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# Integrated Local Energy Communities

## From Concepts and Enabling Conditions to Optimal Planning and Operation

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**Editors**

***Marialaura Di Somma***
Department of Industrial Engineering
University of Naples Federico II
Piazzale Tecchio, 80
Naples, 80125
Italy

***Christina Papadimitriou***
Eindhoven University of Technology-TU/e
Groene Loper 19
Eindhoven
5612 AP
The Netherlands

***Giorgio Graditi***
ENEA
Lungotevere Thaon di Revel 76
Rome, 00196
Italy

***Koen Kok***
Eindhoven University of Technology-TU/e
Groene Loper 19
Eindhoven
5612 AP
The Netherlands

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# Contents

# Preface

Decarbonization of the energy system requires an integrated approach across all different sectors, such as electricity, heating, cooling, and transportation. Sector coupling, through the integrated use of different energy carriers, both at the supply side (e.g. by converting (surplus) electricity into other forms, such as hydrogen) and at the demand side (e.g. by using residual heat from power generation processes for district heating), is represented as a key for reaching the ambitious climate neutrality by 2050. The main benefit associated to sector coupling is related to the increase of flexibility of the energy system through the coordinated management and operation of different sectors and the exploitation of interplay of multiple energy carriers and related technologies. On the other hand, the ongoing transition from traditional centralized energy systems to decentralized schemes brings new opportunities for distributed energy resources integration and for the evolution of the role of final users from passive consumers to active users through energy communities. Combining sector coupling at the local level with energy communities leads to the innovative concept of integrated local energy communities (ILECs), which represent an effective way of managing available energy resources at local level by also fostering consumer engagement and empowerment. The ILEC concept may refer to a set of energy users deciding to make common choices in terms of satisfying their energy needs, in order to maximize the benefits deriving from this collegial approach, thanks to the implementation of a variety of electricity and thermal technologies and energy storages and the optimized management of energy flows. The aim of this book is to present in a thorough and comprehensive way all the critical aspects that are needed when designing, planning, and operating an ILEC from end to end. This book's objective and ambition are timely, as the integrated energy system is an important means to achieve the energy transition and minimize dependence on fossil fuels.

To this end, the following key topics are comprehensively discussed throughout the book:

- Conceptualization of ILECs with analysis of key features, enabling technologies including ICT, actors, business models and key issues for their implementation, and validation of ILEC solutions through simulation and testing in a lab environment and real-world applications.

- Presentation of innovative approaches for the coordinated planning and operation of ILECs, with integrated flexibility identification and employment, and for peer-to-peer (P2P) energy trading.
- Analysis of key social aspects related to the reorganization of the energy system according to the energy community paradigm.
- Definition of guidelines and recommendations for optimal implementation of ILECs.

The book supports readers in finding innovative solutions and detailed insights for the planning and operation of ILECs while fostering research advances to the state of the art on this topic. The book does this by presenting approaches, methodologies, critical assessments, real-time applications, as well as efficient optimization models and algorithms for MCES and emerging technologies/carriers including hydrogen and electric vehicles. The proposed optimization frameworks are scalable and flexible for adaptation to several real contexts thus representing valid tools to provide support to decision-makers for ILECs planning and operational aspects.

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*Marialaura Di Somma*
University of Naples Federico II

*Christina Papadimitriou*
Eindhoven University of Technology-TU/e

*Giorgio Graditi*
ENEA

*Koen Kok*
Eindhoven University of Technology-TU/e

# 1

# Introduction: The Need for Sector Coupling and the Energy Transition Goals

*Marialaura Di Somma*[1], *Christina Papadimitriou*[2], *Giorgio Graditi*[1], *and Koen Kok*[2]

[1] *Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Department of Energy Technologies and Renewable Sources, Lungotevere Thaon di Revel, 76, 00196, Rome, Italy*
[2] *Eindhoven University of Technology, Electrical Engineering Department, Groene Loper 3, 5612 AE, Eindhoven, the Netherlands*

## 1.1 Introduction

### 1.1.1 The Needs and Challenges of the Current Energy System

The present energy system faces several pressing needs. With a growing demand for energy driven by population growth, industrialization, and improved living standards, there is an urgency to meet it in a sustainable manner. Simultaneously, addressing climate change requires a transition to low-carbon or carbon-neutral energy sources. However, integrating renewable energy sources (RESs) poses challenges due to their converter-based, intermittent, and variable nature. To ensure a reliable and resilient power system, aging infrastructure needs to be upgraded and modernized. Grid resilience must also be enhanced to withstand extreme weather events, cyberattacks, and other disruptions. Furthermore, supporting the electrification of different sectors, e.g. heating, cooling, and transportation, necessitates infrastructure development and adequate grid capacity that is now lacking. To this end, advancements in energy storage technologies are also crucial. Lastly, improving energy efficiency across sectors is vital to reduce overall energy demand and greenhouse gas (GHG) emissions, which requires a combination of technological advancements and policy measures.

Addressing the aforementioned needs is not trivial and numerous challenges are present. Balancing energy supply with the ever-increasing demand is a hard task as it does not only presuppose upgrades in related infrastructure and equipment but also changes on how the operators schedule and manage the grid. Transitioning to low-carbon energy sources while ensuring a reliable and uninterrupted power supply poses a complex task that requires careful planning and investment. Integrating RES into the grid requires addressing the intermittency and variability associated with them, by necessitating innovative solutions for effective integration.

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Moreover, upgrading and maintaining aging infrastructure presents financial and logistical challenges. Safeguarding the power grid against risks such as extreme weather events and cyberattacks requires robust strategies and investments in cybersecurity measures but also affects the "business as usual" in the operational planning of the operators. Advancing energy storage technologies is crucial for both dealing with the excess renewable energy and providing flexibility for balancing supply and demand. The electrification of various sectors presents several challenges that impact the power system overall. First, to satisfy all types of energy demands resulting from electrification, a significant amount of additional power network capacity is required. This includes accommodating the increased electricity consumption from transportation, buildings, and industry. Second, contingencies in the power system can have far-reaching consequences. Any disruption or failure can lead to power outages, affecting not only the resilience of the power system and of the electrified sectors but also the overall functioning of society. Grid stability and management become crucial factors in ensuring a reliable and resilient power supply in this case. As electrification changes the energy landscape, operators face new challenges in planning and scheduling. They must consider the increased complexity of managing diverse energy sources, grid capacity, and demand patterns to optimize system performance and ensure uninterrupted power supply.

As such, the distribution operators' planning and scheduling processes need to adapt to the evolving requirements of an electrified system to maintain efficient operations. Promoting energy-efficient practices and technologies across sectors requires changes in consumer behavior as well as supportive policies and incentives.

Finally, creating and implementing effective policies and regulations to facilitate the transition to a sustainable and resilient power system necessitates balancing the interests of different stakeholders and ensuring fair market competition.

Addressing these needs and challenges requires collaborative efforts from governments, energy providers, technology developers, researchers, and consumers to create a sustainable, secure, and affordable energy power system for the future.

### 1.1.2 What Is Sector Coupling?

Sector coupling originally referred to the electrification of end-use sectors such as heating, cooling, and transport, aiming at increasing the RES share in these sectors, based on the assumption that the electricity supply can be mostly renewable. More recently, the concept has been widened by also including supply-side sector coupling, integrating, for instance, power and gas sectors through power-to-gas (P2G) technologies. It must be highlighted that sector coupling is very similar to that of integrated energy systems, introduced by ETIP SNET Vision 2050 [1–3], defined as a *system of systems*. Namely, an integrated energy system is an integrated infrastructure for all energy carriers with the electrical system as a backbone, characterized by a high level of integration between all networks of energy carriers, coupling electrical networks with gas networks, heating, and cooling, supported by energy storage and conversion processes. The creation of these systems is based on the coordination of the planning and operation key processes. Within these processes, different types of energy systems across multiple geographical scales are considered

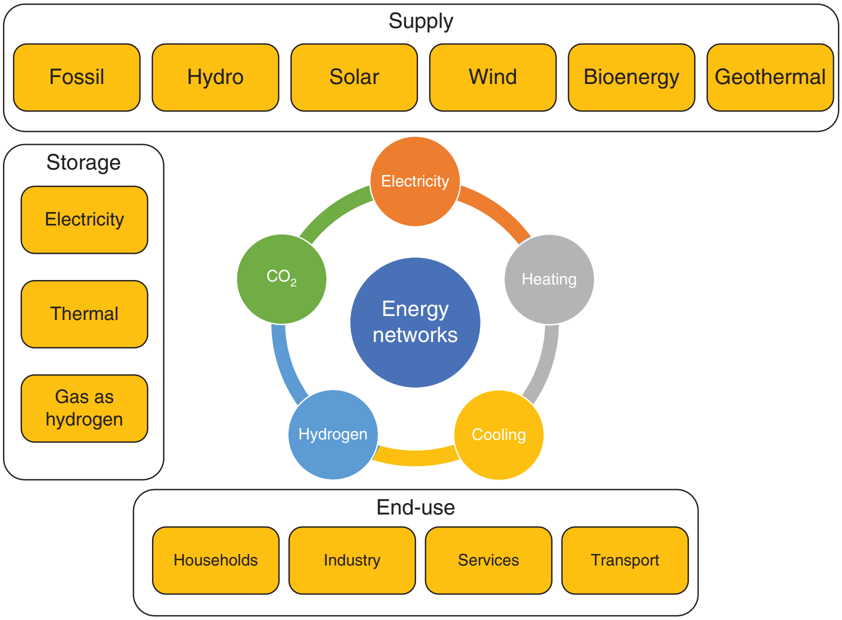


**Figure 1.1** Representation of sector coupling concept. Source: Adapted from Van Nuffel et al. [4].

to foster reliability and efficiency in energy services while also minimizing negative environmental impacts [4]. The different sectors that can be involved under the concept of sector coupling are represented in Figure 1.1.

Two different strategies are considered under the concept of sector coupling, namely [5]:

- **"End-user" sector coupling** aiming at the electrification of end-use sectors and consisting of energy conversion technologies for electrification of final users' energy demand, thus enabling flexibility at the final users/prosumers level. An example of these technologies is well represented by electric vehicles (EVs) allowing for the electrification of the transport sector.
- **"Cross-vector" sector coupling** aiming at integrating multiple energy carriers mainly linking electricity and gas sectors through P2G technologies that can be used to produce hydrogen or synthetic methane when excess renewable electricity is available. The produced gas can be then stored for later re-conversion into electricity when renewable electricity supply is insufficient (and hence high electricity prices), by using the so-called power-to-gas-to-power process. On the other hand, electricity can be produced by hydrogen through fuel cells. Another alternative is that the hydrogen produced can be processed into methane or liquid fuel like methanol by making it reacts with CO or $CO_2$, the so-called power-to-liquid route. These fuels can be used in transport sectors such as shipping.

The combination of these two strategies allows increasing the flexibility of the energy system, while also supporting RES integration through optimal use strategies.

A good example was already provided above, but there is another key example represented by Power-to-Heat technology such as heat pumps. These latter, especially when combined with thermal storage, allow for thermal energy production in periods with excess renewable electricity which can be then stored and re-used in periods with insufficient renewable electricity, thereby representing a cost-effective and efficient solution.

## 1.2 Opportunities for Sector Coupling to Contribute to Decarbonization

### 1.2.1 Electrification and Sector Coupling

Electrification in power systems refers to the process of transitioning from traditional, fossil fuel-based energy sources to electrical power for various applications. It involves replacing the direct use of fossil fuels, such as gasoline and natural gas, with electricity as the primary source of energy.

The concept of electrification has gained significant attention in recent years due to its potential to reduce GHG emissions and combat climate change. So, electrification is one of the main drivers of energy transition as it is perceived nowadays and a reliable solution for effective decarbonization at the end user's side.

Therefore, the electrification scenario can be applied in different sectors. Some examples that can foster electrification are given below:

**Transportation:** Electrification of transportation involves transitioning from conventional internal combustion engines (ICEs) to EVs. This shift reduces reliance on fossil fuels, decreases air pollution, and offers opportunities for smart charging and integration with the grid, e.g. with vehicle-to-grid (V2G) services. EVs can expand services to other vectors/domains as well through the so-called V2X services. For example, in a V2Home scenario, EVs can supply power to homes during power outages or peak demand periods.

**Residential and commercial buildings:** Electrifying buildings involves replacing fossil fuel-based heating systems, such as oil or natural gas furnaces, with electric heat pumps. An instance is provided in Figure 1.2. This approach reduces carbon emissions, improves energy efficiency, and enables demand response programs.

**Industrial processes:** Electrification can also be applied to various industrial processes. For example, using electric furnaces instead of traditional fuel-based furnaces in manufacturing reduces emissions and provides more precise temperature control. Electrification can also power other industrial equipment, such as pumps and motors.

Although electrification presents direct benefits such as reduced GHG emissions and air quality improvement, it also presents challenges that are difficult to overcome. The most persistent challenges of electrification are discussed below.

One significant challenge is the need for additional power network capacity to accommodate the increased demand from electrified sectors related to transportation and buildings. This requires substantial investments in grid infrastructure,

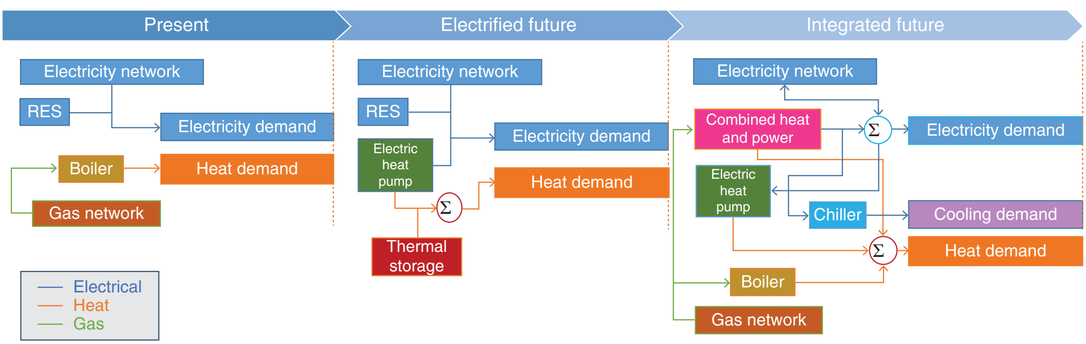


**Figure 1.2** The transition from the present to the Integrated Systems approach.

such as new transmission lines, substations, and distribution networks, to ensure a reliable and resilient electricity supply. Another challenge lies in maintaining stability in the power system, as the integration of RES and the growth of decentralized generation introduce variability and uncertainty. Robust contingency plans and advanced grid management techniques are necessary to handle potential disruptions and ensure system reliability. Grid stability and energy balancing also become crucial considerations, as the intermittent nature of RES and the varying electricity consumption patterns of electrified sectors can impact the balance between electricity supply and demand. Effective energy storage solutions, demand response programs, and grid control mechanisms are required to stabilize the grid and optimize energy utilization. Finally, operators' planning and scheduling become more complex due to the increased number of distributed energy resources, EVs, and flexible loads. Advanced modeling, forecasting, and optimization tools are essential for operators to efficiently plan, schedule, and manage the operation of the power system while considering factors such as demand fluctuations, charging infrastructure availability, and grid constraints.

Nevertheless, if electrification is enhanced by the sector coupling approach that fosters coordinated management and operation of different sectors, then the challenges identified above can be lifted to a certain extent. In Figure 1.2, the current energy system is compared with the electrified and the integrated energy system paradigm. In specific, an example of electrifying the heat demand is shared. In the present, heat demand is covered by gas-fired boilers, whereas in an electrified future the heat demand is covered by electric heat pumps powered by the electricity network. Through the sector coupling approach, the electrified system is further enhanced. In fact, in such a system, multiple hybrid energy technologies are managed with high synergy to satisfy the multi-energy demand, and services can be provided with the most convenient energy carrier and sector. Moreover, sector coupling allows increasing efficiency in the energy resources use through exploiting synergies coming from interplay of different energy carriers and reduction of RES curtailment. In practice, for instance, in case of excess electricity from RES, it can be converted into gas as hydrogen or synthetic methane through P2G technologies, stored and/or transported by existing gas infrastructures for immediate or later usage, or re-converted again into electricity when renewable electricity supply is insufficient to satisfy the loads.

### 1.2.2 Enhancing System Stability and Reliability at the Grid Level Through Sector Coupling

As mentioned, sector coupling refers to the seamless integration, coordination, and operation of different energy sectors, leveraging the synergies between them. By combining the power grid with heating/cooling systems, transportation infrastructure, and other sectors, sector coupling offers numerous benefits that contribute to enhanced power system stability and reliability. An integrated grid can be seen in Figure 1.3. Five different carriers (water, electricity, heating, cooling, and gas) are

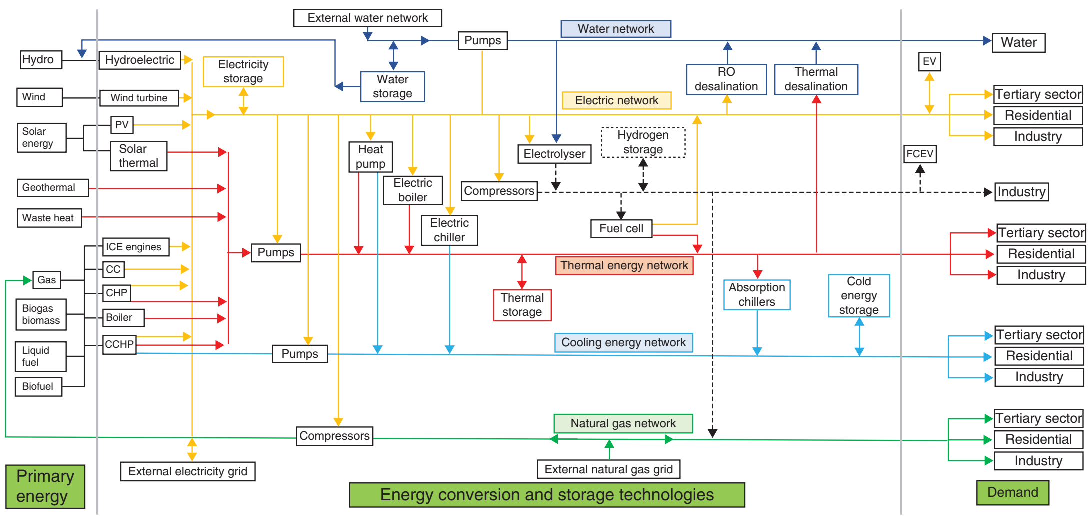


**Figure 1.3** Overview of an integrated grid through sector coupling. Source: Adapted from Papadimitrou et al. [6].

seen integrated through the existence of conversion and hybrid technologies along with storage (thermal, electrical, hydrogen, EVs), allowing the interaction and collaboration of the different carriers when needed.

One of the key advantages of sector coupling is improved grid stability through flexibility and redundancy. The integration of diverse energy sources, such as wind and solar, with complementary technologies like heat pumps or combined heat and power (CHP), enables the balancing of fluctuating supply and demand. This flexibility allows for more efficient management of energy flows and reduces the risk of grid instability, ensuring a reliable power supply even in the presence of intermittent RES.

Additionally, sector coupling enhances power quality and resilience. By integrating energy storage systems into the grid, excess renewable energy can be stored and released when needed to the electricity grid or other carrier as already explained, smoothing out variations and mitigating voltage fluctuations. Furthermore, the coupling of heating, cooling, and power systems enables the utilization of waste heat from power generation, improving overall energy efficiency and reducing reliance on fossil fuels.

Another benefit of sector coupling is its ability to facilitate demand response schemes and load balancing. By integrating intelligent demand response mechanisms, consumers can adjust their energy consumption from technologies residing in different carriers based on grid conditions, helping stabilize the system during peak demand periods. This dynamic interaction between the power system and end-users – that can expand to all carriers – contributes to grid reliability and reduces the need for costly infrastructure upgrades.

Furthermore, the integration of EVs plays a crucial role in sector coupling. EVs can act as mobile energy storage units, offering grid support through V2G technology. During times of high electricity demand, EVs can supply power back to the grid, supporting grid stability and reducing stress on the power system. This bidirectional flow of energy optimizes resource utilization and enhances the reliability of the grid.

However, the successful implementation of sector coupling is not without its challenges. Interoperability and system integration pose significant technical hurdles. Different sectors often use diverse technologies, protocols, and communication systems, requiring seamless coordination and interoperability to ensure efficient energy sharing and control. Standardization efforts and collaboration among stakeholders are crucial to overcome these barriers. Furthermore, the maturity of technologies and the availability of sustainable business models are critical considerations. While some sector coupling technologies, such as heat pumps or CHPs, have matured, others, like P2G, may still be in the early stages of development. Policy and regulatory frameworks also need to adapt to support sector coupling. Clear guidelines and incentives are required to encourage cross-sector integration and investment. Additionally, social acceptance and public engagement are vital to address concerns, educate the public, and promote behavioral changes necessary for successful sector coupling implementation.

In conclusion, by integrating different sectors and leveraging the synergies between them, sector coupling enables flexibility, resilience, and optimized resource utilization. Overcoming technical, regulatory, and social challenges will be crucial to realizing the full potential of sector coupling and building a more stable, reliable, and sustainable power system for the future.

### 1.2.3 Decarbonization of Heating and Cooling in Building Environment (End-User Level) Through Sector Coupling

Today, energy consumption for heating and cooling in the building environment at the end-user level is responsible for a notable share of GHG in industrialized countries such as Europe. Sector coupling offers a great opportunity for decarbonization of final energy use for heating and cooling purposes through several technologies that can be classified into three categories: (i) technologies making direct use of renewable energy such as solar thermal, geothermal energy, or biomass heating; (ii) technologies making indirect use of renewable energy through electrification, such as electric heat pumps; and (iii) cross-vector integration technologies such as CHP or combined cooling heat and power (CCHP). According to Ref. [4], electric reversible heat pumps represent the best option for decarbonizing this specific sector in European countries, and this is mainly due to the good technical performance of this technology represented by a high coefficient of performance, being then followed by CHP for large applications and district heating. The latter also represents one of the main solutions for the decarbonization of heating demand in the building environment especially when based on RES as biomass heating or solar thermal, while also offering a great potential for the sector coupling strategies presented in Section 1.2. In fact, heat pumps and CHPs can be used with optimized strategies in a complementary manner, with the former operating in periods with low electricity prices and the latter operating in periods with higher electricity prices. However, the lack and inadequacy of existing infrastructures is the main barrier to deployment of this technology as it may require significant investments in new assets.

Another benefit represented by heat pumps and CHPs when coupled with thermal storage is represented by the provision of ancillary services to the electrical network [7]. A practical example is given by heat pumps decreasing the produced thermal energy without compromising the user's comfort due to building thermal inertia, thereby providing ancillary services. On the other hand, CHPs also can provide flexibility services to the power system, by decoupling the production of electricity and heat through thermal storage depending on the demand [8].

Another promising option to electric heating for decarbonization of this sector is represented by small-scale micro-CHP that allows for the reduction of distribution network costs, by replacing gas-fired plants. This technology can provide firm capacity (assuming it is able to be managed to provide capacity during non-curtailable or non-shiftable peak demand occurrences) while improving conversion efficiency, since the thermal energy produced recovered from electricity generation is not wasted but used to meet local heat demand.

## 1.3 European Energy Legislation and Initiatives Supporting Sector Coupling

The European energy legislation on energy transition sets forth a visionary path, aiming to foster the transition from traditional fossil fuel-based energy sources to cleaner, renewable alternatives. Toward this, directives at the European Union (EU) level on energy transition were issued some years ago and have been regularly updated ever since. Directives are assumed to be transpositioned at the EU member state level and put in context. Policy measures and initiatives that are supportive are also propelling Europe toward a sustainable and low-carbon future. In the next subsections, the most recent developments that are sector coupling supportive are briefly discussed, whereas Chapter 2 dives deeper into the EU policy.

### 1.3.1 Directives

Clean Energy for All Europeans Package [9]: Since 2018, the EU adopted the Clean Energy Package, which consists of several directives and regulations aimed at accelerating the clean energy transition. The package includes measures promoting sector coupling by encouraging the integration of renewable energy in various sectors and promoting energy storage and demand response technologies. In specific, the package includes the Renewable Energy Directive (RED II) [10]. The RED II sets binding targets for renewable energy consumption in the EU. It promotes sector coupling by establishing a framework for supporting the use of renewable energy in heating and cooling as well as in the transport sector. It encourages the production and use of advanced biofuels and renewable gases, such as biomethane and hydrogen. The Energy Efficiency Directive (EED) [11] sets out binding energy efficiency targets and measures to promote energy efficiency across different sectors. It encourages the use of energy-efficient technologies and promotes the integration of energy systems through the utilization of waste heat, CHP systems, and district heating and cooling networks. Energy Performance of Buildings Directive (EPBD) [12]: The EPBD focuses on enhancing the energy performance of buildings by promoting energy-efficient renovations and setting minimum energy performance standards for new constructions. The new smart readiness indicator (SRI) for buildings addresses sector coupling through the promotion of flexibility and mobility integration in buildings. In addition, the Energy Market Directive – EMD II [13] aims to create a competitive and integrated electricity market within the EU. It emphasizes the integration of RESs and the improvement of cross-border electricity trading. Energy Infrastructure Regulation (TEN-E) aims to facilitate the development of cross-border energy infrastructure, including electricity and gas projects, to strengthen energy security and support the integration of RESs. The Alternative Fuels Infrastructure Directive (AFID) aims to facilitate the deployment of alternative fuels infrastructure, such as EV charging stations and refueling stations for hydrogen and natural gas.