 2025).

The energy system is changing as a result of residents and communities joining together on energy projects. Prosumers, actors who both produce and consume energy, are new stakeholders in the energy transition (Kotilainen, 2020). Prosumers challenge the traditional centralized organization of electricity systems and require new system-level arrangements to coordinate distributed production and consumption (Parag & Sovacool, 2016). By enabling local control, aggregation, and interaction with the main grid, microgrids have the flexibility to transform individual prosumer actions into manageable and reliable system contributions (Hatziargyriou, 2014; Wallsgrove et al., 2021). Energy communities are generally understood as collective arrangements in which local actors actively participate in the production, management, or governance of energy systems, offering advantages to the local community (European Commission. Joint Research Centre., 2020). Their practical implementation often conflicts with centralized grid operation and existing utility business models (Hirsch et al., 2018). Microgrids can mitigate this tension by translating community participation into a technically manageable and institutionally compatible system configuration. Utilities and local users can jointly invest in and manage distributed resources within controlled boundaries (Hirsch et al., 2018; Wallsgrove et al., 2021).

There are more variable and uncertain electricity consumption patterns at the user level. These changes significantly raise the need for ancillary services to maintain system stability. Traditional ancillary services, such as frequency regulation, voltage control, and reserve provision, were historically supplied by large centralized generators, but are becoming less suited to highly variable and decentralized power systems (Hirsch et al., 2018). Through demand response, peak shaving, and load shifting, microgrids transform demand-side uncertainty into a manageable system resource, thereby supporting more efficient and reliable operation under evolving consumption patterns (Uddin et al., 2023). Microgrids increasingly act as active providers of ancillary and system support services, linking the use-side to the energy system closely.

Addressing social and institutional requirements: resilience, accessibility, and equity. Mitigating or halting climate change has become the initial driver of the ongoing energy transition. At the same time, adapting to the threats from climate change, such as extreme weather events, has become a challenge we must confront. (Van Nostrand, 2015). While early microgrids were first created to improve system resilience against a variety of vulnerabilities rather than as methods for mitigating climate change (Wallsgrove et al., 2021). They just happened to come together. The microgrid demonstrated its remarkable resilience in the face of extreme weather. For instance, the current microgrids in New

York performed excellently during Hurricane Sandy (Ajaz & Bernell, 2021). The importance of this grid resilience sometimes reaches the level of life-sustaining importance, particularly in critical infrastructures (Wallsgrove et al., 2021). The ability to anticipate, plan for, absorb, recover from, or more successfully adjust to existing or potential negative situations is known as resilience (Us Salam et al., 2024). In addition to passive resilience, microgrids also demonstrate good resilience in dealing with unstable factors such as war and pandemics because they have the ability to actively disconnect and manage energy (Uddin et al., 2023). It is worth emphasizing that cybersecurity is an increasingly important issue for all infrastructure in the digital age, including microgrids (Nejabatkhah et al., 2020). Decentralized and information-communication-enabled microgrids have the characteristic of improving the overall security of the power grid (Wallsgrove et al., 2021). Resilience and energy justice are interconnected, as seen by the damage created by Hurricanes Irma and Maria in 2017, restoring much more slowly in remote and low-income areas (Román et al., 2019).

Energy access is a human right. Nonetheless, the United Nations reports that 789 million people worldwide still lack access to electricity (Us Salam et al., 2024). The effectiveness of rural microgrids in expanding electricity access has been widely recognized in the literature (Bertheau et al., 2017). For instance, Puerto Rico has transformed its condition through microgrids with small-scale solar and energy storage projects, significantly improving regional energy accessibility (Glattard, 2022). According to estimates by the International Energy Agency, mini-grid systems could provide electricity access to approximately 140 million people in Africa by 2040 (Narayan et al., 2020). Accessibility is a solid first step toward energy justice. Energy justice is meaningless if energy is unavailable.

Traditional relationships between different users and between users and electricity producers make it difficult to broaden participation in decision-making and allocation processes (Sovacool, 2016). Many utilities even attempted to prevent deeper public participation (Hirsch et al., 2018). Microgrids present a chance to restructure conventional positions in the production and use of power, through the new social interactions that arise inside the confines of a microgrid, such as participation, ownership, and control (Bickerstaff et al., 2013). More inclusive participation under collective ownership can better advance energy justice in terms of equitable distribution (Banerjee et al., 2017). For instance, the joint-ownership microgrids being developed for the island of Culebra and Toro Negro in Ciales frequently serve more remote communities (Glattard, 2022). Microgrids can, in fact, contribute in this way, taking into account the three principles of energy justice (Bickerstaff et al., 2013). These dimensions indicate that microgrids contribute to energy transitions not only by enhancing technical performance but also by embedding resilience, accessibility, and equity into the operational design of energy systems.

The extent to which these dimensions are realized varies across different microgrid configurations and governance models. As illustrated in Figure 5, microgrids can be classified by operational mode, geographical setting, size, and application domain (Uddin et al., 2023). Prior studies often distinguish, for example, campus microgrids that emphasize technical–economic optimization within institutional boundaries (Soshinskaya et al., 2014), remote microgrids that operate in stand-alone mode to address energy access constraints (Ton & Smith, 2012), and utility-led microgrids that support reliability and distributed resource integration under incumbent coordination (Hatziargyriou, 2014). This diversity suggests that microgrids contribute to energy transitions through different mechanisms depending on how they are configured and governed (Hirsch et al., 2018).

Against this background, energy community microgrids constitute a distinct configuration in which technical operation is closely intertwined with organizational and participatory arrangements. Energy communities are commonly defined as collective arrangements where local actors, such as citizens, municipalities, small enterprises, or cooperatives, participate in energy generation, distribution, storage, and consumption (Koirala et al., 2016). In the European Union, this concept has been formalized through two legal categories—Renewable Energy Communities (RECs) and Citizen Energy Communities (CECs)—which institutionalize citizen and community participation across a range of energy activities (European Commission. Joint Research Centre., 2020). Within such organizational forms, microgrids can be understood as enabling infrastructures that coordinate distributed energy resources, storage, and flexible loads while also embedding governance structures, ownership models, and decision-making processes into the operational boundary of the system (Warneryd et al., 2020).

The literature further indicates that energy community microgrids can integrate supply-side and demand-side dynamics within a bounded local system, for instance by coordinating renewable generation with prosumer participation, load flexibility, and local energy exchange (Parag & Sovacool, 2016). At the same time, their development often entails interaction with institutional conditions, such as regulation, market rules, and grid codes, because multi-actor ownership and operation require arrangements beyond conventional centralized models (Koirala et al., 2016; Warneryd et al., 2020). Community ownership and collective governance also foreground social dimensions, including participation, equity concerns, and local value creation, as part of system design and operation (Bickerstaff et al., 2013; Walker & Devine-Wright, 2008). In this way, energy community microgrids represent a configuration where technical, institutional, and social elements co-evolve through mutual interaction, which differentiates them from other microgrid forms that are more narrowly oriented toward technical or operational objectives.

The literature suggests that microgrids play multiple and interrelated roles in contemporary energy transitions, contributing to the restructuring of energy supply, the coordination of demand-side transformation, and the realization of broader social and institutional objectives. However, the realization of this multi-dimensional potential is neither automatic nor straightforward. The following chapter examines the key challenges associated with deploying microgrids in energy transitions, as well as future trends proposed in recent research.

2.1.4 Challenges and future trends

Change is always accompanied by obstacles. Recognizing the difficulties we face is the first step towards the future, while understanding future trends is the beacon guiding us there. The ability of microgrids to support energy transitions depends on a range of technical, institutional, and social conditions, and is accompanied by significant challenges related to governance, coordination, and system integration.

From a technical point of view, there are several challenges that need to be addressed. Firstly, microgrids are made up of a variety of power generation sources, which leads to the low inertia of the system, making it difficult to maintain stability. This is because the system's low inertia in islanded mode of operation reduces the system's angular stability, which in turn influences the microgrid's voltage and frequency, causing the system to become unstable (Saeed et al., 2021). Another challenge is to integrate and locate renewable energy resources optimally in the energy system because of their nature of intermittency. Current forecasting techniques are not perfectly accurate to solve it (Us Salam et al., 2024). Additionally, the introduction of bidirectional power flows, grid-connected and islanded operating modes, and multi-objective optimization requirements makes microgrid control and protection significantly more complex than in traditional centralized power systems (Hirsch et al., 2018; Olivares et al., 2014; Uddin et al., 2023).

A recurring theme in the literature is that, although microgrids pose substantial technical challenges, these are often regarded as more readily addressable than the institutional, regulatory, and coordination barriers surrounding their deployment (Hirsch et al., 2018; Olivares et al., 2014; Wallsgrove et al., 2021; Wright et al., 2024). Hirsch et al. (2018) highlighted that significant challenges remain in aligning regulatory frameworks, market structures, and governance arrangements with decentralized and multi-actor system configurations. Wright et al (2024) emphasized the significant obstacles posed by the existing regulatory framework. As Grubler (2012) noted, the benefits of technological innovation depend critically on corresponding organizational and institutional change. Beyond regulatory alignment, a deeper institutional challenge concerns how microgrids are evaluated and valued. Microgrids challenge conventional evaluation approaches that rely primarily on indicators such as the levelized cost of electricity (LCOE). While suitable for centralized generation, such metrics fail to capture the broader system and social values of microgrids, including flexibility, resilience, ancillary services, and contributions to energy justice, revealing a clear mismatch between existing assessment frameworks and the multidimensional roles microgrids increasingly play in modern energy systems (Wallsgrove et al., 2021).

Another obstacle is the process of societal transformation that comes with the creation of a microgrid. Wright et al.(2024) emphasized that determining who in the community would be active and who would profit is opening Pandora's box. New technologies are always rough around the edges, and they are adopted because of their technological expectations, namely, the greater application potential and long-term cost advantages they offer in the future (Grubler, 2012). In this context, conflicts between local actors, utilities, and regulatory frameworks constitute a major barrier (Hirsch et al., 2018). Research on energy justice and prosumers shows that decentralized energy systems challenge existing governance arrangements and require new forms of participation and trust (Bickerstaff et al., 2013; Parag & Sovacool, 2016). A common issue in the literature was the absence of a framework for directing the process of social change, which highlighted how unpredictable and disorganized the innovation process is (European Commission. Joint Research Centre., 2020; Sovacool, 2016; Wright et al., 2024). The literature suggests that without sufficient social acceptance and guiding frameworks, efforts to promote participation and social change risk remaining fragmented, limiting the realization of technological expectations.

While early microgrid developments primarily focused on solving localized technical problems, such as improving reliability, enabling islanded operation, or integrating specific distributed resources, recent developments indicate a broader shift in how microgrids are conceived and governed. Increasing system complexity, coupled with multi-actor participation and diverse societal objectives, has revealed that technical optimization alone is insufficient. Instead, microgrids are increasingly understood as coordination infrastructures that align physical operation, information flows, and decision-making across multiple actors and objectives (Hirsch et al., 2018; Sovacool et al., 2015; Uddin et al., 2023).

Recent developments suggest that the future evolution of microgrids is increasingly shaped by digital and data-driven technologies. Their significance lies not primarily in incremental performance improvements, but in their capacity to enable adaptive, anticipatory, and coordinated system operation under complex and uncertain conditions (Hatziargyriou, 2014; Olivares et al., 2014). Artificial intelligence has been widely applied in microgrid research for forecasting, control optimization, and fault detection (Bilal et al., 2024; Mohammadi et al., 2022; Trivedi & Khadem, 2022). Beyond these applications, AI introduces a qualitative shift by enabling microgrids to move from predefined, rule-based operation toward adaptive and learning-based coordination (Hatziargyriou, 2014). Through continuous sensing, prediction, and optimization, smart systems can respond to uncertainty and multi-objective trade-offs in ways that conventional control architectures cannot (Hirsch et al., 2018). Digital twins further expand the analytical and governance capacity of microgrids by enabling the simulation of system behavior, the evaluation of operational or policy decisions, and institutional learning processes without requiring direct intervention in physical infrastructure (Fuller et al., 2020; Hadi et al., 2025). Similarly, blockchain-based approaches have been explored as mechanisms to support trust, transparency, and coordination among distributed actors, particularly in contexts involving peer-to-peer exchange or shared ownership (Hadi et al., 2025; Hirsch et al., 2018).

These developments suggest that the future trajectory of microgrids is not defined by a single technological breakthrough, but by their growing role as platforms for coordinating supply, demand, and participation under evolving energy system conditions. This shift from isolated technical solutions toward integrated socio-technical coordination provides an important context for understanding both the potential and the limitations of microgrids in energy transitions.

The analysis presented in this section reveals that microgrids embody characteristics that extend beyond their technical configuration. Their deployment involves not only the integration of distributed energy resources and control systems but also the reconfiguration of actor relationships, regulatory frameworks, and social expectations. These observations suggest that understanding microgrid development requires analytical tools capable of capturing the multi-dimensional and systemic nature of change. The following section introduces the concept of socio-technical transitions as a framework for understanding such complex, system-level transformations.

2.2 Socio-technical transition

Modern society increasingly faces systemic problems that cannot be solved through end-point solutions. Structural reform has become a crucial way of thinking to address these challenges (Raven, 2007). At the same time, due to the interconnectedness of modern society's operating mechanisms and the universality of many modern innovative technologies, the application of new technologies always brings about multi-dimensional linkages, leading to structural evolution. This has attracted attention from scientists, policymakers, and industry on the concept of socio-technical transition.

Socio-technical transitions are systemic shifts that involve changes in the broad configuration of transportation, energy, and agri-food systems, which include technology, regulation, structures, economies, customer behaviors, and cultural meaning (F. W. Geels, 2004, 2011). It contains not only technical advancements but also modifications to infrastructure, industrial networks, regulations, user behavior, and symbolic significance (F. W. Geels, 2002). **Transition studies have emphasized that the changes in socio-technical transitions are in the basic elements that constitute the functioning of socio-technical regimes, including technological, institutional, and social dimensions** (Raven, 2007).

These transformations are profound structural changes, involving a wide range of areas, a complex and lengthy process, and multiple interconnected dimensions.

Socio-technical transition is not simply a matter of technological advancement, replacement, or innovation, but rather **an innovation of a system**. The components of a technical system are complicated and messy. The term "Large Technical Systems (LTS)" refers to a specific kind of infrastructure-related technology, such as the internet, telephone systems, railroad networks, and power networks. The components of LTS include physical artifacts (such as turbogenerators, transformers, and electric transmission lines in a power network), organizations (e.g., manufacturing firms, investment banks), scientific elements (e.g., books, articles, and research programs), natural resources (e.g., coal), and legislative artifacts (e.g., laws) that are interconnected with each other (Bijker et al., 2012; Hughes, 1987). The various components influence each other and co-evolve to push the process of transitions (F. W. Geels, 2004). This complex, multi-element system greatly hinders our understanding and discussion of the transition process, requiring a structured dimension to organize the heterogeneous elements.

Dominant regimes in transitions often possess **significant inertia**, exhibiting stability and rigidity, where incumbents resist any structural change (F. W. Geels, 2002). Even with a degree of innovation, reforms tend to proceed slowly and gradually along specific technological paths, leading to so-called path dependence. Existing infrastructure across various dimensions provides this rigidity, raising the barrier to reform and often reflecting substantial vested interests. The established economic power structure formed by stakeholders causes capital to disregard new alternatives, even those with greater social value (Raven, 2007). Therefore, understanding, adapting, and then reforming the existing regimes are crucial. Only by identifying the patterns in how the mechanisms operate can the transformation process be driven forward. Simply focusing on technological innovation cannot break through this rigidity.

Technology is powerless and can do nothing on its own. Technology only serves purposes when combined with human agency, social structures, and institutions (F. W. Geels, 2002). As shown in Figure 7, socio-technical transitions may unfold in different contexts depending on two key dimensions: (1) the degree to which system change is intentionally coordinated or emerges through decentralized co-evolution, and (2) whether adaptive capabilities are located within the incumbent regime or rely on external actors and resources (Smith et al., 2005). These two dimensions yield four stylised transition contexts: endogenous renewal; re-orientation of trajectories; emergent transformation and purposive transitions, each associated with distinct governance challenges and mechanisms.

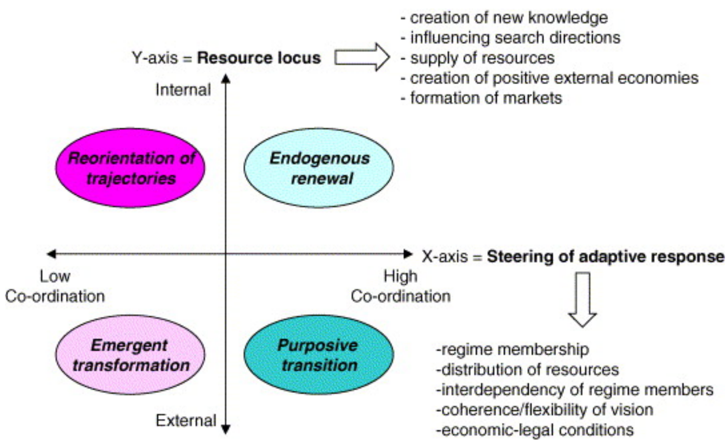

Figure 7. Transition contexts as a function of degree of coordination to selection pressures and the locus of adaptive resources (Smith et al., 2005).

Sustainability transitions have attracted special attention from both the academy and industry among different types of socio-technical transitions because of their systemic implications and social ambitions. Research on sustainability transition is growing rapidly, with diversified topics, expanding geographical scope, and deepening economic and political understanding (Köhler et al., 2019). The transition to sustainability is undoubtedly one of the greatest challenges facing the world, and it has some particular characteristics.

Dynamic process: Sustainability, however, is a vague and undefined concept, or rather, a constantly evolving one. Since the concept of sustainability is highly debated, the best technologies and transition paths for sustainability transitions are frequently discussed by various actors and social organizations (Köhler et al., 2019). This means that the sustainability transition will be a continuously discussed, optimized, and perhaps never-ending process (Stirling, 2009). The dynamic character is also revealed from the non-linear nature of different processes: It may face failures, rapid improvement, or disappointment with expectations in innovation processes; It may encounter delays, obstacles, reversals, or promotion in regulatory processes; It may suffer shifts of hope from the public, or pressure from urgency in social processes (Köhler et al., 2019). These give sustainability transition a more dynamic characteristic.

Efficiency Dilemma: The fact that most "sustainable" solutions don't clearly advantage users is another feature that distinguishes sustainability transitions from others, and often perform worse than existing mature technologies from either cost or performance perspective (F. W. Geels, 2011). Although technology is constantly advancing and research is increasing, its application in practice and daily life is still extremely limited (Köhler et al., 2019). It is unrealistic to expect all consumers to voluntarily pay more for the same or even worse service, companies to proactively reduce their profits and existing market share, and smooth transitions to be completed through full market competition. The dilemma of profitability will persist for a long time during the transition, and it cannot be overcome mainly by relying on technological innovation and public awareness. This means that the institution should play a vital role in this condition and determine the orientation of transitions through subsidies, taxes, standards, and regulatory frameworks (Köhler et al., 2019).

Social value goal orientation: The third characteristic related to the context, according to the four categories mentioned earlier, sustainability transitions belong to purposive transitions that make it goal-oriented, which is quite different from most historical transitions that emerged by commercial chances with internal new technology. Because the objective is linked to a public benefit that cannot be achieved by only engaging individual stakeholders to solve the problems (F. W. Geels, 2011). This kind of transition is considered a structural reform involving the replacement and reorganization of elements. A change in one element will influence another element to change as well, and this requires balancing the interests of each stakeholder to maximize the final benefit (sustainability), which means facing free-ride problems or prisoner's dilemma (F. W. Geels, 2002, 2011; Köhler et al., 2019). This profound transition in socio-cultural values presents unprecedented challenges to a sustainable transition.

The energy transition is widely seen as a cornerstone of achieving broader sustainability goals. **A sustainable future depends on reducing climate change, and energy transition is a key part of this effort** (Us Salam et al., 2024). Energy is not only a necessity but also the driving force behind all human activities, serving as the defining marker of civilization's advancement. Better utilization of energy is an eternal topic for humanity, inherently a “sustainable” process, and the most crucial component of sustainable development. As a central area of sustainability transitions, energy systems provide a particularly appropriate context for analyzing the practical interactions between technological, institutional, and social shifts.

As a typical kind of socio-technical and sustainability transition, the energy transition is not a simple, direct technical process, but a dynamic, complex, and structural transformation. With these special characteristics, an analytical framework is required to reflect the whole mechanism. A major area of study to address this problem is innovation system approaches. Therefore, in the following sections, the Technological Innovation System (TIS) framework is introduced and discussed with its strengths and limitations in sustainability transitions. It provides the theoretical foundation for the analytical framework employed in this study.

2.3 Technological innovation system

An increasing number of academic scholars interested in the mechanisms behind breakthroughs, industrial transformation, and economic development have come to embrace the idea of an "innovation system." International institutions interested in promoting these processes, such as the European Commission, as well as regional and state authorities and agencies, have also embraced the innovation system method (Bergek et al., 2008). The technological innovation system (TIS) approach is one of the two main viewpoints in current research on sustainability transitions and has been widely accepted by scholars (Li et al., 2015; Markard & Truffer, 2008).

A group of Swedish researchers created the framework for technological innovation systems in the period between the years 1980 and 1990. Swedish policymakers started the effort with the goal of building a stronger base for technology policy (Carlsson, 2006). Carlsson and Stankiewicz (Stankiewicz & Carlsson, 1991) defined a technological system as "a network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilization of technology." This definition serves as the foundation for the idea of a technological innovation system.

The functions approach is a significant feature of TIS, with seven vital processes that immediately and decisively affect the creation, adoption, and utilization of new technologies (Bergek et al., 2008). The objective was to determine a common understanding of the key processes that support the system's goal. The original definition of function was the contribution of a component or set of components to the overall function of the TIS (Bergek, 2019). There are some rationales to using that function approach. First, it is a more methodical approach to identifying innovation determinants. Second, this viewpoint makes it easier to compare the performance of innovation systems with various institutional configurations. Third, a defined set of policy goals and tools could be provided by the functional perspective (Hekkert et al., 2007).

The following list of functions (F1-F7) is to be used to define the key processes and to outline and clarify changes in innovation systems:

Function 1: Knowledge development and diffusion are procedures that lead to the expansion and deepening of a TIS's knowledge base that can reflect how it evolves over time and how it is integrated and dispersed throughout the system (Bergek et al., 2008; Hekkert et al., 2007). Since knowledge development and diffusion are essential components of the innovation system, this function is typically positioned at the center of a TIS (Bergek et al., 2008). To define development, three common markers are*: 1) R&D projects; 2) patents; and 3) R&D investments* (Hekkert et al., 2007). The number of *workshops and conferences* devoted to a particular technology issue and the connections between businesses and academic institutions or other businesses can be mapped in order to assess their diffusion (Bergek, 2019; Hekkert et al., 2007).

Function 2: Influence on the direction of search means the mechanisms that affect how businesses and other players search for new possibilities, as well as the issues and solutions to which they devote their resources (Bergek, 2019). To develop a TIS, effective pressures or incentives are needed to engage the organizations in the desired direction of search (Bergek et al., 2008). It should be highlighted that this function relates to *supplier players* along the full value chain, while the direction of actors' choice to implement or purchase a technology for their own use is considered market formation (Bergek, 2019). Qualitative factors of the following kinds can quantify this function: views on the possibility of growth, incentives from product fees, such as electricity prices and taxes, the degree of regulatory pressure, and the expression of interest by top clients (Bergek et al., 2008).

Function 3: Entrepreneurial experimentation is the primary method of reducing uncertainty by trial-and-error exploration with novel technology, applications, and tactics (Bergek, 2019). It has long been recognized that not all technological challenges can be resolved through formal R&D alone, and that real-world experimentations at various levels often play a crucial role in resolving uncertainties and technological problems (F. Geels & Raven, 2006). Because of the complexity of the product system and the risks associated with integrating new technologies into a bigger structure (such as an electrical grid), some articles stress the significance of examining new technologies under practical conditions and at an adequate level before putting them into a business environment (Bergek, 2019). The quantity of competitors, the variety of applications, and the range of technologies utilized are the key factors to analyze this function (Bergek et al., 2008).

Function 4: Market formation is the creation of an environment or field where providers and purchasers can engage in semi-structured exchanges of products and services (Bergek, 2019). Typically, there are three main stages (nursing, bridging, and mature) in the establishment of a market (Bergek et al., 2008). Due to the higher price, poor performance, or uncertain potential, the market for a new technology without advantages may be limited or may not even exist. It is difficult to discuss the market in the very beginning step of an emerging technology. We must examine both actual market development and the factors that influence market formation in order to comprehend the order in which markets are formed (Bergek et al., 2008). Normally, institutional changes are the key indicators for market formation.

Function 5: Legitimation is the procedure by which the new technology, its supporters, and the TIS as a whole gain regulatory, moral, and cognitive legitimacy. This may entail adaptation and making adjustments to existing institutions, or even creating completely new ones (Bergek, 2019). Legitimacy is a necessary condition for the emergence of new industries, as is commonly recognized in organization theory (Bergek et al., 2008). New technologies applied to critical infrastructure, such as transportation and power supply, often face greater challenges in gaining legitimacy. By tracking the emergence and expansion of interest groups and their lobbying efforts, this function can be examined (Hekkert et al., 2007).

Function 6: Resource mobilization is defined as the allocation of the various resources, including finances, human resources, and assets, that are necessary for innovation to take place in the system (Bergek, 2019). Enough resources must be allocated for a given technology in order to enable the generation of knowledge. This function can therefore be thought of as an essential stimulus to function 1 (Hekkert et al., 2007). For industries with strong path dependence, the lack of sufficient resources to allocate to new technologies is a major obstacle. The increasing amount of capital, variations in the quantity, and shifts in complementary assets are the main measurements to test this function (Bergek et al., 2008; Hekkert et al., 2007).

Function 7: Development of positive externalities is the establishment of system-level facilities that are accessible to system participants who did not contribute to their development. The primary sources of these facilities are information flows and knowledge spillovers, the emergence of specialized intermediary products and service providers, and pooled labor markets (Bergek, 2019; Bergek et al., 2008). This suggests that industrial development may have an impact on a TIS's performance even though it is not an industry. Positive externalities typically do not appear when TISs are in their early stages of development. This function strengthens the other six functions rather than operating independently. As a result, it could be considered a sign of the system's general dynamics (Bergek et al., 2008).

The technical innovation systems (TIS) framework is used in the majority of the literature on sustainability transitions to examine how industries like energy are changing (Andersson et al., 2023). There are two reasons that make the TIS be considered as one of the vital frameworks in this field. A wide range of system flaws in the field of environmental advances can be found using the TIS framework. First, a key factor in socio-technical transition is the creation of new technologies. In the meantime, a number of these technologies have developed to the point where they present a serious danger to traditional technology, organizations, and institutions. Second, a number of recent empirical studies employing the TIS technique have examined technology linked to sustainability claims. As a result, the TIS framework is facing more and more challenges related to sustainability and transitions (Markard et al., 2015). This capacity helps the study of sustainability transitions by enabling policymakers to pinpoint the areas of a system where intervention is most likely to have an impact (Jacobsson & Bergek, 2011). In the field of sustainability transition research, TIS studies have already gained significant traction (Markard et al., 2012).

However, as an emerging field of study, sustainability transitions also give increasing new challenges to the TIS, as it is gaining popularity. The main critique is that **the TIS approach minimizes the significance of external context structures** since it is inward-looking (Markard et al., 2015). In actuality, the functions approach was developed to supplement the emphasis on structure by analyzing the system's functions, or sub-processes (Jacobsson & Bergek, 2011). It enables us to distinguish between structure and substance and to define policy challenges and goals in terms of functionality (Bergek et al., 2008). Although the external context has never been ignored in the TIS framework, more improvement in context analysis is needed to give close attention to the dynamics of the structure (Bergek et al., 2015; Markard et al., 2015).

The TIS framework and its function approach provide an effective tool for analyzing innovation dynamics and policy-associated processes in sustainability transition. However, as previously mentioned, this viewpoint is limited in its capacity to systematically explain the structural context where these functions take place. In order to address this drawback, a multi-dimensional analytical framework that arranges innovation dynamics into the Technology, Institution, and Society (T-I-S) dimensions is presented in the following section.

2.4 Multi-dimensional mechanism model

As the TIS framework and its functions approach were discussed, a significant challenge with the integration of innovation processes within wider structural conditions becomes clear. The functions approach tells us what happens, but tells us little about where and under what conditions it happens (Bergek et al., 2008; Markard et al., 2015). This obstacle makes it difficult for us to understand the system's operating mechanism from a structural perspective during analysis, often leading us to get bogged down in the details of specific processes.

TIS scholarship has increasingly acknowledged the importance of this issue. Bergek et al. (2015), for example, introduce four important types of context structures shaping TIS development, including interactions with other TISs, sectoral and geographical embedding, and political structures. These contributions focus on identifying and categorizing contextual structures and describing interaction patterns. Less attention is given to how such contextual influences are translated into innovation dynamics at the functional level of the TIS. This points to the need for a mechanism model that can explain the interactions between them. Moreover, previous TIS literature has also emphasized that functional analysis can guide analysts toward the underlying structural causes of system underperformance (Jacobsson & Bergek, 2011). Although this viewpoint emphasizes the potential of functions, it is still mostly unclear how functional flaws are systematically translated into structural conditions in different contexts. Similar issues have been raised in the literature on sustainability transitions, where researchers find that while TIS functions are useful for identifying system issues, they offer little guidance on how these issues integrate into larger institutional and structural frameworks (Markard et al., 2012). These suggest a methodological gap between functional diagnosis and structural explanation.

This study uses an analytical structuring strategy that enhances the TIS functions approach instead of adding another external framework. The aim is to develop an analytical framework that operationalizes existing insights from innovation systems and transition studies. In the classical TIS literature, the structure of an innovation system is described in terms of actors, institutions, interactions, and infrastructures (Wieczorek & Hekkert, 2012). Rather than treating these as separate structural categories, this study synthesizes them into three analytically distinct but interrelated dimensions, Technology, Institution, and Society (T–I–S), where the functions are embedded. The choice of these three dimensions is grounded in the socio-technical transition literature, in which Raven (2007) consistently emphasizes that regime change involves interconnected technological, institutional, and social transformations. Following on this insight, the T-I-S dimensions are employed as analytical categories that structure the ways in which innovation functions are facilitated, limited, or transformed under various conditions. It also provides a bridge between functions and a structural explanation.

The Technology–Institution–Society (T–I–S) distinction adopted in this study does not represent an ontological decomposition of the system. Rather, it is used as an analytical and heuristic device to structure the analysis of mechanisms operating within complex socio-technical systems. The following section introduces the T–I–S framework and explains its analytical positioning.

Technology refers to the techno-material dimension of the transition, which includes the artifacts, technical concepts, and performance characteristics that a TIS uses to provide its services. The technology dimension is examined in this study as an analytical category that includes the technological opportunities and limitations influencing the types of solutions that can be created, proven, and expanded over time. Additionally, "technology" in this context refers not simply to hardware but also to the technical rationale and design decisions that guide system creation and operation.

Institution refers to the rule-based dimension that systems govern action and coordination. It includes formal (such as laws, standards, and regulations) and informal (such as conventions and routines) institutions that influence what is acceptable and practical in a given system. The institutional dimension serves as an analytical category to describe how innovation processes are enabled, constrained, and guided by rule structure, as well as how institutional shifts interact with technological development during transitions.

Society refers to the social-actor dimension that includes the heterogeneous actors, their capabilities and interests, and the process patterns of resisting, accepting, and promoting the transition. It can reflect how customers, firms, communities, and organizations engage in, react to, and influence innovation processes. Society is used as an analytical category to understand how agency, perception, and social expectation shape the expansion of new solutions and the path of transitions.

These three dimensions are not physically separate; they permeate and influence each other. Additionally, each TIS function occurs through the interactions of institutional, societal, and technological elements rather than being limited to a single dimension. The T–I–S dimensions provide a framework to analyse functions in a specific structural condition. TIS functions are thought of as cross-dimensional mechanisms that emerge when technical feasibility, institutional structures, and societal participation align or misalign.

The multi-dimensional mechanism model of TIS functions is shown in Figure 8. It indicates that socio-technical transitions cannot occur through individual changes in a single dimension. Technological advancements, institutional changes, and societal reactions all constantly coevolve and influence one another. The interactions between Technology, Institution, and Society are considered as reciprocal and iterative rather than linear. Changes in one dimension may trigger changes in others, which can feed back into the original dimension. The functions are located in the intersection of three dimensions, expressing the dynamic results of the dimensions' interaction to give system analysis a bridge between processes and structures.

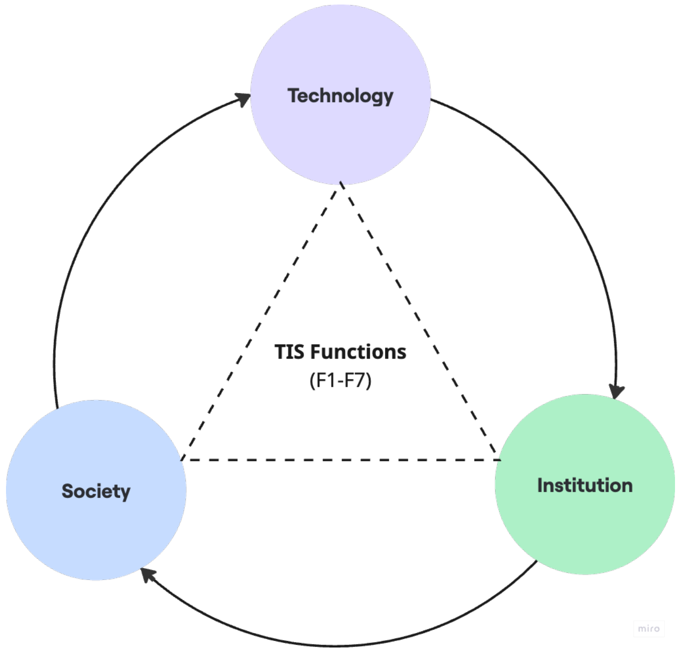

Figure 8. A Technology–Institution–Society (T–I–S) analytical framework embedding TIS functions (Raven, 2007).

The T-I-S framework is employed in this study as an analytical lens rather than a classification system. The approach focuses on how the configuration of technological, institutional, and social contexts impacts the performance of individual TIS functions. It also emphasizes the interactions between dimensions across different functions and their dynamic role in socio-technical transitions. These allow the analyst to understand whether a function is strong or weak in a clear structural way, while also clarifying how combined structural conditions enable, constrain, or promote the shifts in innovation dynamics.

In summary, by addressing the structural contexts under which innovation dynamics take place, the T–I–S framework offers an analytical framework that enhances the TIS functions approach. The framework provides a logical way of linking process-oriented analysis with structural explanation by viewing functions as cross-dimensional mechanisms.

The research strategy and methodology are presented in the following chapter, which also describes how this framework is operationalized in an empirical study of microgrid-related cases.

3 Methodology

This chapter presents the methodological approach adopted in this study. The research employs a qualitative case study design to examine the development of the LEMENE energy community microgrid and its innovation dynamics within the energy transition. The chapter first introduces the research design, followed by the rationale for case selection. It then describes the data collection process and finally presents the analytical framework based on the Technological Innovation System (TIS) approach used to analyze the case.

3.1 Research design

This study employs a qualitative case study approach, which is appropriate for addressing “how” and “why” questions and examining complex real-world phenomena that are closely linked to their context. Case study research is particularly suitable when the researcher has little or no control over behavioural events and when the focus of the investigation is on contemporary phenomena rather than historical events (Yin, 2014). In such situations, the case study approach enables an in-depth investigation of the phenomenon within its real-life setting. In this research, energy community microgrids involve complex interactions between technological infrastructures, regulatory frameworks, and social participation. These dynamics are difficult to study independently from their broader socio-technical context of energy transition, making the case study approach particularly suitable for this work.

In this study, a case refers to a real-world implementation of an energy community microgrid in which distributed energy technologies, institutional arrangements, and community participation interact within a localized energy system. To identify key drivers, institutional constraints, and challenges shaping energy community microgrid development and its contribution to energy transition, this study adopts a single-case design focusing on the LEMENE energy community microgrid located in Lempäälä, Finland. Single-case study designs can be justified in several situations, including critical, unusual, common, revelatory, or longitudinal cases (Yin, 2014). In this research, the single-case approach is justified because the LEMENE project represents a revelatory case. The project provides a rare opportunity to examine the development of an operational energy community microgrid within a real-world socio-technical environment where technological infrastructures, institutional frameworks, and social actors interact during the energy transition. Furthermore, the study adopts an embedded case study design, as the analysis examines multiple dimensions guided by the TIS framework, including technological infrastructures, institutional arrangements, and social participation.

3.2 Case selection

To investigate the development dynamics of energy community microgrids, the case needed to meet several criteria. First, the study focuses on the European and Nordic energy context, where policy frameworks actively promote decentralized energy systems. Finland provides a relevant national context due to its advanced electricity market design and active policy experimentation. Second, the case had to represent an operational system rather than a purely conceptual or simulation-based project. Third, the case needed to involve interactions between technological infrastructures, regulatory frameworks, and multiple actors within a real-world energy system. Additionally, the project needed to be sufficiently documented and available in academic publications, policy reports, project documentation, and other public sources to enable systematic analysis.

The LEMENE energy community microgrid in Lempäälä, Finland, meets these criteria. The project represents one of Finland’s early industrial-scale energy community microgrids integrating multiple distributed energy technologies, including solar power, gas engines, fuel cells, and energy storage. In addition, the project has been recognized as a national flagship renewable energy initiative and has been widely documented in academic studies, policy reports, and media discussions. These characteristics make LEMENE a suitable case for examining the development dynamics and challenges of energy community microgrids during the energy transition.

3.3 Data collection

This study relies primarily on secondary data collected from multiple documentary sources. Given the nature of the research context, which examines a real-world energy community microgrid project, direct primary data collection was not feasible. Instead, the study utilizes publicly available materials that document the development, operation, and policy context of the LEMENE project. Moreover, without direct surveys from the stakeholders of the project, these materials are more unbiased data. A more honest image is obtained by indirect statements in various circumstances. Using secondary data also enables the study to analyze how the project has been described and interpreted across different institutional contexts, including academic research, policy discussions, and industry communications. This variety of sources provides rich empirical material for examining the technological, institutional, and social dynamics of the energy community microgrid.

The collected materials include academic publications, governmental reports, project documentation, policy analyses, and media articles. These sources provide detailed information on the technological configuration, institutional interactions, and social environment surrounding the LEMENE energy community microgrid. The availability of diverse documentary sources allows for a comprehensive examination of the case from multiple perspectives. The use of multiple documentary sources also supports data triangulation, which enhances the reliability of the findings by allowing the same phenomenon to be examined from different perspectives (Yin, 2014).

Data collection continued until sufficient information had been obtained to comprehensively describe the development and operation of the LEMENE energy community microgrid. As additional sources were reviewed, the information increasingly converged, and no substantially new themes emerged. This indicates that a sufficient level of data saturation was achieved for the purposes of the case analysis (Fusch & Ness, 2015).

3.4 Analytical framework

The analysis in this study is guided by the Technological Innovation System (TIS) framework, which has been widely used to examine the development and diffusion of emerging technologies within socio-technical systems. The framework identifies seven key functions of the system that shape technological innovation processes, including knowledge development and diffusion, influence on the direction of search, entrepreneurial experimentation, market formation, legitimation, resource mobilization, and the development of positive externalities (Bergek et al., 2008).

To analyze the LEMENE energy community microgrid, these functions were used as the primary analytical categories. In addition, the analysis considers three analytical dimensions (technology, institution, and society) that reflect the broader socio-technical structure of energy community microgrids. This combination allows the study to examine how technological infrastructures, regulatory frameworks, and social actors interact in shaping the development of the system.

The empirical materials were analyzed using qualitative coding in ATLAS.ti. Initial coding categories were derived deductively from the TIS framework's seven functions and the three dimensions. During the analysis process, more specific subcodes were iteratively developed based on patterns emerging from the data. Through this process, subthemes and themes were formulated, enabling a characterization of how different aspects of the LEMENE project contribute to the functioning of the innovation system. The seven TIS functions and the three analytical dimensions served as the main coding categories. The analysis then examined the interactions between these categories to reveal the mechanisms through which technological innovation operates within socio-technical transitions. The results of this analysis are presented in the following section using the seven TIS functions as the main analytical structure.

4 Case Study Results

This chapter presents the empirical findings of the case study. It begins with a description of the LEMENE energy community microgrid, including its technological configuration, governance structure, and operational characteristics. The chapter then presents the results of the development of the project using the Technological Innovation System (TIS) framework, organized around the seven functions.

4.1 Case description: LEMENE - Lempäälä energy community

The LEMENE (Lempäälän Energia-yhteisö) project is an energy community microgrid located in the Marjamäki industrial area in the municipality of Lempäälä, Pirkanmaa Region, Finland. The project area shown in Image 1 was initiated in 2017 and largely completed in 2019. The project was designed as one of Finland's early self-sufficient energy community pilots. It was awarded the Ministry of Economic Affairs and Employment's (TEM) flagship project support. It integrates electricity, heating, cooling, and storage within a defined industrial district. The system operates as a locally coordinated energy platform combining distributed generation, sector coupling, and market-based participation under existing electricity market regulations. LEMENE thus functions as both an operational microgrid and an experimental platform for distributed energy system innovation (Lempäälän Energia Oy, n.d.; Lintunen, 2023).

Image 1. LEMENE area (Kettunen, 2021a).

The backbone of the LEMENE system is a smart local microgrid built around a 20 kV medium-voltage ring network extending approximately 10 kilometers across the Marjamäki industrial area (Lintunen, 2023). The network consists of six substations and is designed in a ring topology. The system can operate both in grid-connected mode and as an islanded microgrid if disturbances occur in the national or regional grid. The microgrid integrates multiple distributed energy resources, including solar photovoltaic generation, gas engines, fuel cells, battery storage, and district heating infrastructure. A Siemens microgrid controller coordinates electricity network management, heating network operation, storage dispatch, and market interfaces in real time (Lempäälän Energia Oy, n.d.). In autumn 2022, the system was further developed through the installation of a thermal accumulator and a heat pump. This upgrade increases the system's capacity for sector integration and enables more flexible CHP operation in combination with battery storage, particularly in the context of reserve market participation (Lintunen, 2023).

The LEMENE project is governed and operated by Lempäälän Energia, a subsidiary of the municipality-owned energy and property company Lempäälän Lämpö Oy (Koistinen, 2020). As one of eleven national flagship energy projects selected by the government, the governance structure combines national-level strategic recognition with municipal ownership and operational control (Nordic Energy Research, 2023). The project is explicitly directed toward industrial actors in the area, where more than 300 companies operate. These firms constitute the core members of the local energy community, while Lempäälän Energia functions as the coordinating operator between them (Leppänen & Järventausta, 2023). Total investment in the LEMENE has reached approximately €18 million (Koistinen, 2020), which is a combination of national-level funding, regional support, and municipal investment. Approximately €5 million in state funding was allocated to the project as part of a broader national investment program targeting renewable energy and energy technologies between 2016 and 2018. In addition to national funding, financial backing was provided by Lempäälä's Local Council and the Tampere Region Council (Koistinen, 2020; Nordic Energy Research, 2023).

The LEMENE system operates in compliance with existing electricity market legislation and is connected to the national grid. Under normal conditions, the microgrid participates in the public electricity market by sourcing additional electricity when required and selling surplus production to the national grid (Lempäälän Energia Oy, n.d.). The system is capable of participating in multiple reserve and balancing markets, including frequency containment and restoration reserves. The integration of batteries and automation systems enables flexible participation in reserve markets while maintaining local balancing capacity (Lintunen, 2023). In addition to electricity market participation, the system supplies district heating within the Lempäälä area (Koistinen, 2020). The microgrid's operational logic combines local self-balancing with integration into national electricity markets. However, LEMENE's development has been institutionally constrained by the existing Finnish Electricity Market Act. The project did not receive a closed distribution network permit, which limited its ability to connect customers directly within the industrial area (Koistinen, 2020; Lintunen, 2023). LEMENE's institutional embedding can be characterized as structurally constrained: the project was technologically feasible and politically supported, yet institutionally limited by regulatory definitions of network operation and property boundaries. The project was analyzed using the function method, and the results were presented in the next paragraphs.

4.2 Functional analysis

Function 1: Knowledge development and diffusion. The LEMENE project functioned as a structured experimental platform for knowledge development across technological, institutional, and organizational domains. As one of Finland's early industrial-scale energy community pilots, LEMENE generated practical insights into the coordination of distributed generation, sector integration, reserve market participation, and microgrid control architectures (Lempäälän Energia Oy, n.d.; Lintunen, 2023). The project partners span diverse technological domains, including control systems, energy storage, grid infrastructure, and market interfaces (e.g., Siemens, Merus Power, Fingrid, Elenia). Firms deployed relatively advanced products and solutions within the same real industrial district and tested their interoperability under operational conditions to generate first-hand engineering knowledge (Kanabro, 2024; Lempäälän Energia Oy, n.d.). LEMENE was embedded within a research collaboration with Tampere University and Tampere University of Applied Sciences to abstract operational data and system architecture from the project into analytically transferable models and methodological frameworks (Leppänen & Järventausta, 2023; Lintunen, 2023). For example, Ahmed and Vilkko (2025) used LEMENE to develop and validate a two-level MILP-based optimization framework that integrates unit commitment and economic dispatch to quantify flexibility and optimize day-ahead market participation by modeling CHP units, PV, fuel cells, batteries, and heat storage within a unified dispatch structure. Hildén (2021) conducted practical islanding tests to verify microgrid stability and power quality under autonomous operation. These experiments generated operational knowledge on frequency control, voltage stability, and system coordination. The project also produced institutional knowledge through its engagement with regulatory constraints. For example, Lintunen (2023) analyzed the LEMENE system as a sector-integration case, detailing its technical configuration, market participation mechanisms, and regulatory positioning within Finland's evolving electricity framework. In addition, LEMENE facilitated organizational learning by coordinating collaboration among municipal actors, industrial firms, technology providers, and research partners. The project thus contributed to the development of governance and coordination knowledge relevant to multi-actor energy systems (Leppänen & Järventausta, 2023; Nordic Energy Research, 2023). For example, Kanabro (2024) presented LEMENE, showing how municipal ownership, industrial participation, and technology integration coordinated within an industrial energy community framework. LEMENE simultaneously produced knowledge of technological experimentation, institutional experience, and organizational learning.

The knowledge generated within LEMENE was diffused through multiple channels. As mentioned above, the project has been documented and analyzed in academic publications addressing decentralized energy systems in the energy transition. More examples involving the LEMENE: Laitinen et al (2021) examined the economic feasibility and system design requirements of self-sufficient district energy solutions, using LEMENE to illustrate how multi-energy integration can improve local energy autonomy. Sirviö et al (2024) analyzed the evolving roles of prosumers and energy communities across regulatory and market layers, using LEMENE as an example of how industrial-scale communities interact with electricity markets and institutional frameworks. It has also been referenced in governmental and Nordic-level reports as a pioneering example of industrial-scale energy community implementation. For instance, the Finnish Ministry of Economic Affairs and Employment’s working group report on energy communities discussed LEMENE in the context of regulatory challenges and property-boundary electricity distribution, highlighting its role in clarifying institutional constraints for future projects (Ministry of Economic Affairs and Employment, 2023). Nordic Energy Research (2023) presented LEMENE as a case of sector integration and market participation within industrial energy communities, situating it within broader regional discussions on decentralized energy system transformation.

As an operational pilot, LEMENE produced the initial technological, institutional, and organizational knowledge. **The latter Edelläkävijyys Energiayhteisössä (EE) initiative**

represented a deeper stage of knowledge development and diffusion, investigating the prerequisites and boundary conditions for transferring the innovative solutions of the LEMENE project to a different operating environment and scale. Early experimental findings from LEMENE were methodically reexamined, extended, and converted into more organized technological optimization, regulatory interaction, and coordination procedures throughout this stage (Kettunen & Kivioja, 2021).

The EE project integrated previously fragmented engineering experience into structured, scalable knowledge models for evaluating energy community implementation under different spatial and ownership conditions. The report categorized energy communities into property-internal, cross-property, and distributed models and specified their technical and legal boundary conditions, formalizing implementation requirements beyond the original industrial pilot. Two real estate areas in Lempäälä were examined in the project: Hakkari and Lempäälä-talo (Nova Lempäälä). The Hakkari case operationalized cross-property energy community planning in accordance with current legislation. The analysis quantified district heating flexibility at approximately 20–30% of instantaneous load in selected properties and evaluated the economic feasibility of virtual power plant functionalities. In contrast, the Lempäälä-talo case addressed a newly developed mixed-use area with multiple property owners and advanced building automation. The study examined legal conditions for property grouping and constraints related to electricity distribution across property boundaries (Kettunen & Kivioja, 2021; Lintunen, 2023). The EE project also extended the technological scope of knowledge. One extension concerned artificial intelligence and machine learning. In collaboration with Aalto University, the project examined forecasting methods for consumption and production variables and their integration into energy management and market participation processes with AI applications in energy communities. It formalized data requirements and preprocessing protocols necessary for applying AI in local energy systems and demonstrated how predictive models can be integrated into energy management and flexibility assessment (Kettunen & Kivioja, 2021; Taneli, 2021). Another extension is about hydrogen-related technologies. The project examined fuel cell and electrolysis technologies as potential components of future energy community configurations, discussing solid oxide fuel cells (SOFC) and solid oxide electrolysis (SOE) technologies. Convion has been a developer of the fuel cell process, and two solid oxide fuel cells (SOFC) are in operation in Lempäälä. It has a plan to develop and pilot a solid oxide electrolyzer (SOE) (Edelläkävijyys Energiayhteisössä, 2021b; Kettunen, 2021e; Kettunen & Kivioja, 2021).

Within the EE project, institutional knowledge was generated through formal clarification of the “property group” concept under the Finnish Electricity Market Act. The project documentation records a request for interpretation submitted to the Energy Authority regarding whether electricity distribution across property boundaries could be organized without a separate network permit. The administrative practice established that a property group can only be formed between geographically adjacent properties under the control of the same party, where control refers specifically to the management of the land rather than ownership of individual buildings. There is no separate permit procedure for a property group, but the property owner must prove that he owns the properties in question through a request for clarification. The project consolidated regulatory boundary conditions relevant to cross-property energy community implementation. The clarification was referenced in discussions concerning the reform of the Electricity Market Act, where cross-property energy sharing and property-group definitions were identified as regulatory bottlenecks for energy communities (Kettunen, 2021d; Kettunen & Kivioja, 2021). The project also documented how existing tax rules were primarily designed for centralized distribution networks rather than locally integrated multi-actor energy systems. The Tax Authority does not separately recognize the concept of an energy community but deals with taxation on a production and consumption unit-by-unit basis. As a result, even when electricity was produced and consumed within a geographically confined area, tax obligations could arise if the internal distribution did not strictly meet the legal criteria of a property group. The project highlighted inconsistencies between the objectives of energy community policy and the operational logic of electricity taxation (Kettunen, 2021c; Kettunen & Kivioja, 2021).

The EE project actively propagated social and organizational learning through a continuous framework of stakeholder involvement and public communication. The project maintained a dedicated website that continuously documented goals, progress, and outputs, functioning as a “living knowledge hub”. It included news updates, thematic blog posts, webinar materials, and downloadable publications so that lessons from LEMENE could be interpreted, questioned, and reused (Edelläkävijyys energiayhteisössä, 2021a). First, through a blog stream, EE converted difficult microgrid and energy community topics into understandable explanatory content (e.g., definitions of energy communities and microgrids, reasons for technical direction choice, technical explanations like microgrid power quality and islanding) (Hildén, 2021; Kettunen, 2021b, 2021d). It enabled non-specialist stakeholders to follow the project logic and understand why regulatory and technical choices mattered. Second, through collaboration with the education sector and public discussions, EE organized communication and feedback. EE held meetings and visits with higher-education institutions (e.g., an “oppilaitos tapaaminen” for universities, technology demonstrations at TAMK) (Edelläkävijyys energiayhteisössä, 2021b, 2021c). The project organized a public webinar as a publication event for its key findings, accompanied by a dedicated Q&A post that collected and responded to audience questions (Edelläkävijyys energiayhteisössä, 2021d). Third, EE synthesized the project's lessons into deliverables that were repeatable. The publication section aggregated the project’s final report, handbook, webinar presentations, AI-related study outputs, and consultation materials, indicating an intentional effort to convert project experience into transferable guidance and wider public discussion (Edelläkävijyys energiayhteisössä, 2021e).

Function 2: Influence on the direction of search. The development direction of energy strategies is influenced by the EU, national, and local frameworks. One of the EU's key energy policy programmes is the Energy Union, established in 2015, which aims to provide affordable, secure, and sustainably produced energy. The Energy Union focuses on strengthening energy security, deepening the internal energy market, improving energy efficiency, promoting low-carbon transition, and supporting innovation and competitiveness (Energy union, n.d.). The goals of the Paris Climate Agreement, in turn, are met through the European Green Deal, which aims for a green transition and carbon neutrality (Council of the EU, n.d.). EU Directive on the internal market for electricity 2019/944 entered into force on 5 June 2019. The directive stated that the Union would achieve its renewable energy targets most efficiently by creating a market framework that rewards flexibility and innovation. The directive calls for national legislation that enables investments in distributed and flexible energy resources, including storage and demand response, while ensuring that electricity pricing reflects actual market conditions. The role of the consumer in the future energy system is emphasized. The provisions of the directive have to be transposed into national legislation by the end of 2020 (Directive (EU) 2019/944, 2019). The subsequent Fit for 55 package and REPowerEU plan further accelerated renewable deployment, flexibility investments, and energy system decentralization across the EU (Ministry of Economic Affairs and Employment, 2024). The report from Nordic Energy Research (2023) noted that the relatively low population density in the Nordic context requires local production and consumption to reduce the need for grid expansion in rural areas and the transportation losses caused by centralized energy production.

Finland's national energy strategy aims to implement the EU's climate, renewable energy, and energy efficiency targets, as well as the government's planned carbon neutrality targets. Carbon neutral Finland 2035 – national climate and energy strategy and Finland's Integrated National Energy and Climate Plan Update, developed by the Ministry of Economic Affairs and Employment of Finland, aims to increase the share of renewable energy to 51% by 2030, cut greenhouse gas emissions by 60% by 2030, and reach carbon neutrality by 2035 (Ministry of Economic Affairs and Employment, 2022a, 2024). Roadmap to fossil-free transport, published by the Ministry of Transport and Communications of Finland in 2021, stated that Finland aims to halve transport emissions by 2030 from 2005 levels. To encourage emission-free transportation, the government would put in place a variety of incentives and assistance programs. The distribution obligation legislation's inclusion of biogas and electric fuels, as well as other assistance related to the purchase and distribution of gas and electric vehicle infrastructure, is one example

(Ministry of Transport and Communications, 2021). In autumn 2022, the Ministry of Economic Affairs and Employment of Finland appointed a working group to evaluate the need to develop the regulation of energy communities further. It emphasized that energy communities can promote the production and distribution of renewable electricity (Ministry of Economic Affairs and Employment, 2023). The Smart Grid Working Group published the report Flexible and Customer-Centred Electricity System in 2018. The report identified demand response, energy storage, energy communities, and aggregators as key components of a flexible electricity system, while proposing reforms in distribution tariffs and metering to enable broader market participation. It positioned flexibility and decentralized participation as structural priorities in Finland’s electricity market reform (Ministry of Economic Affairs and Employment, 2018). The report Practices of Innovation-Friendly Regulation in Growth Sectors (2022) examined how regulatory experimentation can support emerging industries through innovation-oriented regulatory practices. The study emphasized regulatory experimentation as a tool to accelerate innovation and market entry in growth sectors. It recommended launching an energy-sector regulatory sandbox, particularly to test decentralized energy community models, thereby signaling institutional openness toward distributed and experimental energy system configurations (Ministry of Economic Affairs and Employment, 2022b). VTT (Technical Research Centre of Finland) identifies artificial intelligence as an important component of future energy systems, especially for managing flexibility, forecasting demand and generation, and integrating distributed energy resources in decentralized electricity networks (VTT, 2022).

Pirkanmaa region, where the LEMENE project is located, has articulated its own regional energy strategy (Pirkanmaan energiastrategia 2030), positioning the region as a fossil-free, energy-efficient, and reliable energy system that is environmentally friendly and fair by 2030 (Pirkanmaa, 2022). The regional strategy translates these ambitions into territorially grounded priorities. The region has pledged to achieve carbon neutrality by 2030, reducing its emissions by 80% from 2007 levels. Heating and transportation are the region's largest carbon-emitting sectors. The strategy emphasized the future trend of high electrification in these two sectors and predicted that regional electricity consumption will increase by more than one-fifth by 2035 and double by 2050.

In technological orientation, the strategy prioritized expanding renewable generation capacity, particularly through the controlled and system-compatible deployment of solar power, the replacement of fossil fuels and peat in district heating with renewable energy sources and heat pumps, and the subsidization of heat pump research and implementation. It also emphasized strengthening energy infrastructure by investing in power distribution lines between production areas and consumption centers and improving the availability and functionality of alternative energy charging and refueling networks. In terms of flexibility and balancing, the strategy promotes the development and piloting of innovative storage solutions, such as batteries, and supports the direct production and management of energy through smart microgrids to meet local demand. It also encourages research and commercialization in emerging sectors, particularly hydrogen energy technologies (Pirkanmaa, 2022). In institutional Orientation, the strategy strengthens policy predictability and implementation capacity through several institutional measures. It aims to create a stable investment environment by leveraging public sector action and predictable public procurement practices. It also seeks to improve the overall business environment through clear regional policy signals. For example, streamlining solar permitting processes and accelerating the planning and licensing of electricity network investments to simplify regulatory procedures by increasing governmental and municipal resources. The strategy promotes innovation-oriented coordination by fostering multidisciplinary R&D collaboration in industrial energy solutions. Moreover, it supports structural market reform by encouraging the formation of networks that facilitate the emergence of energy communities and by promoting reforms to the Electricity Market Act to expand their operational opportunities. In socio-organizational orientation, the regional energy strategy was developed through a participatory process involving municipalities, political actors, regional advocacy groups, companies, energy-sector stakeholders, educational and research institutions, other organizations, and residents of the

Pirkanmaa region. It was co-created through workshops and group discussions, reflecting a collectively shaped direction for regional energy transition (Pirkanmaa, 2022).

At the municipal level, Lempäälä's Energy Programme 2030 translates broader climate ambitions into locally grounded and operational measures. The programme aims to enable the municipality to achieve near carbon-neutral energy procurement, use, and production in a cost-effective manner. Lempäälä has joined the national carbon-neutral municipalities network (Hinku) and signed the municipal energy efficiency agreement (KETS), embedding these targets into administrative practice. The municipal programme specifies concrete local actions. These include expanding electric vehicle charging infrastructure in municipal properties, integrating energy citizenship education (for example, by promoting awareness of energy saving), and preventing energy poverty by actively communicating available energy advisory services to residents. Geographical constraints also shape the local direction of energy development. Due to Lempäälä's proximity to Pirkkala Airport, the construction of large wind turbines is largely infeasible. The plan of energy strategy was presented and discussed in municipal board meetings, open virtual discussion events were organized via Teams for residents, and the municipal council held dedicated workshops on the programme. Within this local framework, the municipal energy company and the LEMENE project are explicitly highlighted. The programme recognizes LEMENE as a platform for developing and piloting distributed energy production, storage, and smart automation solutions (Hanna & Liejumäki, 2024).

Taken together, these policy signals prioritize decarbonization, flexibility, decentralization, customer participation, and sector coupling. LEMENE operationalizes this direction by combining local generation and storage with coordinated microgrid control and participation in electricity and reserve markets. However, the Energy Authority, Finland's national electricity market regulator operating under the Ministry of Economic Affairs and Employment, rejected LEMENE's application for a closed distribution network permit in 2020 (Lintunen, 2023), restricting the project's intended cross-property electricity sharing model despite broader governmental policy efforts promoting decentralized energy systems.

Function 3: Entrepreneurial experimentation. From a technological experimentation perspective, the LEMENE project brings together advanced technological achievements from multiple companies to transform into commercial experiments. The energy is generated by solar power plants, gas engines, and fuel cells, and also includes battery energy storage, thermal energy storage devices, heat pumps, and six substations, all connected by a microgrid to form a distributed energy system as shown in Figure 9 (Lempäälän Energia Oy, n.d.). Solar installers Solarigo and Kiwatti are partners in building two solar plants with a combined power of 4 MWp, which were the first solar power plants of this size in Finland in late summer 2019 (FIMER, 2020; Lempäälän Energia Oy, n.d.; Solarigo, n.d.). Solar inverter company FIMER provided PVS980-58 central inverters as part of the PV installation. Within a dual-layer aluminum and stainless-steel casing, the PVS980-58 offers a small, high-performance solution that can survive Finland's severe weather and bitterly cold winters. (FIMER, 2020). INNIO supplied six Jenbacher gas engines with a total capacity of 8.1 MWs. They use a CHP system on carbon-neutral biomethane, making them a dispatchable renewable energy source to improve energy reliability and reduce carbon dioxide emissions (INNIO, 2019). Convion's unique technology and the Estonian-Finnish company Elcogen's manufacturing capacity serve as the foundation for the C60 fuel cell utilized in LENEME. C60 generates roughly 25 kW of heat and 60 kW of power. At 60%, the power production efficiency is the highest in its category and the greatest on the market (Hakala, 2021). Merus Power delivered a Merus ESS 1.6MW energy storage system with advanced technology. The Merus Power facility in Nokia, Finland, designed and manufactured turnkey equipment. Its primary components are the Merus MCC controller, power conversion system (PCS), lithium-ion batteries, and battery management system (Merus Power, 2018).

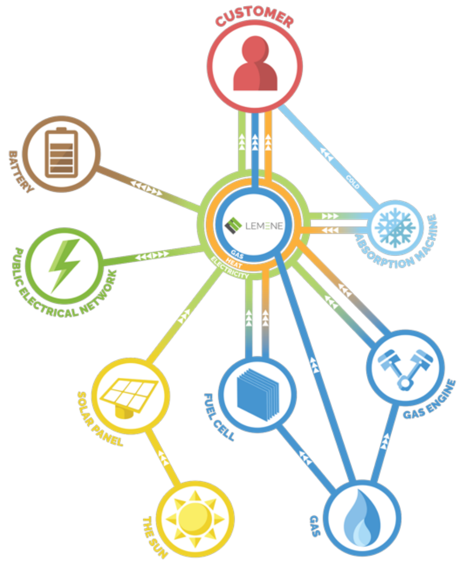

Figure 9. LEMENE system (Lempäälän Energia Oy, n.d.).

The virtual power plant solution creates a single system by combining various production kinds. Siemens' Microgrid Controller (MGC) functions as a system for optimization and control (Lempäälän Energia Oy, n.d.). Figure 10 shows the microgrid controller with its functionality and interfaces. Siemens installed cutting-edge technologies, such as the SICAM Microgrid Controller, which guarantees dependable monitoring, control, and blackout prevention. It ensures the best possible use of the generation systems by providing flexible communication, flawless continuity, maximum security, and unrestricted migration. It also has EnergyIP DEMS, which enables the combination of distributed energy systems to offer ancillary services or engage in intraday energy trading (Siemens, 2018).

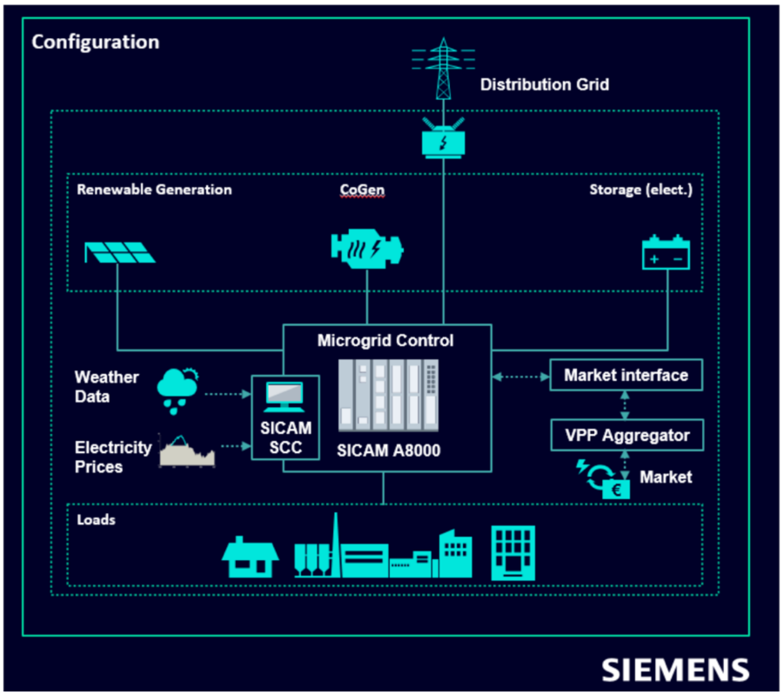

Figure 10. Siemens microgrid controller (Lintunen, 2023).

In autumn 2022, new components were added to the system, including a heat accumulator and a heat pump. The heat accumulator in the system is a 450 m water accumulator, which can store up to 30 MWh of energy. The heat accumulator enables cogeneration operating on the terms of the heating network. The heat pump has replaced the traditional cooling system, and this is able to recover CHP production, battery storage, waste heat from boilers, and fuel cells. It can be used for the needs of the reserve market (Lintunen, 2023). Figure 11 outlines the expansion pathways explored within the LEMENE sector-integrated energy system. The platform enables experimentation with alternative fuels, including locally produced biogas, LNG/LBG, synthetic methane, and future hydrogen production. It also supports the integration of electrified transport through optimized EV charging and potential aggregation for reserve markets. Electrically driven heat production strengthens coupling between electricity and district heating networks, allowing heat loads to absorb excess renewable generation. In addition, LEMENE functions as an open infrastructure platform, enabling external energy producers and flexible customers to connect to existing networks and market interfaces, thereby extending the system's scope beyond its original configuration (Koistinen, 2020; Laakso, 2025; Lintunen, 2023).

Figure 11. Lemene energy system development projects (Lintunen, 2023).

From an operational perspective, the LEMENE system has supplied electricity to the national grid, delivered heat to the district heating network, and participated in reserve markets. It tested the commercial feasibility of integrated generation and flexibility services within existing market frameworks. Nevertheless, the scope of experimentation remained institutionally bounded. Due to regulatory constraints, particularly the absence of a closed distribution network permit and limitations on cross-property electricity distribution, the project could not establish a fully autonomous local market structure. Consequently, direct customer connection and internal energy sharing objectives were not fully realized (Kettunen & Kivioja, 2021; Laakso, 2025; Lempäälän Energia Oy, n.d.; Lintunen, 2023).

Function 4: Market formation. Sector integration shown in Figure 12 is a key way to help Finland achieve its objective of becoming carbon neutral by 2035. In order to build a smart energy system where energy may be stored and transferred in the most techno-economically appropriate form for the moment, several energy sectors—mainly electricity, heat, gas, and transportation—are being integrated. The integration of Finland's electrical and heating systems into a better, more energy-efficient whole will be the most significant shift (Brink, 2020). Sector integration can greatly optimize energy flow and create the preconditions for new market configurations. Finland has established a working group on sector integration to study various measures to achieve sector integration. They noted that in an increasingly electrified society, the need for flexibility increases. Through sector integration, this flexibility can be introduced into the electricity system (Ministry of Economic Affairs and Employment, 2021). The need for flexibility brought about by the energy transition has created new market opportunities and new ways of value creation.

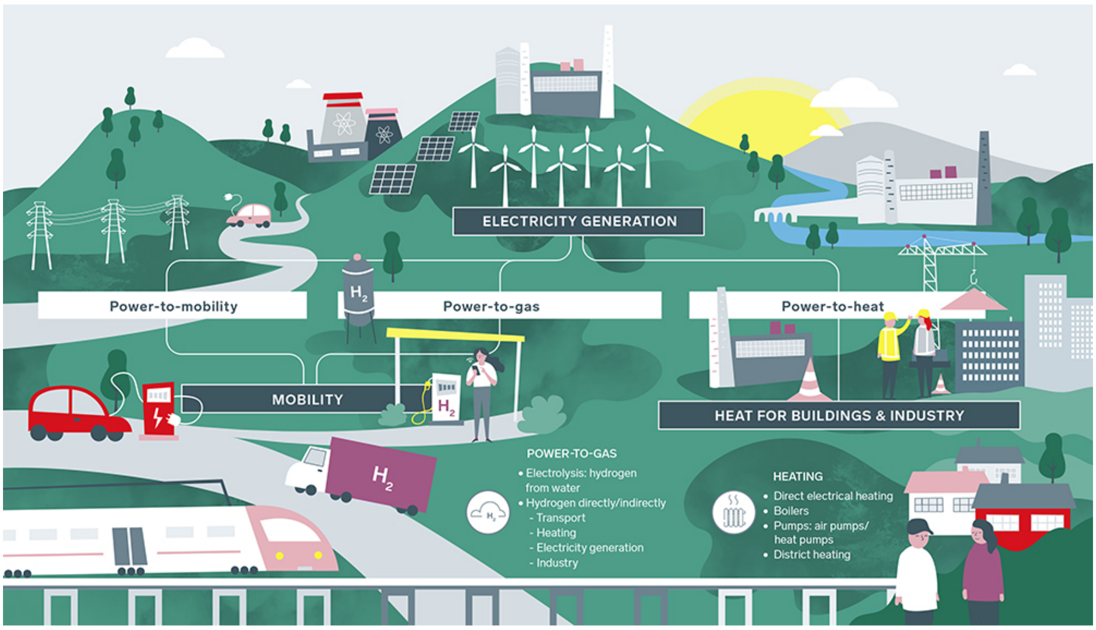

Figure 12. Sector integration (Brink, 2020).

Nord Pool is one of the world's largest and most liquid power markets, facilitating the trading of electricity in the Nordic and Baltic regions of Europe. The Nordic Electricity

Exchange trades electricity hourly each day, with the price per hour determined by supply and demand. (Aslani et al., 2013; Lintunen, 2023). To maintain power balance, Fingrid has established a reserve market. Fingrid utilizes this system to maintain power balance. Different participants can provide flexible generation and load to the severe market and obtain additional revenue (Haanpää, 2024). Different reserve products are designed to respond to different network disruption situations, as shown in Figure 13. Combining multiple end-user loads or electricity generation for sale, purchase, or auction in the electricity market is known as aggregation. A third-party unattached to the end-user's open electricity supplier is known as an independent aggregator. All of the balance chain's markets presently permit aggregation. Currently, the FFR, FCR-D, FCR-N, and aFRR products permit independent aggregation. The mFRR market intends to be active in the autumn of 2026 (Fingrid, 2023).

Figure 13. Fingrid's reserve products (Nortio, 2019).

LEMENE achieved sector integration in multiple ways. Heating, cooling, electricity, and natural gas are interconnected within the system, and the entire system is comprehensively optimized based on the characteristics of different energy forms and market conditions (Lintunen, 2023). Using meteorological forecasts and demand estimates, the system determined day-ahead CHP production volumes based on expected electricity prices and heat network requirements. Identified production volumes were then submitted to the day-ahead spot market, while flexibility capacities were offered to reserve markets. Through this mechanism, LEMENE entered the electricity exchange as a market participant, selling solar energy to the national grid and supplying district heating services to the Lempäälä region. It also fully utilizes its production capacity and energy storage in multiple balanced markets, including FCR-N, FCR-D, aFRR, and mFRR. The microgrid controller coordinated internal production and consumption with external market agreements by coordinating dispatch decisions in response to confirmed market orders (Koistinen, 2020; Lintunen, 2023; Tamara.smolej, 2025).

In the energy sector, multiple forms of energy flow simultaneously in multiple directions. This presents challenges for metering, reporting, and billing. There is no readily available entity capable of managing data across an entire energy community based on community needs now. In terms of taxation, the tax authorities do not recognize the concept of an energy community in isolation, but rather tax production and consumption on a unit-by-unit basis. Currently, LEMENE's power network is not considered a taxable network. However, if LEMENE’s application for a closed distribution network permit is approved, its power network will become a taxable network. Taxes are based on total annual revenue, not on how much of the electricity produced by a production unit is used by energy communities or how much is transmitted to the grid for use (Kettunen & Kivioja, 2021; Lintunen, 2023). These regulatory and fiscal arrangements constrain the emergence of an autonomous local electricity market within the community. Market formation remains structurally embedded within existing centralized electricity market rules rather than evolving into a distinct local market configuration.

Function 5: Legitimation. The project's progress has been accompanied by gradual legal reforms and lobbying efforts, particularly regarding the electricity market framework. Figure 14 presents a chronological overview of legislative and regulatory amendments alongside key project-related institutional and political engagement. The upper track depicts changes in the electricity market framework, while the lower track summarizes major project actions, regulatory processes, and policy initiatives linked to LEMENE. The timeline highlights how legal adjustments and project-driven engagement unfolded concurrently over time.

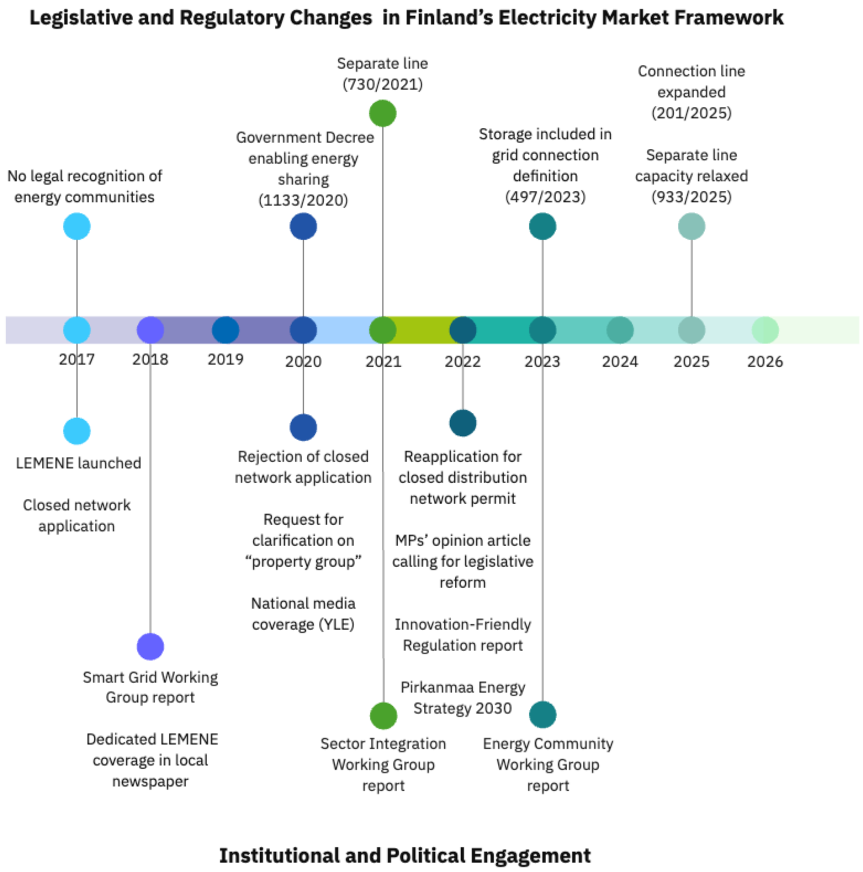

Figure 14. Parallel evolution of legislative and regulatory amendments and project-related institutional engagement in Finland's electricity market framework.

In 2017, when the LEMENE project started to be established, the law did not acknowledge energy communities as a legal entity in the power sector. The legal framework did not allow cross-property sharing of self-generated electricity (Horn et al., 2022). Because of the EU Directive on the internal market for electricity 2019/944, which requires EU countries to legislate before the end of 2020 (Directive (EU) 2019/944, 2019), Finland has begun to amend its laws. It wasn't until the Government Decree 1133/2020 in late 2020 that energy sharing was added to Finnish law. The Decree's 2020 update includes clauses about the sharing of energy generated jointly in a community or cooperative, which is defined as a single building or a collection of structures situated geographically close to one another (Clean energy for EU islands, n.d.). In 2021, Finland's Electricity Market Act was amended to include the concept of a separate line. Under the updated law 730/2021, a separate line allows small-scale generating facilities with a total capacity of less than 2 MW to be connected across a property boundary to a single point of use. The Act also clarified that electrical networks operating at a voltage level of at least 110 kV are not considered distribution networks, and, in exceptional cases, a distribution network may be constructed if a connection line or backup supply connection to a distribution system operator's network is established, which may include connecting one or more power plants to the distribution system operator's network (Finlex, n.d.; Lintunen, 2023). The Act's Section 3, Paragraph 5 was modified in 2023 to include energy storage installations in the definition of a grid connection line. The amendment 497/2023 expanded the legal definition, enabling storage installations to be part of a grid connection line, although operational interpretation remained contingent on regulatory practice. If energy storage facilities use the same connection line as power plants to connect to the network, the system has to be categorized as licensed electrical network operations (Finlex, n.d.; Sokka, 2025). In April 2025, the definition of a grid connection line is expanded in the Electricity Market Act 201/2025 to include an electric line that connects "one or more power plants and one or more energy storage facilities connected to them" to the electrical network. An electric line that serves several connecting parties would fall under the definition of a connection line rather than being categorized as an electricity network that requires a network license. The change took effect on July 1, 2025 (Finlex, n.d.; Huomo, 2025; Borenius, 2025). In October 2025, other amendments to the Finnish Electricity Market Act 933/2025 broadened the application of separate line provisions. Under the revised regime, operation of separate lines does not constitute network operation subject to licensing requirements even if the connected generation capacity exceeds 2 MW, thereby easing regulatory barriers for larger distributed generation and hybrid facilities. On January 1, 2026, this amendment became operative (Borenius, 2026; Finlex, n.d.). These legislative adjustments occurred during a period of continuous regulatory interaction and policy engagement related to the LEMENE project.

As the LEMENE project evolved, the municipal energy company and its partners actively engaged with regulatory authorities to overcome regulatory hurdles and achieve better operational objectives. In 2017, the company Lempäälän Energia tried to apply for a permit for a closed distribution network. The request was turned down by the Energy Authority, the power regulator, in February 2020. Because the system did not satisfy the unique requirements outlined in section 11 of the Electrical Market Act for an electrical network permit for a closed distribution network, the application was denied (Energy Authority, n.d.; Horn et al., 2022). The requirements are as follows: Applicants operating power networks in geographically limited industrial or commercial areas, areas providing public services, or high-voltage distribution networks that do not supply electricity to consumers may apply for a closed distribution network license if, for specific technical or security reasons, the network user's operation or production process constitutes a single entity, or if the network primarily supplies electricity to the network owner or network operator or a company with which it has an ownership relationship (Energy Authority, n.d.; Finlex, n.d.). The Electricity Market Act lists the idea of a property group as one of the exceptions that permits the building of an electricity network (also known as a property network) linking properties without the need for a separate electricity network permit. In 2020, Lempäälän Lämpö Oy submitted a formal request for clarification to the Finnish Energy Authority about the interpretation of the “property group” under the Electricity Market Act. The company sought legal confirmation that electricity could be distributed across municipally controlled adjacent properties without a distribution network licence. The Authority clarified, based on established administrative practice, that only geographically adjacent properties under the control of the same party qualify as a property group. The regulatory limits for LEMENE’s cross-property energy community model (Energy Authority, 2020, 2021; Kettunen & Kivioja, 2021). Lempäälän Energia applied again for a closed distribution network permit from the Energy Authority in April 2022 (Lempäälän kunta, 2024). There is no official final result while writing this thesis.

The project also triggered reactions from incumbent actors in the electricity distribution sector. Local distribution network operator Elenia expressed concerns that allowing cross-property electricity distribution within energy communities could blur the regulatory boundary between local energy systems and licensed distribution networks (Koistinen, 2020).

The Ministry of Economic Affairs and Employment of Finland was the main actor in the national government pushing for reform of the law. They established a Smart Grid Working Group whose task was to investigate and present concrete actions by which a smart electricity system can serve customers' opportunities to participate in the electricity market and promote the maintenance of security of supply. They released a report in 2018 that explicitly recommended enabling energy communities and independent aggregators to participate in electricity markets on equal and market-based terms, while promoting demand response and market-based ownership of energy storage (Lintunen, 2023; Pahkala et al., 2018). Recommendations that directly support the operational logic of microgrid-based projects such as LEMENE. In the summer of 2020, the Sector Integration Working Group was established to explore ways to promote integration in the energy sector. Their 2021 report highlighted electricity–heat integration and flexibility provision as central mechanisms for achieving Finland’s carbon neutrality goals, emphasizing the requirement of regulatory adaptation to enable distributed energy systems and cross-sector flexibility, thereby providing a policy foundation for integrated microgrid configurations (Lintunen, 2023; Ministry of Economic Affairs and Employment, 2021). Promoting regulation to facilitate and accelerate the entry of innovation and new business models into the market is an important national initiative. The Ministry of Economic Affairs and Employment explored how to leverage innovation-friendly regulatory practices to support the development of emerging growth sectors, thereby supporting pilot projects. The 2022 report Practices of Innovation-Friendly Regulation in Growth Sectors, published by the Ministry of Economic Affairs and Employment, recommended establishing a national regulatory sandbox framework, specifically proposing preparatory work for an energy-sector sandbox to enable experimentation with decentralized energy community models (Laakso, 2025; Lintunen, 2023; Ministry of Economic Affairs and Employment, 2022b). On 14 September 2022, the Ministry of Employment and the Economy made a decision to establish an Energy Community Working Group to investigate and assess the benefits of distributed energy communities and propose specific action plans for their active participation in the electricity market. The 2023 Energy Community Working Group report assessed the compatibility of Finnish electricity market legislation with emerging energy community models and identified regulatory constraints related to property grouping, separate lines, and cross-boundary electricity sharing, thereby laying the groundwork for subsequent amendments to the Electricity Market Act. It highlighted the feasibility of establishing separate lines in municipal energy communities (Kanabro, 2024; Lintunen, 2023; Ministry of Economic Affairs and Employment, 2023). The regional government of Pirkanmaa is also involved in the effort to reform the law. They reported Pirkanmaa Energy Strategy 2030 (2022), including the promotion of amendments to the Electricity Market Act to improve the operational conditions of energy communities, highlighting the LEMENE project (Pirkanmaa, 2022). However, discussions surrounding the regulatory framework have also revealed opposite concerns. Petteri Kuuva, an Industrial Counsellor at the Finnish Ministry of Economic Affairs and Employment, noted that extensive liberalization of electricity network construction could lead to selective investment in profitable areas while leaving sparsely populated regions with increasing network costs. Given Finland’s large geographical area and low population density, electricity networks also serve an important public service function, ensuring supply in remote areas (Koistinen, 2020).

The LEMENE gained national media attention. A 2020 report by Finland’s public broadcaster YLE highlighted how existing Electricity Market Act provisions constrained cross-property energy sharing, framing the project as a test case for needed legislative reform. It noted conflicting messages from the state. On the one hand, the state promotes the project by providing it with subsidies, while on the other hand, the state authority blocks its implementation. (Koistinen, 2020). Since 2018, local media coverage by Lempäälän-

Vesilahden Sanomat has also followed the regulatory challenges of the LEMENE project over several years, including opinion pieces by local politicians and reports on permit applications (Lempäälän-Vesilahden Sanomat, n.d.). This sustained public attention indicates that the project evolved into a broader local policy issue. In March 2022, two Members of Parliament representing the Pirkanmaa constituency, Pauli Kiuru (National Coalition Party) and Veijo Niemi (Finns Party), published an opinion article in Lempäälän-Vesilahden Sanomat calling for accelerating legislative reform of the Electricity Market Act. The article urged Pirkanmaa's parliamentary representatives to advance necessary amendments, presenting LEMENE as a concrete example of regulatory barriers affecting local energy initiatives (Kiuru & Niemi, 2022).

Function 6: Resource mobilization. The LEMENE project mobilized a wide range of resources to support its development and operation, including funding, technological capabilities, knowledge, and organizational resources. As of 2020, the total investment in the project had reached approximately €18 million (Koistinen, 2020). At the national level, LEMENE was selected as one of the Ministry of Economic Affairs and Employment's eleven flagship renewable energy projects and received €4.74 million in funding. The government made a significant decision to invest €100 million in renewable energy and technologies between 2016 and 2018, and LEMENE became a part of it (Nordic Energy Research, 2023). In addition, the project secured €9.7 million in green financing from Municipality Finance Plc (MuniFin) (Seppälä, 2021), a major Finnish public-sector financing institution supporting sustainable infrastructure investments. At the municipal level, Lempäälä consistently explores and utilizes various financing solutions, such as lease financing models and subsidies for research and investment, to support energy initiatives (Hanna & Liejumäki, 2024). The Regional Government of Pirkanmaa allocated €86,175 in joint funding from the European Regional Development Fund (ERDF) and national sources to the project Edelläkävijyys energiayhteisössä, a follow-up initiative supporting the further development of the LEMENE energy community. This funding covered 60% of the total project budget, while Lempäälän Lämpö Oy provided the remaining 40% co-financing. (Edelläkävijyys Energiayhteisössä, 2021a; Kettunen & Kivioja, 2021).

Beyond financial resources, the project mobilized significant technological and knowledge resources to support innovation. The development of the LEMENE system also relied on a broad network of industrial partners contributing technological expertise, equipment, and system integration capabilities. Figure 15 illustrates the key companies participating in the project. Merus Power highlighted that its participation in the project showcased the company's capability to deliver megawatt-scale battery energy storage systems (Merus Power, 2018). Convion's CEO described LEMENE as "a valuable reference", demonstrating the future direction of smartly controlled distributed energy systems integrating multiple technologies (Hakala, 2021). Knowledge resources were mobilized through collaboration with several universities, including Tampere University of Technology, Tampere University of Applied Sciences, and Aalto University, contributing research expertise and analytical support to the development of the system (EnergiaKokeilut, n.d.; Kettunen & Kivioja, 2021; Lempäälän Energia Oy, n.d.). Professor Pertti Järventausta from Tampere University's Department of Electrical Power Engineering noted that the LEMENE project provides an opportunity to test the concept of an energy community in practical conditions (Koistinen, 2020). Collaboration with universities was also facilitated through project networking activities. For example, a meeting organized under the Edelläkävijyys energiayhteisössä initiative brought together representatives from several higher education institutions in the Pirkanmaa region to discuss research collaboration related to the LEMENE energy community (Edelläkävijyys energiayhteisössä, 2021b).

Figure 15. Industrial partners contributing technological resources to the LEMENE (Lempäälän Energia Oy, n.d.).

The project also mobilized organizational resources through engagement with government institutions. At the national level, the Ministry of Economic Affairs and Employment suggested and approved the project as an important one for future energy solutions in 2017. The Ministry coordinated several policy initiatives and working groups addressing smart grids, sector integration, and energy communities. These initiatives created an institutional environment supporting experimental energy systems such as LEMENE (Lintunen, 2023; Nordic Energy Research, 2023). However, the Energy Authority, which operates under the Ministry of Economic Affairs and Employment, did not grant the permit to the LEMENE project, even though the project itself had been supported by the ministry as a flagship renewable energy initiative (Seppälä, 2021). At the local level, the Regional Government of Pirkanmaa and the Lempäälä municipality also contributed to the mobilization of organizational resources by incorporating the project into their local energy strategy.

Function 7: Development of positive externalities. The LEMENE project has generated positive externalities, such as knowledge spillover, demonstration effect, and legitimacy building. Several studies on community microgrids and energy communities reference the LEMENE project as a demonstration case, highlighting its relevance in discussions on local energy communities and distributed energy systems. For example, Leppänen and Järventausta (2023) presented the LEMENE project as a demonstration of an industrial-scale smart microgrid and distributed energy community in Finland. Horn et al. (2022) included the project as one of the key international case studies of energy communities alongside projects such as the Brooklyn Microgrid. In addition, Nordic Energy Research (2023) referred to the LEMENE system as an example of an experimental local energy community integrating multiple renewable generation technologies and storage solutions.

The project has also generated broader demonstration effects that have been discussed in public and policy debates. For instance, Professor Pertti Järventausta from Tampere University noted in a media interview that LEMENE enables companies to experiment with technologies, conduct product development, and build reference cases that facilitate entry into European energy markets. Such projects could become export opportunities for Finnish energy technology as energy communities expand across Europe, following the new Electricity Market Directive. However, the realization of this demonstration effect has been constrained by regulatory barriers and unresolved closed network permit issues. The Professor suggested that experimental permits could enable practical testing of energy community models. He further argued that, in the long term, Finland could potentially develop hundreds of energy communities operating as microgrids if regulatory conditions evolve to support such systems (Koistinen, 2020).

The LEMENE project has also been referenced in governmental policy analyses examining the regulatory framework for emerging microgrid-based energy systems in Finland. For example, the report Energiayhteisöt ja erilliset linjat discusses the project as a practical case when assessing regulatory issues related to separate lines and cross-property electricity distribution within locally integrated energy systems. The inclusion of the project in such policy discussions indicates that LEMENE has contributed to broader debates on the legal and institutional conditions for microgrid-based energy communities.

5 Discussion

This chapter discusses the empirical findings of the case in relation to the research questions. The discussion first examines the innovation dynamics of energy community microgrids through the functions of the Technological Innovation System framework. It then analyzes how technological, institutional, and social dimensions interact in shaping system development. Finally, the chapter considers the opportunities and constraints that energy community microgrids create for the broader energy transition.

5.1 Innovation dynamics of energy community microgrids

Functional analysis of energy community microgrids is the first step in this process. Based on the empirical results reported in Chapter 4 and the understanding of TIS functions outlined in Chapter 2, the LEMENE case shows a distinct pattern of innovation dynamics rather than an evenly developed innovation system. Knowledge development and diffusion (F1), entrepreneurial experimentation (F3), and resource mobilization (F6) appear as the strongest functions in the case, reflecting the project's role as a real-world demonstration and experimentation platform. Influence on the direction of search (F2) and legitimation (F5) developed more unevenly and remained relatively weak under changing regulatory and policy conditions. Market formation (F4) remained clearly limited, as the project faced obstacles in establishing local electricity markets across different energy sectors. Meanwhile, development of positive externalities (F7) did emerge through knowledge spillovers, demonstration effects, and policy influence, but their broader impact remained incomplete. The case shows a pattern where technological and organizational development progressed more quickly than institutional adaptation. Table 2 summarizes the overall functional conditions of the innovation system and the key enabling and constraining factors identified in the LEMENE case.

Table 2. Functional conditions and key enabling and constraining factors in the LEMENE.

Function	System condition	Enabling factors	Constraining factors
F1 Knowledge development and diffusion	Strong	pilot microgrid operation, university collaboration, follow-up EE initiative	limited transferability under current regulatory conditions
F2 Influence on the direction of search	Moderate	multi-level policy signals emphasizing decarbonation, flexibility, decentralization and sector coupling	implementation uncertainty, rejection from Energy Authority
F3 Entrepreneurial experimentation	Strong	real-world demonstration platform, participation of industrial partners, integration of multiple advanced energy technologies	regulatory barriers, closed distribution network permit issues and cross-property electricity distribution limits
F4 Market formation	Limited	participation in day-ahead and reserve markets, district heating supply, coordinated multi-energy operation	absence of autonomous local market, metering/reporting complexity, taxation rules and property-boundary restrictions
F5 Legitimation	Contested	policy working groups, legal reform efforts, permit applications and regulatory clarification, media visibility, regional and municipal support	resistance from incumbent network actors and regulatory ambiguity
F6 Resource mobilization	Strong	national and local funding, green finance, industrial partnerships, university participation, and multi-level government support	dependence on regulatory approval and continued institutional support
F7 Development of positive externalities	Emerging	demonstration effects, knowledge spillovers, policy references	unrealized broader system objectives, regulatory barriers, incomplete replication beyond the pilot context

The close interplay and relationship between resource mobilization (F6), entrepreneurial experimentation (F3), and knowledge development and diffusion (F1) is the strongest functional pattern in the LEMENE case. The project was able to mobilize substantial financial, technological, knowledge, and organizational resources through national and local funding, green finance, industrial partnerships, collaboration with universities, and multiple-level government support. By employing these resources, LEMENE was able to operate as a platform for real-world experimentation, integrating and testing various distributed energy technologies, sector coupling solutions, and market interfaces under practical operational environments. Through the participation of multiple industrial partners (e.g., Siemens, Merus Power, Fingrid, Elenia), the project brought together advanced energy technologies and enabled their coordinated entrepreneurial commercial experimentation within the microgrid infrastructure. In turn, this experimentation produced valuable knowledge on microgrid control, islanded operation, flexibility management, and cross-sector energy coordination. Beyond generating knowledge, which only remained internal to the project, knowledge was continuously being developed and diffused through academic publications, policy reports, and public discussion. The follow-up Edelläkävijyys Energiayhteisössä (EE) initiative represents a more advanced stage of knowledge development and diffusion, systematically translating and developing the lessons of the LEMENE pilot into transferable technological, regulatory, and organizational implementation models for future energy community projects. These three functions formed a mutually reinforcing dynamic that works as a loop. The mobilization of resources facilitated experimentation, which in turn created knowledge that diffused and increased the broader attention and analytical significance of the energy community microgrid.

The other pattern concerns the development of influence on the direction of search (F2) and legitimation (F5), both of which showed clear strategic orientation and some degree of progress in the LEMENE case but remained uneven and unstable. The project was strongly aligned with broader energy transition priorities at the EU, national, regional, and municipal levels, particularly those related to decarbonization, flexibility, decentralization, and sector coupling. It had the same strategic direction as the regulatory guidance, which increasingly encouraged the solutions of the project aimed to be put into practice. It can be said that these policy directions actually shaped the project's inception and development. Legitimation also gradually progressed along with the project, as LEMENE gained attention through permit application, concept clarification, policy reports, media coverage, public debate, and legislative discussion. However, this strategic alignment and conceptual recognition did not translate into stable institutional acceptance. Concerns about the extensive liberalization of electricity network construction from incumbent network actors and the government, regulatory ambiguity about the property group, and unresolved permit issues about the closed distribution network indicated that the project was valid in theory but contested in reality. This implies that policy direction and regulatory guidance may progress ahead of consistent institutional stabilization in the development of energy community microgrids.

Market formation (F4) and the development of positive externalities (F7) remained limited and incomplete in the LEMENE case. Although the project participated in national electricity and reserve markets and integrated multiple energy sectors within the microgrid, the emergence of a community energy market remained constrained. Existing electricity market rules, taxation policies, and property-boundary regulations limited the possibility of establishing an autonomous energy exchange within the community and with the main grids. Market activities remained embedded within the centralized electricity market structure rather than evolving into a distributed market configuration. At the same time, the project generated several positive externalities, including knowledge spillovers, demonstration effects, and policy attention. LEMENE has been referenced in academic research, governmental policy reports, and public discussion as an example of industrial-scale energy community implementation. However, these spillover effects remained partial, as the broader replication and standard establishment have not yet materialized at a larger scale. These features imply that the innovation system around energy community microgrids still reflects a formative stage, as market mechanisms and system-wide diffusion are still restricted.

The functional patterns together reveal the broader innovation dynamics of energy community microgrids. Innovation initially emerges guided by broader policy directions and is promoted by experimentation-driven processes, where resource mobilization, technology coordination, and commercial trials generate practical experience and knowledge. At the same time, the development of such systems is supported by increasing institutional recognition. However, institutional frameworks remain unsettled, and regulatory interpretations continue to evolve. Due to that, reformed market structures and large-scale influence remain constrained, leading to an early formative stage of system development. This pattern is consistent with observations in the Technological Innovation Systems literature, which suggests that influence on the direction of research can trigger virtuous innovation cycles in sustainable technologies. In such processes, societal challenges and policy goals mobilize resources, stimulate experimentation, and foster knowledge development that further strengthen expectations regarding emerging technological options (Hekkert et al., 2007). However, the LEMENE case indicates that these virtuous cycles may remain incomplete when institutional frameworks have not yet stabilized to support new technological configurations.

5.2 Multi-dimensional mechanisms shaping development

While the functional analysis reveals the dynamics of the innovation system, it does not fully explain the structural conditions shaping system development. To better understand the underlying mechanisms, the analysis further examines how technological, institutional, and social dimensions interact with the different system functions. Table 3 summarizes how the technological, institutional, and social dimensions interact with the seven innovation system functions in the development of LEMENE.

Table 3. Structural dimensions shaping LEMENE development.

Function	Technological dimension	Institutional dimension	Social dimension
F1 Knowledge development and diffusion	real-world microgrid pilot, multi-technology integration	regulatory interpretation and institutional learning	collaboration with government, universities and industry
F2 Influence on the direction of search	technological potential of microgrids, sector coupling	multi-level energy strategies, but regulatory constraints	co-created local energy visions with multi-party participation
F3 Entrepreneurial experimentation	integration of multiple energy technologies within microgrid	permit requirements limiting experimentation scope	industrial partnerships enabling experimentations
F4 Market formation	multi-energy sector integration	electricity market rules, taxation, property-boundary restrictions	limited local market stakeholders
F5 Legitimation	demonstration of technological feasibility	legislative debates and regulatory interpretations	media attention and public debate
F6 Resource mobilization	investment in microgrid infrastructure	public funding and national flagship programmes	collaboration networks and municipal ownership
F7 Development of positive externalities	demonstration of integrated microgrid technologies	policy learning and regulatory discussion	knowledge spillovers across research and industry

From a technological perspective, the case demonstrates a relatively coherent pattern of development. The microgrid platform enabled the integration and coordinated operation of multiple distributed energy technologies, allowing continuous experimentation, learning, and system improvement. No major technological bottlenecks were observed in the system functions, indicating that the technological feasibility of energy community microgrids has largely been established in practice. From an institutional perspective, the development revealed a more constrained pattern. Although multi-level policy strategies promoted decentralized energy systems, existing electricity market laws, property-boundary rules, and network permit requirements limited the practical implementation of local energy sharing. This indicates that institutional frameworks have not yet fully adapted to the operational logic of decentralized microgrid-based energy systems. From a social perspective, the case demonstrates a supportive but still limited pattern of societal embedding. Collaboration among municipal actors, industrial partners, universities, and government institutions created a conducive atmosphere for the project, which also gained considerable attention in public debate and policy discussion. However, broader societal participation remained limited, and a wider societal consensus around the role of energy community microgrids had not yet fully emerged.

The interaction among the technological, institutional, and social dimensions reveals a more complex pattern of system development. Institutional dynamics initially acted as a key trigger by directing policy attention and resources toward decentralized energy solutions. This policy orientation encouraged technological experimentation and attracted collaboration among various stakeholders. As technological experimentation expanded and collaboration increased, the system generated practical experience, operational knowledge, and increasing social attention. These developments gradually fed back into the institutional field and brought regulatory limitations and governance questions into policy discussions. However, the institutional dimension played a dual role in this interaction. While institutional signals initially enabled innovation, existing regulatory structures simultaneously limited the broader expansion of the system and the depth of societal participation. Technological development could partly continue under experimental and pilot conditions, whereas wider societal participation remained dependent on electricity market regulations. Due to the complexity and inertia of established energy system institutions, institutional adaptation occurred more slowly than technological development and social engagement.

This interaction suggests that the processes of development are along with engaging technological, institutional, and social structures simultaneously. Such multi-dimensional interactions indicate the potential of this emerging system to influence broader socio-technical dynamics in the energy transition. This interpretation is consistent with sustainability transition research, which suggests that innovations interacting with multiple structural dimensions of a system are more likely to influence broader socio-technical change processes (F. W. Geels, 2002; Markard et al., 2012; Möller et al., 2025).

5.3 Opportunities and constraints for energy transition

Based on the preceding discussion of innovation dynamics and multi-dimensional interactions, the findings can be further interpreted in terms of the opportunities and constraints that energy community microgrids create for the broader energy transition. The LEMENE case highlights both the practical potential of decentralized energy coordination and the structural barriers that continue to shape its realization.

The case analysis reveals several opportunities for broader energy transition processes. First, the LEMENE project demonstrated the capability of microgrid systems to integrate multiple distributed energy technologies within a coordinated operational framework. It is not just an electricity grid but a multi-energy integrated bidirectional network. Renewable generation, energy storage, flexible demand, and sector-coupled energy solutions were connected through the microgrid infrastructure, enabling locally coordinated energy management to improve flexibility, resilience, and reliability. Second, the system functioned as a platform for coordinating diverse actors, including industrial partners, local authorities, grid operators, and energy technology providers. This configuration illustrates how decentralized energy infrastructures can support new forms of local energy coordination beyond the traditional centralized electricity system. Third, the project created a practical environment for experimentation and learning. Through pilot operation and collaboration among multiple stakeholders, the system generated operational experience, technological knowledge, and policy-relevant insights. These features highlight how energy community microgrids provide practical opportunities for developing decentralized energy systems to promote the energy transition.

The case also reveals several structural constraints in which institutional conditions play a central role. The institutional framework governing electricity systems has not yet adapted to the operational logic of decentralized energy systems. As shown in the LEMENE, existing regulatory arrangements, including network licensing rules, property-boundary regulations, and taxation structures, remain largely designed for centralized electricity systems. As a consequence, new forms of decentralized market relations were difficult to establish. The community cannot be recognized as an energy entity interacting with the main grids, internal energy exchange within the community remained restricted, and bidirectional market participation by prosumers was hardly realized. These institutional limitations also influenced the social dimension of system development, hindering broader social participation within the energy transition. These reflect the tension between emerging decentralized energy innovations and institutional frameworks originally designed for centralized electricity systems.

Overall, these findings are broadly consistent with existing studies that emphasized both the potential and the challenges of microgrids in energy transition processes. While microgrid systems can technically enable decentralized energy experimentation, their wider utilization remains strongly shaped by institutional conditions. The LEMENE case further illustrates how the integration of microgrid infrastructures with energy community initiatives brings technological, institutional, and social dimensions of energy transition into closer interaction. This highlights the importance of aligning regulatory frameworks with emerging decentralized energy configurations to fully realize their transition potential.

6 Conclusions

The contemporary energy transition is driven by climate change, rising energy demand, justice concerns, and security risks, and is aimed at achieving sustainability goals, necessitating deeper structural changes in energy systems. In this context, decentralized and locally coordinated energy configurations, especially microgrids, have attracted growing attention due to their ability to integrate distributed renewable energy resources, storage, flexible demand, and local coordination within bounded energy systems. To examine how such systems develop and contribute to broader energy transition, this study employed a qualitative case study approach and analyzed the LEMENE case through the Technological Innovation System framework, interpreted across technological, institutional, and social dimensions. The findings show that energy community microgrids develop through a distinctive innovation pattern characterized by strong experimentation, knowledge development, and resource mobilization, while their wider transition potential remains significantly constrained by insufficient institutional adaptation.

This study has both theoretical and practical contributions. Theoretically, it extends the analytical application of the Technological Innovation System framework by integrating functional analysis with technological, institutional, and social dimensions, enabling a clearer understanding of how innovation dynamics interact with structural conditions. From a practical perspective, the findings highlight several implications. First, the case demonstrates the technological feasibility of microgrid-based decentralized systems through real-world experimentation. Second, the results indicate that institutional adaptation plays a critical role in enabling the wider development of decentralized energy systems. Third, the findings suggest the significance of adaptive policy environments characterized by regulatory responsiveness, experimental spaces for localized implementation, and stable long-term policy signals. Such governance conditions can help realize the potential of energy community microgrids within the broader energy transition.

Despite these contributions, several limitations should be acknowledged to help direct future research. First, this study is based on a single case analysis of the LEMENE industrial energy community in Finland, meaning that the findings remain context dependent. Future research could extend through comparative studies across multiple cases and institutional environments to further examine the generalizability of the observed innovation dynamics and structural mechanisms. Second, the analysis relies primarily on secondary data sources. They may limit the directness and depth of insight into the internal decision-making processes and actor interactions within the system. Future research could therefore benefit from primary empirical approaches such as interviews or participant observation to further explore the evolving dynamics. In addition to these limitations, further theoretical reflection is needed. This study extends the TIS framework by integrating technological, institutional, and social dimensions to better capture structural interactions. Future research could focus on validating this analytical extension to assess the robustness and explanatory power of this integrated approach in analyzing energy transition processes. Moreover, other perspectives from sustainability transition research may provide complementary insights. For example, future research could apply the Multi-Level Perspective (MLP) to explore how energy community microgrids are positioned within broader transition processes, such as whether they primarily function as localized innovations or have the potential to influence whole system configurations.

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Appendices

Appendix 1. Documentary sources used in the LEMENE case study

Category	Author / Organization	Year	Document title
Academic literature	Ahmed, H., & Vilkko, M.	2025	Quantifying flexibility and optimizing energy communities' participation in energy markets through dispatch strategies: A Finnish case study
Academic literature	Aslani, A., Naaranoja, M., & Wong, K.-F. V.	2013	Strategic analysis of diffusion of renewable energy in the Nordic countries
Academic literature	Laitinen, A., Lindholm, O., Hasan, A., Reda, F., & Hedman, Å.	2021	A techno-economic analysis of an optimal self-sufficient district
Academic literature	Sirviö, K., Motta, S., Rauma, K., & Evens, C.	2024	Multi-level functional analysis of developing prosumers and energy communities with value creation framework
Academic literature	Kanabro, J.	2024	How to utilize energy communities in the future in Finland
Academic literature	Lintunen, J.	2023	Sector integration and energy communities in energy transition: Case LEMENE
Legislation and policy documents	European Parliament and Council	2019	Directive (EU) 2019/944 on common rules for the internal market for electricity
Legislation and policy documents	Finlex	2013	Finnish Electricity Market Act (Sähkömarkkinalaki 588/2013)
Legislation and policy documents	Ministry of Economic Affairs and Employment	2018	Flexible and customer-centred electricity system: Final report of the Smart Grid Working Group
Legislation and policy documents	Ministry of Economic Affairs and Employment	2021	Sector integration working group final report
Legislation and policy documents	Ministry of Economic Affairs and Employment	2022	Carbon neutral Finland 2035 – national climate and energy strategy
Legislation and policy documents	Ministry of Economic Affairs and Employment	2023	Energy communities and separate lines – final report

Legislation and policy documents	Ministry of Economic Affairs and Employment	2024	Finland's Integrated National Energy and Climate Plan Update
Legislation and policy documents	Ministry of Transport and Communications	2021	Roadmap to fossil-free transport
Legislation and policy documents	Council of the European Union	n.d.	European Green Deal
Legislation and policy documents	Council of the European Union	n.d.	Energy Union
Institutional and project reports	Kettunen, M., & Kivioja, O.	2021	Edelläkävijyys Energiayhteisössä – project final report
Institutional and project reports	Energy Authority (Finland)	2020	Statement regarding Lempäälän Lämpö Oy
Institutional and project reports	Energy Authority (Finland)	2021	Statement regarding Lempäälän Lämpö Oy
Institutional and project reports	Nordic Energy Research	2023	Energy Communities
Institutional and project reports	Pirkanmaa Region	2022	Pirkanmaa energy strategy
Institutional and project reports	Lempäälä Municipality	2024	Lempäälä energy programme 2030 background document
Institutional and project reports	Leppänen, K., & Järventausta, P.	2023	Smart district demonstrations
Institutional and project reports	VTT	2022	What is the role of artificial intelligence in the future of energy systems
Institutional and project reports	Taneli, H.	2021	Artificial intelligence report
Institutional and project reports	Energy Authority	n.d.	Electricity network licensing requirements
Industry and company sources	Siemens	2018	Siemens and Lempäälän Energia to build microgrid in Finland
Industry and company sources	Merus Power	2018	Energy storage system delivery to LEMENE project
Industry and company sources	FIMER	2020	FIMER powers energy community in Finland
Industry and company sources	INNIO	2019	INNIO to supply Jenbacher gas engines for innovative microgrid project

Industry and company sources	Solarigo	n.d.	LEMENE solar energy project
Industry and company sources	Convion	2021	Fuel cells providing clean energy for microgrid in Lempäälä
Industry and company sources	Business Tampere	2025	LEMENE energy community project overview
Industry and company sources	Lempäälän Energia Oy	n.d.	LEMENE – Lempäälä energy community
Media and public discussion	Koistinen, A.	2020	The state supported a pioneering energy community in Lempäälä with 5 million euros – Now the project is complete, but the law prevents customers from connecting
Media and public discussion	Kiuru, P., & Niemi, V.	2022	Support for the LEMENE project and legislative reform
Media and public discussion	Seppälä, J.	2021	LEMENE pioneering project in Marjamäki
Media and public discussion	Fingrid-Lehti	2020	Sector integration and power balance discussion
Media and public discussion	Fingrid-Lehti	2024	Reserve market participation opportunities
Media and public discussion	Lempäälän-Vesilahden Sanomat	n.d.	Public discussions related to the LEMENE project