FLEXI GRID

Interoperable solutions for implementing holistic **FLEXI**bility services in the distribution **GRID**

Contributions to future network development plans

Deliverable 7.4

WP7

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ABBREVIATONS

AC:	Alternative Current
AMM:	Automated Market Maker
CA:	Consortium Agreement
CEF:	Connecting Europe Facility
DC:	Direct Current
DER:	Distributed Energy Resources
DSOs:	Distribution System Operators
DYMASOS:	Dynamic Management of Physically Coupled Systems of Systems
EC:	European Commission
ENTSO-E:	European Network of Transmission System Operators for Electricity
ENTSOG:	European Network of Transmission System Operators for Gas
EV:	Electric Vehicles
FACT:	Flexible AC Transmission System
GA:	General Assembly
H2020:	Horizon 2020
HV:	high Voltage
HVAC:	Heating, Ventilation, and Air Conditioning
HVAC:	High Voltage Alternating Current
HVDC:	High Voltage Direct Current
ICT:	Information and Communications Technology
IEA	International Energy Agency
IMS:	Information Management System
IPR:	Intellectual Property Right
LV:	Low Voltage
M:	Month
MV:	Medium Voltage
OECD:	Organisation for Economic Co-operation and Development
OPT:	Optimal Power Flow
PCI:	Project of Common Interests
R&D:	Research and Development
RES:	Renewable energy systems
S:	Solution
TSOs:	Transmission System Operators
TSs:	Transmission System
TWh:	Terawatt hour
TYNDP:	Ten-Year Network Development Plan
UCs	Use Cases
WP:	Work Package

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EXECUTIVE SUMMARY

This executive summary provides findings of deliverable D7.4, part of FLEXIGRID project under WP7. The deliverable, titled "Contributions to future network development plans", specifically addresses the Ten-Year Network Development Plan (TYNDP). The TYNDP represents the comprehensive pan-European blueprint for electricity infrastructure expansion crafted by ENTSO-E. It takes a holistic view of the prospective power network, addressing how the European power interconnections network and storage solutions can be strategically employed to facilitate the energy transition in a cost-efficiency and security manner. TYNDP 2020 has been developed through the collaborative expertise of 35 European Transmission System Operators (TSOs).

The FLEXIGRID project aims to advance the development of flexible and efficient distribution networks to support the evolving demands of future distribution systems. Thus, deliverable D7.4 is a critical component of this project, as it explores the intersection of network development and environmental considerations. The deliverable was developed within the FLEXIGRID project's M43 to M48 work plan.

The other key findings of this deliverable highlight the European distribution network's critical role in advancing the member states' technological, economic, social, and environmental pillars. The power network plays a vital role in achieving regional security, development, stability, progress, and industrial competitiveness. Therefore, the deliverable emphasizes the crucial role of the distribution network in helping the EU achieve its agenda, including the carbon neutrality target by 2050. Thus, the distribution network has a significant impact on advancing this goal through integrating renewable energy sources, supporting electrification of key sectors, and enhancing demand response such as energy storage systems and smart metering, among others, helping the distribution network become a crucial enabler of decarbonization. That can be achieved through expanding and modernizing the EU distribution network. Moreover, the deliverable findings show that the European power network uses the technology roadmap as its evolution and development footprint from its previous national grid to multinational interconnection, as evident in TYNDP.

Implementing FLEXIGRID solutions demonstrates smart grid technologies' effectiveness in addressing the EU power network's past, present, and future challenges. These innovative solutions provide a range of benefits, including flexibility, reliability, sustainability, and cost-efficiency, which greatly contribute to the increased integration of renewable energy sources (RES) into the grid. The FLEXIGRID solutions present advanced network functionalities such as bi-directional power flow protection, smart metering with feed mapping capabilities, On-Load Tap Changer (OLTC) transformers, communication facilities, location coordination, fault detection, and self-healing mechanisms, as well as various optimization algorithms. These features enhance grid forecasting, congestion management, and virtual thermal energy storage capabilities, among other advantages. Overall, deploying FLEXIGRID solutions align with TYNDP's strategy of achieving a modern and efficient power grid system.

Finally, the deliverable thoroughly examines the environmental impact of the various use cases implemented across FLEXIGRID demo sites and highlights their significant contributions.

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1. INTRODUCTION

This deliverable D7.4 is part of the WP7 of the FLEXIGRID project. This deliverable D7.4 is titled "Contributions to future networks development plans." Moreover, the deliverable was developed per FLEXIGRID project schedule M43 to M48.

The main objective of deliverable D7.4 is to ensure that all the evaluations needed for the outreach of FLEXIGRID project solutions are analysed and further considered to propose a series of recommendations for improving the European power distribution network. To achieve the same, previous materials, information, knowledge acquired, and lessons learned from FLEXIGRID solution, and the use cases deployed across the demo sites have been substantially applied and will inform this deliverable report.

One crucial aspect discussed in this deliverable is the significant role and profound impact of FLEXIGRID on the future development of European distribution networks. Implementing FLEXIGRID is poised to enhance our comprehension of the evolution of power systems while effectively addressing the existing and future requirements of the European distribution network. It aims to ensure that the European distribution network remains adaptable, resilient, and capable of accommodating emerging and future developments in the power sector. Offers invaluable insights into the future development plans of the European distribution network, aligning with the Ten-Year Network Development Plan (TYNDP). It furnishes comprehensive information regarding the intended advancements and strategies to be implemented.

Furthermore, this deliverable goes beyond to present insightful recommendations on how deploying FLEXIGRID use cases across various demonstration sites has contributed to environmental protection. These recommendations highlight the positive impact of FLEXIGRID in reducing carbon emissions, promoting renewable energy integration, and fostering sustainable practices within the European distribution network. By emphasizing environmental considerations, the deliverable underscores the importance of incorporating clean and efficient energy solutions in shaping the future of the European distribution network. Also, it emphasizes the crucial role of the European distribution network in achieving climate goals.

The existing power systems have substantially contributed to the current global warming or greenhouse effects that adversely impact the environment due to heavy reliance on high carbon emissions energy sources on the power grid. The European energy mix on the power network has undergone severe changes to limit the global temperature rise to 1.5°C above the pre-industrial levels and achieve the European Green Deal, aiming to attain carbon neutrality by 2050 [1]. In the context of clean energy, renewable energy sources (RES) offer a free or low-carbon energy source. Moreover, RES are environmentally sustainable and technologically effective. Even though RES provide an alternative energy source, they pose a significant challenge for the current grid network system, where they are not fully dispatchable due to their intermittent nature. The stumbling block to their full utilization is the current European grid network system since it is inflexible, unstable, and unresponsive to provide the intelligent information necessary for a modern grid operation that offers stability, flexibility, and energy security [1].

Biennial, the European Network of Transmission System Operators for Electricity (ENTSO-E) usually adopts a non-binding TYNDP. The TYNDP is a European Union initiative that aims to develop a coordinated and efficient energy infrastructure network in Europe. The TYNDP plays a vital role in developing European electricity network transmission. Other key objectives of TYNDP include identifying European grid network development and investment gaps, including cross-border capacities. To support cross-border interconnection that enhances the effective functioning of the market and competition.

Further, it ensures that the European electricity transmission network has greater transparency. These national investment plans contribute to future network development plans and environmental protections [2]. Aligned with the TYNDP, the deliverable thoroughly examines how FLEXIGRID project has made significant contributions and will continue to achieve the TYNDP goals. Furthermore, the deliverable discusses the plans and anticipated contributions of FLEXIGRID project, indicating its ongoing commitment to aligning with the TYNDP and driving positive transformations in the European distribution network.

Finally, this deliverable D7.4 is organized into five chapters.

- The first chapter serves as an introduction to the deliverable, providing an overview and stating the objective of the report while setting the context of the subsequent chapters.
- The second chapter discusses the European network development evolution covering its past, current, and future needs. This chapter discusses some of the short-medium-long terms plans for developing Europe’s distribution network. Generally, it provides insights into the strategic direction and goals of the European distribution network growth and adaptation in response to evolving requirements.
- The third chapter focuses on the contribution of FLEXIGRID project to the future European distribution network. This section explores how individual FLEXIGRID solutions align with the EU development plans and how the project supports and enhances the network's development objectives.
- The fourth chapter provides recommendations for the environmentally friendly deployment of all FLEXIGRID use cases across the demo sites.
- The fifth and the last chapter summarises key findings, insights, and recommendations discussed in the deliverables.

2. EUROPEAN NETWORK DEVELOPMENT EVOLUTION

2.1 Overview

The European power network has been one of the most critical infrastructures in Europe, supporting security, development, stability, progress to the member states, and industrial competitiveness. It is considered one of the ubiquitous and universal items within the continent. The network infrastructure is the backbone of the electrical value chain development. The European national power grids are interconnected through cross-border lines. The physical grid interconnection facilitates the power flow, exchange, trading, and integration of the wholesale electricity market across the EU member states. In that sense, the grid network system enables the electricity flow from regions with excess and cost-effective electricity generation to be dispatched to the areas experiencing shortages, mostly based on the merit order. Hence, the power network has been a key pillar in modern European society's scientific, economic, and cultural progress.

Typically, the electricity is dispatched through a mesh of transmissions. The TSOs operate high-voltage lines, while the medium and low-voltage lines operate either by TSOs or DSOs. In between, substations and transformers adjust voltage either up or down before distribution to the end users. The European grid network has been evolving with time. Traditionally, the network has been connected with large and centralized power plants making it inflexible and unadaptable.

As Europe is shifting towards decarbonization and decentralization of the power market, the European network transformation is experiencing a tectonic shift in full swing. This network modernization enables the grid to be future proofed to digitalization, demand response, storage, and flexibility to intermittent energy generation sources. Subsequently, the power network system can, in a cost-effective manner, integrate the electricity behaviours of generators and consumers connected to it. It further ensures that the network is economically efficient and sustainable with minimum electricity losses characterized by high supply security, flexibility, and high quality and safety level. Thanks to the TYNDP and EU energy market plan, the European grid system has been dramatically evolving, largely driven by EU climate and energy policy, short, medium, and long terms goals, as well as commitments towards a net zero-emissions continent [3].

The TYNDP are infrastructure development plans that facilitate a strategic approach to developing a pan-European electricity and gas grid network. The TYNDP is drawn and coordinated by the ENTSO-E, an association for the cooperation of the European TSOs, with the assistance of the European Network of Transmission System Operators for Gas (ENTSOG). The ENTSO-E represents about 39 interconnected TSO members across 35 countries in Europe [4]. Its core mandate is to coordinate operations and secure the European grid network infrastructure transparent and trustworthy manner. Therefore, the current TYNDP road map is rationalized to use the highest technical rigor that absorbs innovation to overcome the European grid network's current challenge and prepare a sustainable network that responds to the future. The continent cannot achieve its climate goals without enhancing the Europe grid network system. However, the European network development and utilisation should happen on time. On this basis, this section of the report recommends the past, current and future needs, development dynamics, and perspective of the European network impacted by the short-, medium- and long-term goals. The provided Figure 1 illustrates the primary drivers behind the evolving development of the EU grid network over time.

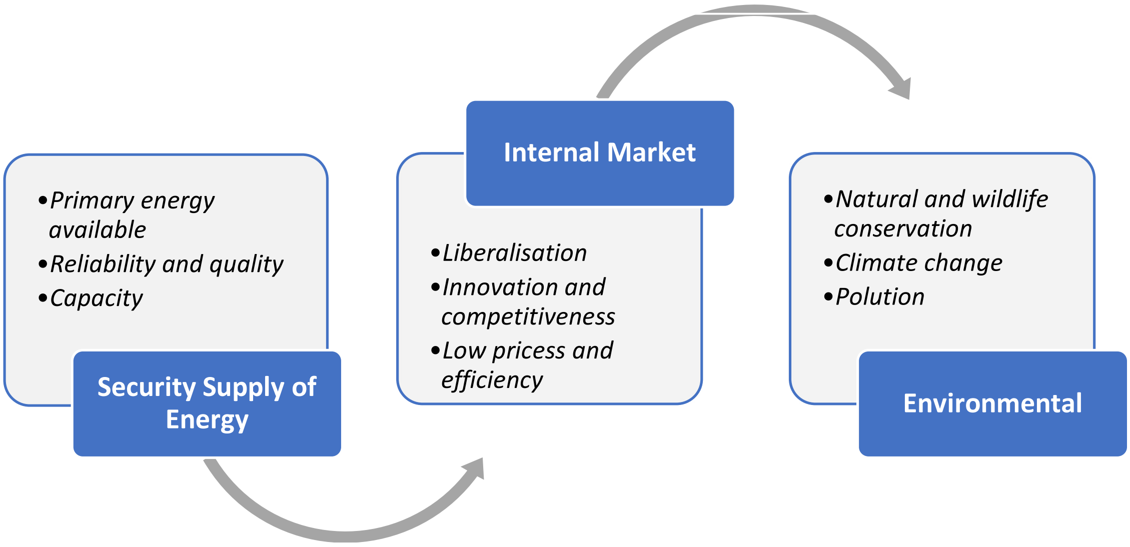

Figure 1: Summary for Reasons for European grid network Development Evolution

2.2 Past Situation for EU Grid Network Development

The European grid network is generally characterized by non-uniform load distribution with high load density; hence, the European grid network connection structure is relatively dense and compact. The European network has experienced decades of development to meet the ever-changing energy demands. Historically, the networking process of the EU grid interconnection has been primarily driven by political factors, economic situations, and energy development strategy. The scale of the European grid network has continuously developed from a simple exchange of electricity between countries to robust multinational interconnection at various interstage. The European grid network has undergone four major development stages, including the origin development of the power-grid technology, the gradual formation of the power network across various countries, the establishment of the European transitional interconnected power grid, and the realization of the transcontinental interconnection [5].

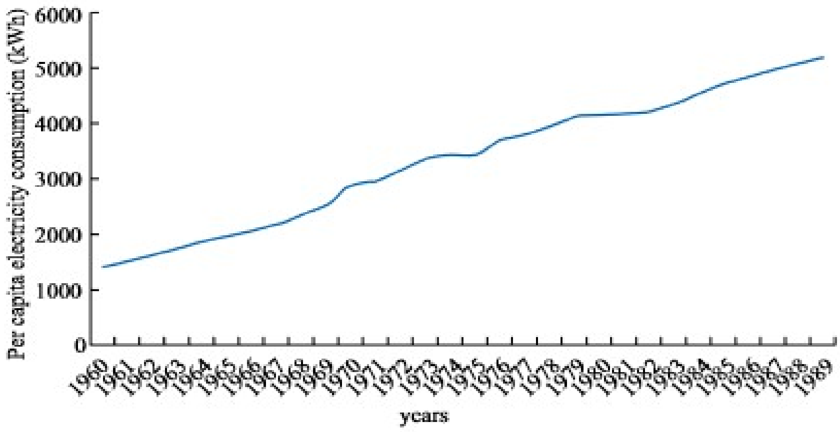

Figure 2: Per-capita electricity consumption in Europe from 1960 to 1990

Source: Global Energy Interconnection Development and Cooperation Organization (GEIDCO)

In the late 19th century, the European economy promoted innovation, science, and technology. This breakthrough led to the creation of a technically viable high-voltage European transmission line largely accelerated by the advancement of the industrial revolution needs in Europe. In the mid-20th century, European industrial production accounted for approximately 48 percent of the global output. By the early 90s, the per-capita energy demand heightened about four-fold, as shown in Figure 2 [5]. Therefore, European power transmission and exchange gained considerable interest in meeting this rapid economic development and high electricity demand. As a result, the power trade across the neighbouring countries strengthened, which accelerated the development of the European power grid network.

In the past, the power network interconnections between the European countries existed mainly between the countries that could and could not meet their internal energy demand. Large power plants were mostly built-in areas rich in coal, oil, and water resources to reduce power production costs. The aim was to achieve a low cost of investment, resource sharing, and low cost of electricity. At this point, the transmission network was enhanced, the AC voltage level was further optimized, and each country's power grid improved. Owing to the rapid growth of the European power demand and the expansion of the grid network, large and more efficient power-producing units were operated successively. A high voltage direct current (HVDC) was successfully applied to the grid network to enhance high-power trade in EU countries.

By the end of the 20th century, the European regions that were not interconnected due to geographical restrictions were later linked thanks to the DC submarine cable network's development, which enabled optimum transmission capacity and helped in voltage control. Additionally, with the development of the DC submarine cable network, the continent managed to asynchronous interconnects and emerge the other major grid networks among; the Nordic power grid, British power grid, and European continent grid into one. The interconnection and merging of the abovementioned grids facilitated the realization of a giant grid with superior power harmonization and reciprocal and peak-shaving resource sharing. As the European economy keeps improving, the grid network's scale constantly expands and develops. In short, the European power network adapted the technology roadmap as its development footprint, which enabled the evolution and development of power generation units from small to large, low to high voltage, and national to multinational interconnection. In a nutshell, the development of the European power network, which was designed mid-nineties with the idea of strengthening the Europe market competition, enabled electricity liberalization, which benefited the end-user with a lower price of electricity.

In 2009, the EU legislation developed Lisbon Treaty, containing an EU energy policy chapter. Despite the prior effort by the European Union, this policy represented a crucial milestone in the area of energy since it came at a time when there was a significant energy shift. The EU's energy policy aimed to promote energy sustainability, affordability, and security. To achieve such objectives, the policy ensured the efficient operation of the energy market, promoting energy efficiency, promoting renewable energy sources, and strengthening the interconnection of energy networks to ensure solidarity between the member states [8]. In the policy, several new developments related to grid networks were introduced. At the national level of the member states, the independence of the transmission network operators was strengthened. Also, it heightened the harmonization level of the electricity transmission network between the operators. Subsequently, the power transmission network increased its power handling capacity levels while simultaneously achieving the power transmitter's (TSOs) independence. In all the Member States, TSOs were obligated to operate and obtain certification under their respective national regulatory authorities. At the European level, the policy established Agency for the Cooperation of Energy Regulators (ACER). ACER, among its other functions, helps formulate rules and developments of the European network [9]. In addition, it brought together the TSOs in pan-European organizations, namely ENTSO-E and ENTSO-G, for electricity and gas, respectively.

To implement the Paris Agreement of 2015, the EC set the 4th Energy Package called Clean Energy for All European package. It outlined an ambitious set of energy reforms to enable the EU to meet its proposed climate and energy targets. The 4th Energy Package created reforms in European energy design and network operations to enable the integration of renewable energy generation, which is decentralized and variable, thus demanding greater flexibility on the grid network. To ensure the network's better functioning, the package defined network usage tariffs and promoted the adoption of congestion income distribution methodology for TSOs [10]. As mentioned in this section of the report, all those past measures contributed to developing the EU grid network to cope with the evolving energy dynamics in the European energy market.

2.3 Current Situation for EU Grid Network Development

Despite decades of the European integrated power market demonstrating significant technical progress in achieving a single power network and market liberalization, however, the already built-up system still faces several dysfunctions. As shown in section 2.2 of this report, a large part of the European grid network is decades old and was built when the electricity generation was large and centralized, connected to one main grid, and flows unidirectionally to the end users. Beforehand, the power demand for consumers was stable, and the electricity price was inelastic. Then, the main risks were largely attributed to network failures and large generators.

Therefore, the current network was mainly reinforced to accommodate peak load and needed to be equipped and flexible to understand consumer demand patterns.

The power landscape has undergone significant transformation primarily due to factors such as climate change and the global energy market crisis, among others. The energy mix share in the European power grid has dramatically changed, and a growing electricity share production is weather-dependent and variable renewables such as solar, wind, etc. The grid network must be flexible to match the production and consumption behavioural pattern to support the intermitted nature of these variable energy generators. Renewable energy technologies are primarily decentralized, posing another challenge to the present grid network due to bi-directional power flow. For instance, at some periods, the prosumers exceed the capacity of the inflexible power grid, causing frequent grid congestion, among other challenges [6].

To date, the European grid network's development needs to be properly envisioned, which is still largely characterized by large and centralized power plants in geographical proportions and ownership structure. The network power mix is largely based on environmentally unfriendly energy sources like fossil fuels. Additionally, the power plants produce constant electricity notwithstanding the consumption demand of the end users alongside an inefficient, wasteful, and aging grid network. The multinational jerry-built network systems for decades have been highly inconvenient and uneconomically. However, the current climate change policy, high dependency on energy imports, especially Russian energy, and citizens' design to utilize friendly energy are drivers that push and transform the Europe energy sector towards a cleaner, decentralized, and highly efficient grid network. The Europe-wide grid network should be flexible enough to integrate vast, cheap, clean, renewable energies while warranting a steady energy supply. Such a grid network system should bring vast business and technical opportunities and support the interconnections of island electrical markets and regions. Further, it should be too adaptive to the electricity market and price coupling to lower electricity prices in the European region [11]. A well-developed grid network will significantly help mitigate climate change's effects while improving grid flexibility, reliability, and resilience.

Architectural-wise, the distribution network takes the largest share of the overall European grid networks. According to European Committee for Electrotechnical Standardisation, in 2020, about 60% of the European grid network comprises low voltage lines, while medium and high voltage lines comprise about 37% and 3%, respectively. Further, the European DSOs operate about 10 million power lines, connecting to about 300 million consumers, supplying approximately 3,000 TWh of electricity annually [19]. Thus, the network losses are sizeable and are more pronounced in the distribution network, as shown in Figure 3, by Member States. Moreover, DSOs are experiencing new challenges of the increase in intermittent power production connected to the distribution level and changing consumer demand patterns.

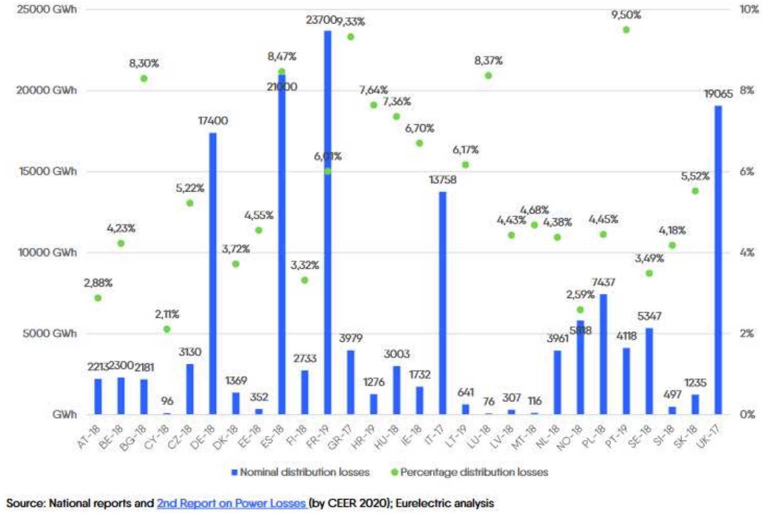

Figure 3: EU Distribution Network Losses Level, by Member States

To address these issues, the EU issued an Energy Efficiency Directive to ensure that each Member State offers incentives to their respective DSOs to improve the efficiency of the design and operation of power grid network infrastructure. Further, the European Commission has emphasized the importance of minimizing the volume of power network losses to attain at least 32.5% energy efficiency targets by 2030 [19]. Since the DSOs are pivotal enablers of Europe meeting their long-term decarbonization goals and energy transition, to minimize those network losses, there is a need to increasingly explore smart innovations and flexible solutions, among them smart grids.

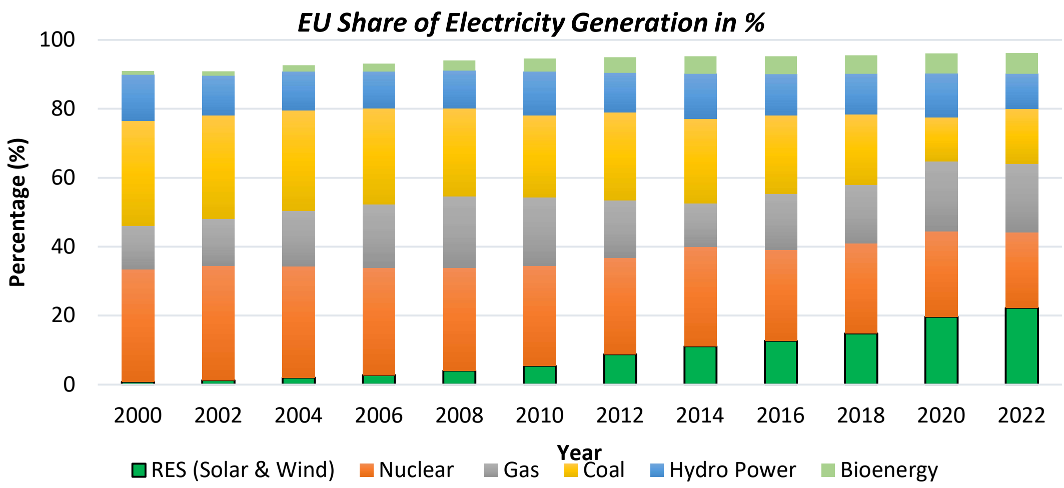

Figure 4: EU Energy Generation Contribution to the Grid

Source: Carbon Brief data

Figure 4 shows that for the first time in 2022, the EU managed to feed more renewable energy to the grid, which stands at about 22% 2022 [12]. Renewable energy was mainly from (solar and wind) which surprisingly surpassed the dominant coal, nuclear, and gas. As the penetration of renewable energy keeps increasing, clean energy is expected to continue leading into the energy mix of the European power grid network.

As previously highlighted in this section, the main shortcomings of renewable energy resources (RESs) are their intermittency and unpredictability nature. Thus, the production-consumption energy balance becomes of main interest to the power network operators. Hence, it creates the need to analyse the operational (such as grid flexibility, load performance characteristics, back-up capacity, actual local weather patterns, quality, and capacity) and economic aspects of the current state of the European grid network.

The current infrastructure network is highly affected by the physical impact of climate change and its variability. For instance, OECD modelling illustrated the potential exposure impacts caused by climate change events. It demonstrated that about 30% to 55% of extreme weather events, such as floods, in Europe (Paris, France) affected the infrastructure, mainly transportation and electricity supply assets, directly resulting in about 35% to 85% business losses [20]. An infrastructure asset resilient to climate hazards will help the continent reduce direct and indirect disruption costs in the long run. Therefore, Europe should plan, build, and operate a climate-resilient power infrastructure asset network that considers future uncertainty. Having a climate-resilient power infrastructure will enable adaptive management of the grid, including easy scheduling of maintenance, enhancing network protection, and improving structural integrity. Such a system will have the potential capacity to protect asset return, improve the reliability of the network service provisions and increase asset lifespan. Furthermore, having a climate-resilient network infrastructure contributes to the Paris Agreement's achievement. It will align with the climate-resilient development plan, thus facilitating the financial flow of low carbon emissions in support of Sustainable Development Goals.

As mentioned earlier, all the current grid network challenges have forced the grid operators to manage proactively and advance the network system beyond the-meter resources. However, it is a challenging task since as power increasingly becomes variable; consumers are responding to the price signals dynamics to gain from a low cost of electricity. The grid operators need more visibility and control capabilities to predict the generations of variable energies. Therefore, the Europe grid network development plans should be based on a coherent and ambitious carbon net zero vision to address the same.

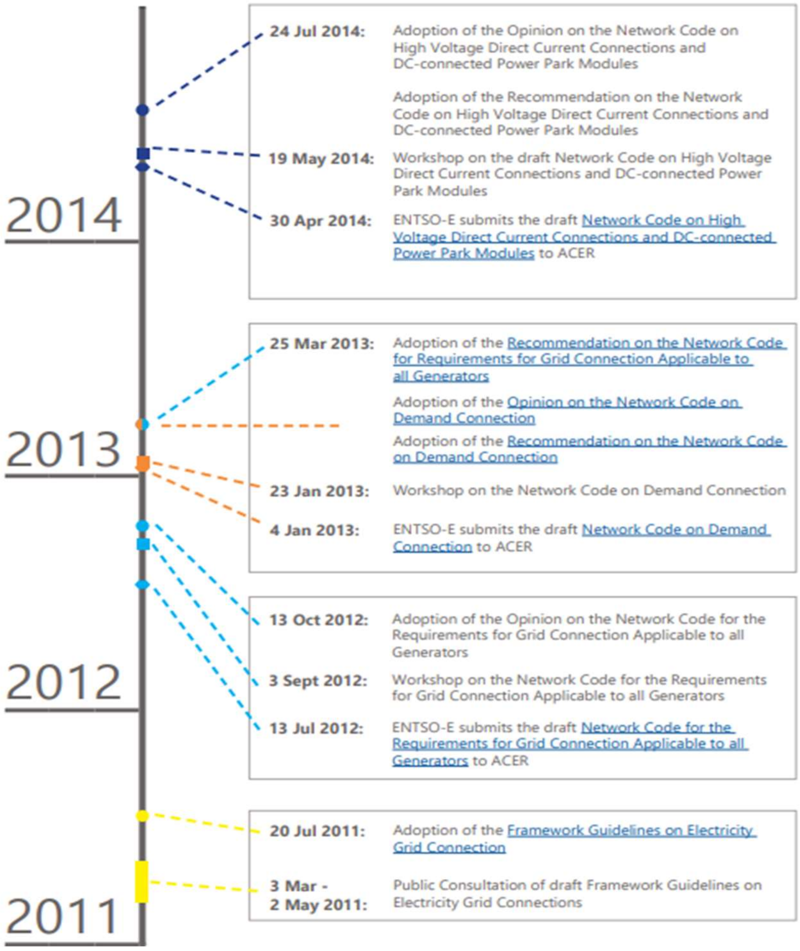

Figure 5: Brief Summary of lately European Grid Network Development Milestones

Source: European Union Agency for the Cooperation of Energy Regulators (ACER), 2021.

Figure 5 shows a brief history of the latest development milestones on the European power grid network. ACER adopted an electricity grid-connection guideline that defines codes and the requirements to develop the European network. Such requirements entail minimum standards, derogations, requirements for connections on (power generators, HVDC, and distributors connections), compliance testing and monitoring, coordination, and information sharing between parties concerned. These framework guidelines aim to help the EU meet the renewable energy generation targets while offering a solution to integrating the demand response of the future grid network.

Further, the European Commission has established a fifth list of EU Projects of Common Interests (PCIs) [13]. These PCIs are major cross-border energy infrastructure projects that aim to develop a more resilient and integrated EU network according to energy and climate goals and the integration of renewable energies. In this list, about 67 projects in a total of 98 PCI projects comprise electricity transmission and storage while 20 are in gas, 6 projects in CO2 network, and 5 projects in smart grid [13]. These projects are eligible for the EU Connecting Europe Facility (CEF) funding program that enables investments with a cross-border impact in Europe. Between 2014 and 2020, the CEF financed these listed EU energy interconnect network projects for about €5 billion. In the 2021-2027 phase, the CEF funding program has been allocated about €6 billion to strengthen energy interconnectors [14]. Therefore, once fully implemented, these electricity transmission and storage projects on the PCI list will significantly contribute to the uptake of renewable energy in the European grid network as per the European Green Deal.

Among the 5 smart grid projects in the PCI list includes:

- The Carmen smart grid, a joint Romania-Hungary project. The project, which is estimated to be worth €120 million, provides for the digitalization of about 140 substations, modernization of approximately 200km of high voltage transmission and distributions overhead lines, smart metering deployments, installation of FACTS devices for grid network control voltage and development of a platform that facilitates sharing of operational data. The project will improve the efficiency of the network operation and service of the quality rendered by the network and enable secure renewable energy electricity flow in the transmission and distribution network system [15].
- The ACON Smart Grids, which integrates the Czech and Slovak electricity markets, comprise two main segments: Deployment of massive smart equipment such as (AMM, IMS, new technology TSs, remote controls, cables) and other supporting conventional parts. The smart technologies will create a communication element with intelligent load management to ensure the network has a better connection, high awareness, and future usability of the distribution network to accommodate high renewable energy intake and usage of digital infrastructure [16].
- The Danube InGrid (Slovakia, Hungary) which enhances the electricity network cross-border coordination and management with a close focus on the smartening collection and exchange of information, data flow, smart metering, and knowhow sharing to improve the stability and robustness of the power grid in the area.
- The GreenSwitch Project will optimize the grid operation, increase cross-border capacity and extend the lower voltage levels. In this project, various techniques and technologies will be rolled out, including control systems, battery storage, power flow prediction, and optimal supply of physical islands. The result will be a grid network that can handle renewable energy and variant load between Slovenia, Croatia, and Austria.
- The Gabreta Smart Grid whose objective is accelerating the digitization of the distribution grid between the Czech Republic and Germany (Bavaria) with an estimated project value of about €672 million [17]. This project increased the number of electric mobility, renewable energy sources, and advances in the coupling sector as well as improved services such as resilient, modern, and digital grids on the distribution system level.

These shortlisted common interest smart grid projects are marked as a milestone in the evolution of the transmission and distribution network in Europe. Overall, these smart grid projects aim to improve the efficiency of the grid networks, enhance cross-border data coordination, and safer grid management. They will ensure a proper upgrade on the transformer stations and substations, improvement of high voltage overhead lines, modern voltage control, and integration of communication and IT technologies on the energy system. Additionally, the smart grid projects will increase the capacity takeover of a medium-low voltage network of electricity supplied mainly by the prosumers of renewable energy sources. Intrinsically, intelligent grid projects signify a crucial step towards accelerating the decarbonization and digitalization of the electricity network in the context of the energy transition in Europe.

On a bigger scale, according to the data that has been compiled and published by the EU Joint Research Centre, which reviews the number of smart grids funded by the EC under the Horizon 2020 Seventh Framework Programme known as (FP7), and innovation and competitiveness programs on intelligent energy and ICT shows that EC has already invested over €3 billion on Europe smart grid research and innovations which serves a significant contributor towards the development of the grid network in Europe. Presently, there are over 120 R&D projects and over 300 demonstration projects to show the role of smart grids in accelerating the twin digital and energy transition [18].

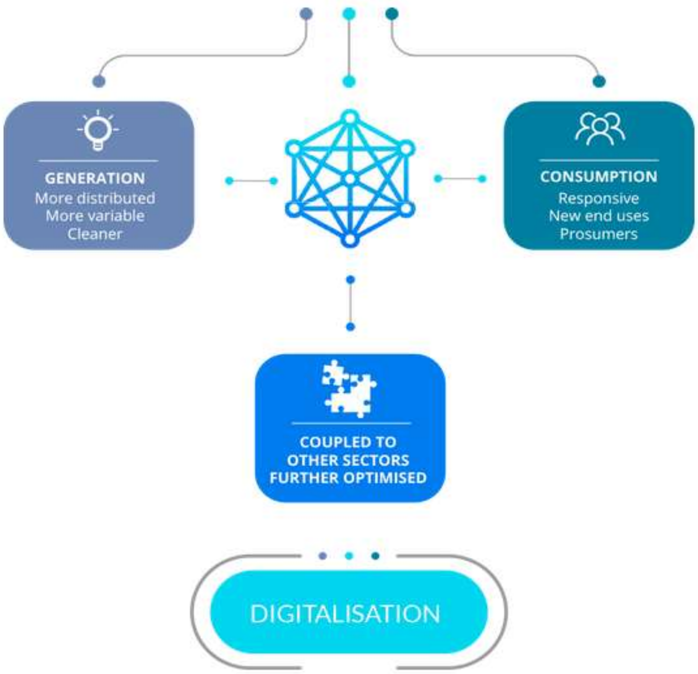

Figure 6: The Major Modern Trends Reshaping the European Power Grid System (2019-2023)

Source: ENTSO-E

As shown in Figure 6, the European power grid network is undergoing unprecedented change. The figure shows that this change is largely attributed to the uncertain supply of renewable energy and variation pattern on a supply-and-demand balance in the EU power grid network. Navigating these changes is a big challenge to utilities, traders, and consumers. Hence, the need to optimize, modernize and digitalize the power system to manage risks, increase system flexibility, and ensure energy security while addressing future uncertainty. Even in an enterprise dimension, the power grid network, which will deliver the differentiated propositions, will operate in a new modern way, build resilience to the currently identified challenges and future uncertainties, and create efficiencies.

2.4 Future Prospect for the EU Grid Network Development

The European future power grid network angles towards (3D's) decarbonization, decentralization, and digitalization. However, several significant trends identified, as outlined in Figure 7, are likely to significantly contribute to the configuration of Europe's future offshore and onshore linear energy infrastructure development.

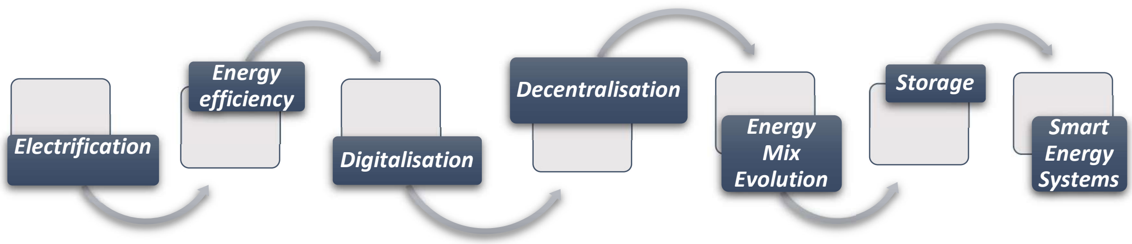

Figure 7: Future Trends likely to Impact the Development of Power Infrastructure Network in Europe

As Figure 7 demonstrates, the Europe grid operators must apply new functionalities compatible with the renewable-based energy system in establishing a future-proof grid. Therefore, the grid network upgrading process is not just a rollout of new power cables. Different technology such as superconductivity, HVDC, and multi-terminal setups have matured and exist with multiple vendors; therefore, it is a matter of fully integrating them with the network services for bi-directional information exchange. Applying these technology developments will open access and connection to onshore and offshore energy sources and large energy storage assets. Besides, these technologies facilitate high power transfer capacity, low maintenance, corrosion resistance, and long-life expectancy of the equipment. Hence, it is a cost-effective and long-term solution to European power network development.

The European Commission has adopted a new ambitious long-term goal to facilitate offshore renewable energy sources deployment on the EU's Sea basins up to 2050. The intermediate targets for this deployment are to be attained by 2030 and 2040. To achieve these goals, the Commission continues to create a trans-European framework that enables the expansion of a cost-effective grid that will tackle the internal bottlenecks of intermittent renewable energy systems on the grid and have a positive environmental impact. This agreement is achieved based on the robust regional cooperation instruments formulated on the latest revision of the trans-European energy network (TEN-E Regulation). With these milestones, the ENTSO-E will combine the regulations with the proposed strategic integrated offshore network development plans and information on maritime spatial planning to provide a clear and well-defined offshore grid network system visibility of up to 2050 to the grid operators, investors, and the entire value chain.

In 2022, the European Commission introduced its EU Action Plan for digitalizing the European energy system. This initiative aims to tackle the climate crisis and end the EU from overdependence on energy imports, especially Russian oil, and gas, through a deep transformation of the European energy system. The digitalization of the energy network will serve a central role in achieving those objectives. On the other hand, in the wake of the unstable energy market, largely experienced in Europe, accelerating the digitization of the energy sectors will enable users to be more conscious of their consumption. Smart meters, smart buildings, electric vehicles, and the Internet of Things offer helpful information to monitor energy production, consumption patterns, and renewable energy system integration. Energy management systems, innovative data services, and apps have a huge untapped potential in developing the energy system hence the need for adequacy policy support and boost measures to become ubiquitous. In the medium term, the digitalization of the energy systems will enable seamless interactions among the grid actors. In the long run, the grid network will achieve flexibility, energy optimization, integration of renewable energy, security, independence, and less exposure to price volatility.

To further support the development of the grid network in the future, the European Commission has formally established a Smart Grid Expert Group. The group promotes a digital twin of the roll-out of the smart grids and deployment of the smart metering systems in the European energy system. The two digital twins will heighten the future grid network's intelligence and efficiency, allowing an easy flow of communication and data exchange. These twin digits will significantly strengthen and equip the EU’s power grid to support the continent's energy needs. The Commission will continue offering financial support to boost the uptake of digital technologies and enhance R&I in power networks through programs such as Digital Europe Programme, cohesion funds, and Energy under Horizon Europe, amongst others. Collaborating with European Green Digital Coalition, the Commission has been keeping developing methodologies and tools to determine the climate impact of enabling digital technologies in the European power grid network.

REPowerEU is a European initiative focused on advancing renewable energy sources and sustainable power generation across the European Union. It encompasses a range of policies, strategies, and projects aimed at accelerating the transition to clean energy sources, reducing carbon emissions, and fostering a greener and more resilient energy landscape within the EU. REPowerEU plays a pivotal role in driving the region's efforts to combat climate change and achieve a sustainable energy future. Therefore, the REPowerEU plans to increase the EU power network's investment, electrification, and efficiency. In particular, to scale up the acquisition of cross-border connections of the electricity grids. To improve the storage capacity and flexibility of the grid network and investment in the Trans-European energy network among increasing the renewable energy generation. Therefore, the plan offers a critical moment to make Europe's future infrastructure digital by design. It will enable Europe to achieve a dynamic, realistic digital, physical asset representation, system, or process that interlinks the physical infrastructure network asset and the virtual world while simultaneously synchronizing the network to make the entire asset lifecycle responsive to both the generation and demand sides [19].

According to IEA (2023), Investment in smart grids needs to more than double through to 2030 to get on track with the Net Zero Emissions by 2050 (NZE) Scenario, especially in emerging economies, despite the adverse impact of the COVID-19 pandemic [20]. In the coming days, factors such as deployments of smart grid technologies and increased investment in EV chargers, smart meters, and other associated smart grid infrastructure technologies are projected to be the market driver in the energy sector. In addition, Advanced Metering Infrastructure (AMI) is expected to increase the growth of smart grid technologies deployment across Europe. Europe grid operators view smart grid technology as a strategic infrastructural investment to help the EU attain their net carbon emission and drive long-term economic prosperity. An increase in the advanced metering infrastructure will reduce transmission and distribution losses on the grid network and accelerate the effort to modernize the power grid network. Moreover, the smart grid technology is highly expected for growth and uptake in transitions and distribution systems, demand response, AMI and metering.

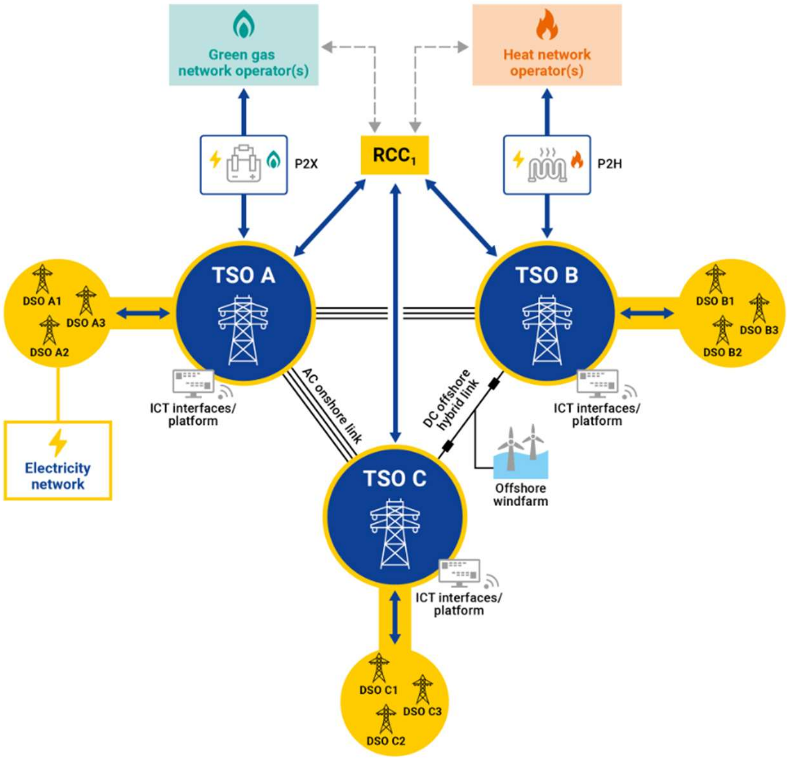

Figure 8: European Future Grid Network

Source: European Commission (European Technology platform smart grids)

Figure 8 represents a typical example of a future European grid network, its functions, and changes as presented by the European Commission. The commission envisioned a distribution grid network that would be active and flexible enough to accommodate di-directional power flows. The power generator is anticipated to be dispatched according to the market forces. The grid control centre will undertake the overall supervisory role, such as ancillary services among voltage stability and active power balancing. In addition, Europe's future electricity grid model will have to meet technological changes, the environment, commerce and social values. Therefore, such change should demonstrate sustainability, cost-effectiveness and sustainability in response to change requirements in a liberalised market environment across Europe for effective development.

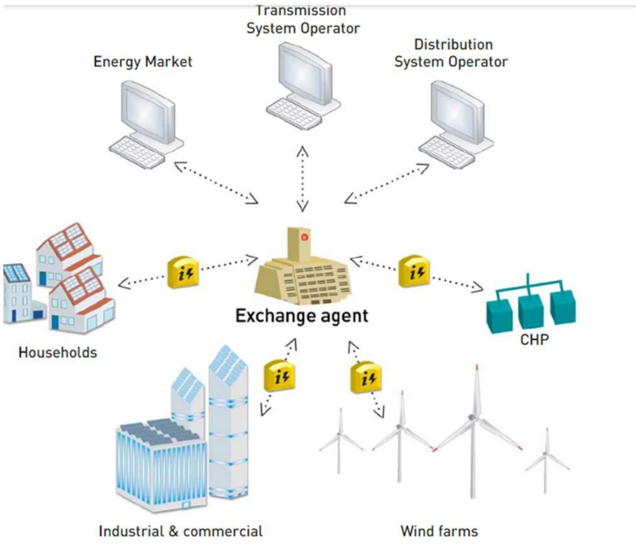

Figure 9: Share vision of Grid Nework in Europe

Source: European Commission (European Technology platform smartgrids)

As Figure 9 demonstrates, the operations of the future grid network will be shared between the central and distribution power generators. The control system of the distribution power generators will be aggregated to form microgrids (a controlled entity that operates as a single aggregated power generator or load within the primary grid to provide ancillary services supporting the grid network) or virtual power plants (an internet-like model enabled by modern information technology) that will facilitate their integration both in the physical design and in the market. In that sense, the electricity grid network will be smart in several ways, including: the envisioned smart power grids will provide greater efficiency as it will be linked across Europe and beyond to enable efficient energy exchange while drawing the available resources; demand management becomes an indirect source of generation while the savings are rewarded. Further, the interactive grid will contribute to addressing environmental issues thanks to its intake, flexibility and high integration of renewable energy sources [21]. In a nutshell, the grid will become intelligent (smart) with flexible and controlled power flows supported by advanced information technology.

3. FLEXIGRID IN THE FUTURE EUROPEAN NETWORK CONTRIBUTIONS

3.1 Overview

Europe has been working to reshape and advance its electricity grid network to meet the growing energy demand, integrate more sustainable power generation resources, and enable a trans-European electricity market. European grid transmission and distribution operators identified the deployment of smart grid technologies as the most effective solution that will accelerate the innovation and development of the current grid network system. Furthermore, the adoption of smart grid technology will enable the future European network to be interactive, user-centered, market-based, flexible, reliable, and sustainable. As such, Europe will be able to address the challenge faced by the current grid network and help to achieve the carbon emission targets set out by the European Commission.

To ensure the deployment of smart grid technologies into the European network. The smart grid was considered one of the three thematic priority projects under the Trans-European Networks for Energy (TEN-E), enabling consumers to regulate energy demand, integrate renewable energy sources, and complete the European energy market. Therefore, to fasten the market uptake of smart grid solutions in the European grid to address the challenges facing the current network, which have been previously discussed, the European Commission supported several smart grid research and innovations (R&I) projects through European Union’s Horizon 2020. Thanks to the Horizon2020 program, the FLEXIGRID project was among the smart grid projects identified, supported, and funded through this program.

The FLEXIGRID project addresses most of the common present and incoming challenges experienced in the grid network (as mentioned in the second chapter of this report) to improve the distribution grid operation making it more flexible, reliable and cost-efficient through the development of 9 innovative (hardware and software) practical solutions when a large share of variable renewable electricity sources is connected to distribution (low and medium voltage) grids. Furthermore, for the FLEXIGRID project to significantly impact the European distribution grid network, eight use cases (UCs) were identified to address the most common challenges facing the EU distribution grid network. Integrating the new technological solutions, FLEXIGRID project offers into the EU distribution grid network will make renewable energy more reliable and affordable since it will enhance energy's flexibility, reliability and security. As a result, FLEXIGRID project solutions will accelerate the growth of renewable energy sources and ultimately enable the EU, in 2030, to achieve above 45% of their renewable energy targets [12].

To ensure that these 9 innovative FLEXIGRID solutions are interoperable and integrable to the real-life grid situation, they were further demonstrated in four European demo sites: Spain, Croatia, Italy, and Greece. These solutions were deployed into demo sites to ensure they seamlessly integrate into an open-source platform and harmonized data flow for a distribution grid network. Therefore, this section demonstrates how FLEXIGRID solutions will directly impact and contribute to the future European distribution grid network development in accordance with TYNDP strategy.

3.2 S1: Secondary Substation of the future

The operation of the European distribution network has been evolving over the years, considering various economic and technical changes to overcome multiple challenges. The need for high-quality services, energy, and efficient asset management demands a more remarkable ability to monitor the distribution network, especially the medium voltage (MV) and low voltage (LV) distribution networks. On the same breath, with the continuous increase in the share of renewable energy sources (RES), distributed small power generators, prosumers, and electrification of society, among others, increasing uncertainty and variability on the distribution side requires adopting new concepts of effective operational and management of the distributions grid network which closely aligns with the goals outlined in the TYNDP.

Given these and other challenges, the new paradigm of FLEXIGRID solutions includes a secondary substation (SS) of the future. This hardware solution offers upgrading and automation of the present outdated substation, and it serves as a critical infrastructure in enhancing the overall performance, reliability, and safety of the power network in the future. Moreover, this solution has faster fault detention, protection controls, and advanced metering infrastructures with a remote metering capability. These new components of the secondary substation (SS) of the future enable grid real-time monitoring and high-level protection (faster fault detention, isolation, and restoration), which minimize power disruptions, allow virtual energy metering, and improve grid resilience and overall efficiency of the MV/LV distribution system.

For instance, the SS of the future solution was deployed on the Use Case (UC5) on coordinating distribution network flexibility assets and protection schemes in the urban district of the Croatian demo site. The MV distribution grid was incorporated with modern protection relay devices. The installed relays enable change in the network's topology that protects from unwanted events, including high voltage fluctuations and line congestions that potentially lead to power losses and line failures due to continuous increases in the renewable energy share on the MV grid. In addition, the relays have high and faster tripping capacity, which ensures the safety of the power system hence improving reliability and indicators of electric power utilizes such as System Average Interruption Duration Index (SAIDI) & System Average Interruption Frequency Index (SAIFI). Therefore, such improvements and advanced features are a critical contribution to the protection of the MV/LV distribution system to ensure its maximum operational capacity and efficiency.

The SS of the future has additional cutting-edge functions, including advanced switchgear with high workers safety and control gear assembly that enables the MV/LV distribution grid to integrate large amounts of renewable energy sources shared on the grid. These advanced functionalities on FLEXIGRID solution allow smooth integration of small-scale distribution power generators to the grid network. It is vital in increasing intermittent energy sources such as solar and wind in the European distribution grid network. Consequently, it enhances grid flexibility and increases resilience while facilitating the transition to a cleaner and more sustainable energy mix in the future of the European power grid network, which aligns with the European electricity infrastructure development plan (TYNDP).

Other unique functionalities incorporated in the intelligent secondary substation are ready for future network challenges, including the ability to provide local grid intelligence, which gathers and analyzes data at a local level from various sources, including power generators, consumer loads, and energy storage within the distribution grid. Based on this local intelligence, the solution helps identify energy imbalances at a point of power generation and utilization, optimizing the power flows, adjusting energy distribution, and coordinating energy resources with the grid. As a result, the solutions ensure that the power grid has efficiently and effectively reduced managed energy usage patterns and power losses. Consequently, it improves MV grid stability and minimizes the need for extensive distribution infrastructure.

This solution goes far beyond its protections and network assets monitoring to control and automate the MV/LV distribution grid to implementing high-level algorithms and deploying modern smart hardware, including On-Load Tap Changer (OLTC) transformers. The OLTC transformers are well equipped for automatic voltage regulation while the transformer remains energized. In addition, the OLTC transformer adjusts the voltage ratio to improve the power factor within the MV/LV distribution grid. Through the optimization of the grid power factor, the transformer helps to reduce losses and improve efficiency. Moreover, the OLTC transformer feature incorporated in this solution enables dynamics load balancing, which prevents overloading and ensures even distribution of loads, improving grid stability and mitigating the risk of equipment failures. These are essential functions incorporated to help automatically regulate power quality (voltage, power factor correction, and load balancing) in response to the current and future challenges facing the grid network, such as fluctuating power generation, intermittent energy supplies, and variable load which are current and future necessaries in power system.

Furthermore, the future Smart Grid (SS) infrastructure embraces flexible communication technology, providing a modular and adaptable communication framework. This framework facilitates the transmission of personalized and tailored information to different stakeholders within the grid ecosystem, including grid operators, end users, and prosumers, based on their specific needs and demands. By offering enhanced understanding and actionable insights, this communication flexibility aligns with the 10-Year Network Development Plan (TYNDP) objectives. It empowers stakeholders to make informed decisions and take appropriate actions, thereby facilitating the realization of the 10YNDP's goals. The FLEXIGRID solution, enabled by this advanced communication infrastructure, ensures that the grid system is well-prepared to navigate the future markets, technological advancements, and evolving ecosystems of the European grid network while maintaining its adaptability and flexibility as envisioned in the TYNDP.

It further creates the capability for the future grid to integrate new power equipment, including renewable energy sources, distributed storage systems, electric vehicles (EVs) charging infrastructure, and other energy management systems. This gives rise to possibilities for flexibility of new solutions attributed to future technical, economic, and environmental changes. Therefore, SS of the Future is designed to facilitate compatibility and interoperability of a wide range of power equipment and technologies, enabling efficient integration, management, and digitalization of future electricity in Europe.

Overall, the Secondary Substation of the future, a FLEXIGRID solution, will significantly contribute to the future development of the European MV/LV distribution grid network by providing functionalities that enable integration of renewable energy systems, promoting grid efficiency through losses optimization (technical and commercial), energy balancing and grid constrain reduction, voltage regulation, support storage and EVs integrations, fault detection, location, and management. In addition, its advanced control mechanism will contribute to the effective deployment of the smart grid. All these contributions align with the EU policy, regulation, and requirement and the Ten-Year Network Development Plan, which provides a pan-European electricity infrastructure development plan.

3.3 S2: Smart meters with feeder-mapping capabilities

The second hardware solution developed through the FLEXIGRID project was the new generation of smart meters with feeder-mapping capabilities. These new smart meters are incorporated with advanced metering infrastructure (AMI) systems that are well-designed to cater to the needs of increasingly knowledgeable and digitally savvy consumers. At the same time, reduce operational expenses (OPEX) for distribution system operators. In this solution, the most significant aspect of innovation was integrating feeder mapping within the smart meters.

Feeder mapping refers to the ability of the smart meters to identify the low voltage (LV) feeders where the two are usually connected. The low-voltage feeders are the last part of the distribution lines directly connected to dispersed small-scale loads of the power end-users [22]. By mapping the connection of each smart meter to a specific LV feeder, the DSOs can gain valuable insights into how the power flows within their networks to the consumer. Thus, integrating feeder-mapping capabilities in the smart meters allows the DSOs to monitor their power flow and analyze power demand at the last stage of the power network-feeder level. Moreover, the smart meters interfaces give the users real-time information about the power demand and patterns. With this information, consumers can actively manage their energy demand by adjusting their consumption based on the real-time data offered by these smart meters. This solution enables consumers to be more energy efficient, potentially lowering their electricity costs.

From the perspective of Distribution System Operators (DSOs), integrating feeder-mapping capabilities in smart meters at the low voltage (LV) level provides significant insights into load distribution along the power lines. This aligns with the goals outlined in the 10-Year Network Development Plan by enabling DSOs to enhance their understanding of the network and identify anomalies or potential issues. By utilizing aggregated energy data from multiple smart meters connected to the same LV feeders, DSOs can proactively detect and address network problems. This solution empowers DSOs to streamline grid maintenance and troubleshooting processes, as they can promptly identify issues in specific LV feeder lines or respond swiftly during power outages. Implementing this solution in the future will increase efficiency in maintenance operations across the European Union distribution grid network, ultimately reducing network downtime, a key objective of the TYNDP.

Another area where this FLEXIGRID solution proves invaluable is voltage regulation and monitoring capability. Given the continuous increment of volatile renewable energy sources integrations in the distribution grid, the nature of underlying distribution systems is continuously changing. Consequently, the passive operation of the distribution network (especially the low voltage system) quickly reaches its operational limits capacities, leading to local voltage violations, primarily when peak feed-in occurs, resulting in congestion. To guarantee a fail-safe grid operation and to mitigate breaches of the grid associated with integrations of renewable energy sources, these meters can monitor voltage levels at different LV feeders' points and identify voltage irregularities and fluctuations. Grid operators can take prompt corrective measures to ensure stable voltage levels, enhancing the power supply quality while safeguarding the health of electrical appliances and equipment in the distribution system.

Furthermore, these smart meters with feeder-mapping capabilities contribute to effective asset planning and management for grid operators. The real-time information on the performance and condition of grid infrastructure provided by these meters enables operators to prioritise maintenance and upgrades of the grid network as opposed to relying on reactive repairs and scheduled inspections. This proactive approach helps the utilities reduce the risk of equipment failure, minimize outage durations and improve the longevity of the grid assets. The solution, therefore, enables the grid operators to optimize their investment in infrastructure upgrades by targeting areas that require immediate attention, which ultimately plays a significant role in accelerating the advancement of the present grid network within the Europe zone.

Overall, integrating feeder-mapping capabilities in the new generation of smart meters enhances the functionality and value of AMI systems. It enables real-time information and control, which facilitates faster fault detection, and localization, enhances asset planning and management, ensures voltage regulation and monitoring, and helps load balancing and grid optimization for the DSOs, contributing to a more efficient and reliable electricity distribution network. Moreover, the combined capability of grid mapping and advanced metering on LV feeders enables the grid operators to make data-driven decisions that enhance future grid performance. These outcomes contribute to the overall efficiency and reliability of the electricity distribution network, in line with ENTSO-E's strategy. Additionally, the combined capability of grid mapping and advanced metering on low voltage feeders empowers grid operators to make data-driven decisions that enhance future grid performance, further aligning with the goals and objectives of ENTSO-E as illustrated in the TYNDP.

3.4 S3: Protections for high-RES penetration

The existing protection systems within the European distribution network are not resilient enough to handle the current high renewable energy sources (RES) penetration. The conventional MV/LV distribution network protection gears were designed to protect a centralized power generation system with steady and unidirectional power flows from the generator point to the load (consumers). However, nowadays, with the increase of decentralized energy systems primarily from renewable energies, the role of the distribution network has significantly shifted from solely being a distributor to a distributor and generator, resulting in bidirectional energy flow. Furthermore, renewable energies are intermittent in nature so, they can subsequently constrain and overpower the present traditional protection systems of the distribution network if it is not flexible enough to accommodate them.

To address these and other issues associated with high-RES penetration, the FLEXIGRID project developed a solution to enhance the performance of the protection systems within the existing distribution system. This solution developed an innovative protection device installed on the MV grid to ensure the present system is safe and reliable when subjected to uneven energy supplies and can effectively handle bidirectional energy flow. One protection switchgear developed was protective relays deployed on the MV grid for all four pilots’ demos. This advanced switchgear has the capacity for fault detection, isolation of circuit breakers, and other control techniques that can respond to specific power parameters, such as changes in current and voltage ratio and power flow directions, amongst other functions on the MV distribution lines. With the ability to identify anomalies, faults, and isolation of the distribution network, this protection switchgear can reduce the impacts of fault power when the power operating parameter deviates from the allowable limits, thereby reinforcing the goals and objectives outlined in the TYNDP.

For instance, the Croatian and Spanish pilot demos deployed these advanced protective devices on their MV grid. The grid has recently experienced high-RES penetration, and it's connected to some critical power consumers. Hence, with the previous protection states, there was a high possibility of element or line failure within the distribution system. Furthermore, the current advanced protective switchgear can regulate the RES's excessive energy supply to minimize financial losses, which these critical users have experienced through a network topology change. This means that this advanced protection system can reroute the electricity flow and isolate the faulty element from the rest of the network. By doing so, the new system ensures that the supply of electricity is maintained to the critical end-users by redirecting power through alternative paths.

Integrating FLEXIGRID solution into the grid infrastructure strongly aligns with the goals set forth in the 10-Year Network Development Plan strategy. One of the key objectives of the TYNDP is to build a resilient and efficient electricity network capable of accommodating high levels of renewable energy sources. With the increasing penetration of RES in distribution grid networks, power faults arising from multiple distributed generation sources become more frequent. The FLEXIGRID solution effectively addresses this challenge by ensuring proper coordination between protective devices and other medium-voltage grid elements, such as power generators, transformers, and lines. By employing reliable fault detection mechanisms, selective isolation techniques, and coordination algorithms facilitated by advanced communication systems, FLEXIGRID solution enables the seamless operation of the grid while ensuring the continuity of electricity supply to critical end-users. By incorporating the FLEXIGRID solution, the TYNDP strategy's objective of developing a robust and sustainable energy infrastructure that can handle the growing RES penetrations is effectively supported and realized.

The ability of these relays to detect abnormalities in the MV grid, respond appropriately, change the network topology, and restore are critical features that minimize power interruption of the grid instead of waiting for a lengthy restoration process of manual intervention. This helps to reduce the downtime and financial losses for the important load connected to the MV grid. Therefore, it helps maintain grid's reliability despite changing energy resources and increased risks. The undersign protection scheme can provide reliable protection in both islanded and grid-connect modes of operation.

Furthermore, developing protective devices with robust intelligent monitoring and control systems can significantly enhance the protection when handling bundles of RES on the MV grid network. Real-time monitoring of grid network parameters such as current, voltage, and frequency, which can fluctuate due to introducing a high level of RES, is essential for adaptive protection strategies. Therefore, this protection device was designed to mitigate these stability issues and ensure grid stability even when subjected to varying RES output conditions.

In the future power system, designing the protection schemes on distribution grid networks is becoming crucial, especially with the increased integration of inverter-based photovoltaic RES. Inverter-based photovoltaic RES poses a challenge to traditional protection devices since it results from short-circuiting currents. The narrow margin between fault conditions and normal loading makes it difficult for traditional protection devices to differentiate between them accurately. Thus, there is already a need to develop a new and advanced protection scheme to address these challenges to ensure effective and reliable protection on the distribution grid in the context of this FLEXIGRID solution it targeted at addressing such a challenge associated with the protection of high-RES penetration to secure the operation of the MV distribution grid network. This FLEXIGRID protection scheme for high-RES penetration considers the unique characteristics of inverter-based photovoltaic RES, such as weak fault currents. Further, the protection device can accurately detect and distinguish between these power systems' faults and normal operating conditions. At the same time, it ensures precise and timely actions against fault-feeding sources to minimize system disruptions.

Similarly, to other modern protection mechanisms being developed, this FLEXIGRID solution is as well designed to enhance the flexibility and reliability of the MV distribution grid with high levels of RES integration, particularly in the case of island and off-grid scenarios, which is one of the emerging areas of interest in power system. These power systems tend to be dynamic and complex since their systems topology is incorporated with various systems such as (small local generators and energy storage, amongst others) and have a mix of alternative currents (AC) or direct current (DC) components present in the systems [23]. Therefore, the unique characteristics of these decentralized systems demand extra protection. Hence, the FLEXIGRID solution contributes to the overarching TYNDP strategy to develop a resilient and sustainable electricity network that can accommodate and harness the potential of renewable energy sources.

3.5 S4: Energy Box

The Energy Box (EB) is a hardware solution developed to operate key functions such as advanced electrical networks, distributed energy sources (DER), and smart grids in the distribution grid network. Thus, it is an embedded computer with multi-purpose features that contribute to the optimal operation of the grid. Generally, the EB was designed as a universal and versatile computing tool that enhances intelligence, reliability, and efficiency in advanced distribution grid networks. In other words, it is one of the cutting-edge solutions the FLEXIGRID project deployed for efficiently managing DER and smart grid infrastructure.

One of the essential features of the EB is the embedded computer that offers a versatile communication and processing capability. This feature facilitates the operation of distributed computing techniques that enables the systems to undertake various functions such as information capture and storage, execution of complex algorithms, and controls of the entire grid asset. It can be widely applied in the distribution grid network development by leveraging distributed computing techniques. It can further enable seamless integration with other systems, including grid assets and devices such as smart meters and sensors within the network, for optimizing energy flows and managing the DERs through real-time data monitoring and comprehensive data analysis on grid performance.

As part of the solution, the developed EB has enhanced its present designed prototype to enable its retrofitting into the existing secondary substations. The capability of EB to retrofit it enhance the asset control within the substations. As a result of intergrading the EB into the existing infrastructure it now become possible to monitor and control physical assets more effectively, enabling better response, voltage regulation, load management and fault detection and enhance decision-making processes.

This solution was deployed on Greek and Spanish demo sites. For instance, in the Greek demo site, the energy box was installed on one of the bungalows (B250), and other equipment such as inverters, network switches, and more. The Energy Box Served as a local data management system to collect the information from the field devices of the site, utilizing field communication protocols that are appropriate for the equipment and the local network infrastructure. This payload was sent to the FUSE platform for further treatment by other s/w modules developed within the project. Moreover, the Energy Box acts as a bidirectional gateway, receiving control signals from the FUSE platform and sending them to the field devices.

The Energy Box (EB) is an already established innovation that has recently gained widespread applicability in power market. Initially, it has proven a valuable solution for demand response energy management, including energy storage and grid interaction, particularly for large residential, services, and industrial consumers. This innovation has enabled the end users to have greater control over electricity use and costs. It has helped consumers promote energy efficiency through energy monitoring and contributed to a more reliable and stable grid. By actively being involved in the demand response side, alternatively, the EB provides valuable information to grid operators on how to effectively manage peak demand and flatten the power sector's aggregate demand curve. Doing so enables grid operators to meet forecasted demand growth using the existing portfolio of generation sources, which help the grid developer to know when to expand and to upgrade the grid network.

Another similar application for EB in the power sector is that it serves as a critical facilitator in integrating renewable systems into the power market, thus offering technical capabilities that optimize the utilization of RES (wind turbines, solar panels, etc) and energy storage. Through leveraging these advanced control and coordination mechanisms, the EB ensures the efficient generation, distribution, and storage of renewable energy while seamlessly integrating it into the grid. Overall, the Energy Box represents a technically advanced solution that can potentially supports the development of the European Union's distribution grid network. By leveraging its versatile communication capabilities, embedded computing power, and asset control enhancements, the EB contributes to the grid's optimization, reliability, and sustainability, paving the way for a more efficient and resilient energy system in the EU.

To further demonstrate how this innovative idea of Energy Box (EB) has gained popularity since the advancement of RES, a similar concept refers as Renewable Energy Box has been developed. Like FLEXIGRID Energy Box, it also emphasizes the integration of RES and advanced energy storage technologies (fuel cell technology) to create a sustainable power grid. The objective of this device aligns well with FLEXIGRID Energy Box by enabling multiple functionalities such as predictive maintenance and remote control, optimizing energy distribution through technology integration, and monitoring grid performance. Therefore, the development and implementation of the Renewable Energy Box showcase how the concept of an Energy Box, like FLEXIGRID Energy Box or any other similar innovation, can be integrated into real-world applications. It demonstrates the scalability and adaptability of these technologies, highlighting their potential for transforming the energy sector and enabling a sustainable and efficient power grid to achieve the plans stipulated on the TYNDP.

3.6 S5: Software module for fault location and self-healing

This FLEXIGRID solution is a software module designed to enhance the fault location and self-healing capabilities, and they play a crucial role in developing a medium voltage (MV) distribution grid network. Its primary objective is to provide users with real-time information. It controls the MV distribution grid network, which significantly enhances the security of energy supply and uninterrupted power supply and contributes to this grid network's overall efficiency and reliability.

The main contribution of this FLEXIGRID solution to the EU MV grid is its upgraded location and fault detection algorithms with the ability for energy supply restoration. Through the use of advanced algorithms, the solution makes it precise and swift to identify any fault that might occur in the EU distribution grid, especially the MV grid. Facilitating prompt fault detection and consequent action is taken to alleviate the fault effect, the integrity of the MV distribution grid network will be maintained throughout. Furthermore, the software module's advanced control features and real-time system operations empower DSOs to actively monitor and manage the MV distribution grid network within their locality. As a result, the grid operator can comprehensively view the status of the network in a real-time situation, enabling them, whenever necessary, to react accordingly.

Moreover, the software integrated into this module, once it detects any anomalies or faults within the MV grid network, commands the relevant switch breakers to be open and close and then initiates the self-healing process. This is an upgrade to the current installed protective gears, which lack such advanced capability whereby the restoration must be done manually. The FLEXIGRID solutions are intertwined, and this solution is linked with solution 3 protection to RES penetration in various approaches, including how the module in this solution isolates the affected areas to prevent the disruption and spreading of fault in other parts of the grid. Remarkably, the solution response and isolation occur in the millisecond range, significantly reducing consumer inconveniences and downtime. Overall, the enhanced system provided by this software module, including location coordination, fault detection, and self-healing mechanism, improve the resilience and reliability of future MV grid network in the EU.

This solution was implemented on demonstration sites in both Spain and Croatia. Specifically, for the Spanish demo site, the fault passage indicators were installed at the Madepi secondary substation. ZIV incorporated a voltage-restrained unit into the fault passage indicators to enhance their reliability, especially in phase-phase faults.

Similar to FLEXIGRID solution, the British Columbia Hydro and Powertech have also made a stride in the development of an outdoor testing facility, Smart Utility Test Center (SUTC), and one of its key roles is the implementation of FLISK (Fault location, isolation, and service restoration) within the commercial distribution management system (DMS). It is dedicated to the integration and interoperability testing of distribution automation technologies [24]. Similar to the FLEXIGRID solution, in this particular, the FLISR is a crucial component of self-healing power distribution systems as it enables the DMS to detect and locate faults in the MV distribution grid automatically, isolate the affected zones, and restore service on the unaffected sections. Therefore, SUTC demonstrates a practical overview of how modelling power systems work to support FLISR functions. Its services as a real-world environment for evaluating and validating the performance of various smart grid solutions before they are rolled out in the market at a large scale.

There are many scientific publications published related to fault locator development, for instance, a study in the CSEE Journal of Power and Energy Systems (2021) presented a novel and cost-efficient algorithm for real-time fault detection in power systems. The algorithm is designed to accurately detect faults, even in challenging situations where traditional methods struggle. Instead of relying on conventional machine learning (ML) algorithms or hybrid signal processing techniques, the proposed framework utilizes an optimization-enabled weighted ensemble method that combines essential ML algorithms [25]. This adaptive and self-healing approach enhances the accuracy and efficiency of fault detection. The use of real-time information and the flexibility to work with different systems and topologies make this technique a promising solution for enhancing fault detection and self-healing capabilities in distribution grid network.

Taking a holistic approach, developing the software module for FLEXIGRID solution strongly aligns with the objectives set by the European Commission, specifically regarding the construction of a resilient and highly responsive EU infrastructure grid. By contributing to the identified features, this solution undeniably enhances the future functionality of the EU grid network. Its implementation facilitates the flexibility and robustness of the medium voltage grid, allowing for the seamless integration of renewable energy sources and the electrification of diverse power systems. Consequently, this solution significantly supports the European Union's transition towards a low-carbon economy. The alignment with ENTSO-E on the 10-Year Network Development Plan strengthens the relevance and significance of the FLEXIGRID solution in advancing the EU's energy infrastructure. By incorporating this innovative technology, the TYNDP strategy's goals of developing a resilient and sustainable electricity network that accommodates high levels of RES penetration are effectively pursued. The collaboration with ENTSO-E ensures that the FLEXIGRID solution aligns with the broader European agenda, enhancing the coordination and harmonization of grid operations across the continent. Ultimately, this integration reinforces the European Commission's commitment to building a greener and more interconnected energy landscape within the European Union.

3.7 S6: Software module for forecasting and grid operation

This software module, in particular, is designed for the efficient operation of the MV distribution grid by accurately projecting the amount of energy to be dispatched to the grid, consumers' energy demand patterns, and the electricity pricing on the grid. This software module uses a set of sophisticated forecasting algorithms which work on verified measurements from various source feeders, including sensors, Intelligent Electronic Devices (IEDs), and other signals installed along the MV grid system. The information captured on these devices includes energy generation from RES and energy consumption patterns. This information is essential to grid operators and other stakeholders in the distribution grid chain as it enables these players to make data-driven decisions and optimize the operation of the MV distribution grid with respect to electricity feed-in and feed-out curves.

This software module is interlinked with optimization algorithms developed within the FLEXIGRID solutions to predict power generation by analysing relevant factors such as weather patterns and historical data. The capability of this solution to accurately predict the power feed-in in the grid is essential with the increasing integration of renewable energy sources such as wind and solar into the EU grid. Forecasting power supply on the grid system is critical since the RES is highly weather dependent and exhibits significant fluctuations in their output. Hence, with this solution, the grid operators can balance the power supply-demand curves while optimizing the integration RES generation without compromising the security of the power supply and grid stability. Integrating this FLEXIGRID solution into the existing MV distribution grid will enable the existing EU network to increase its capacity uptake of RES significantly. Subsequently, it corresponds with the TYNDPs target to achieve a 64 GW capacity increase of clean energy after 2025 on over 50 borders [14].

For the Greek demo site, this forecast module service is crucial in providing localized consumption and generation predictions over time. This service is instrumental in empowering the grid operation module to formulate its objective function, which is influenced by the status of non-controllable components as the baseline. On top of this baseline, the module evaluates various scenarios involving flexible devices, particularly the battery storage system, while adhering to operational and economic constraints. The forecast module comprises two primary sub-modules: Load and Generation forecasting. These sub-modules are distinct from a computational perspective, and each encompasses separate models for long-term and short-term forecasts. Once the connectors and database are exposed, the initial in-loop tests will be conducted, with the forecast module hosted on the LINKS physical server. On the other hand, the primary objective for the Spanish demo site is to test the algorithm's capability to predict photovoltaic (PV) generation by forecasting solar radiation levels.

Similar to forecasting power generation, this FLEXIGRID solution can predict the expected power demand in different time intervals. This set of algorithms uses historical data, load trend characterization, and other dynamics estimations based on time of the day, season, and interval data to provide insight into the expected power demand curves. Such information will be helpful to the grid operators for effectively planning and operational management of the MV distribution grid to ensure the power supply matches power demand. Therefore, this solution has made accurately predicting future energy supply and demand in real-time becomes increasingly possible. As a result, the solution allows proper management of the dispatch of energy resources on the grid based on a demand-oriented approach.

In addition to forecasting both energy production and demand profile in the distribution grid, the solution also offers electricity pricing prediction in the market within the network. Electricity pricing forecasting is essential in an increasing energy competitiveness market and energy trading, especially within the European power system. It has become an area of interest due to the non-storability of electricity, seasonality production, the day-ahead market price change, variations in consumption patterns, and other variance trends. Therefore, with this sophisticated algorithm, the module enables the grid operators and market participants to optimize their trading strategies, taking advantage of the elasticity of the price throughout the day. Thus, utilities, traders, and big consumers connected to a particular distribution network can forecast the price of the future to secure electricity at more favourable terms and decrease the risk of price fluctuations. In the long run, this solution will play a crucial role in determining the feasibility and profitability of renewable energy projects, which, in turn, influence the development rate and integration of renewable energy sources in the market.

In conjunction with the optimization algorithm, this forecasting module enhances predictability and reliability, driving increased investments in renewable energy projects and accelerating their development. This, in turn, facilitates the integration of renewable energy sources in the market, aligning with ENTSO-E's goals of decarbonizing the transmission infrastructure and promoting integrations of renewable angry sources in European grid. Additionally, the forecasting module supports the Ten-Year Network Development Plans by enabling power developers to conduct comprehensive financial analyses and facilitating the deployment of renewable energy projects, ultimately contributing to a reliable and efficient distribution grid operation.

Overall, this FLEXIGRID solution is a valuable complement to ENTSO-E's framework for supporting the integration of renewable energy sources and helps avoid the curtailment of RES generation. Curtailment occurs when the electricity grid cannot accommodate the total amount of renewable energy being generated. This can lead to a waste of valuable renewable resources and hinder the achievement of ambitious RES penetration targets. By implementing this FLEXIGRID solution, grid operators gain enhanced visibility and control over the grid's operation. They can dynamically manage the balance between supply and demand, considering the intermittent nature of renewable energy sources. This allows for the efficient utilization of RES generation, minimizing the need for curtailment.

3.8 S7: Software module for congestion management

The software module for congestion management is another innovative solution designed in the FLEXIGRID project to address EU grid congestion issues through the implementation of various technical mechanisms that are commercially feasible. Power grid congestion mainly occurs when the existing transmission or distribution lines cannot accommodate all required loads during periods of high supply and high demand, including emergency load conditions. Grid congestion significantly decreases the efficiency and reliability of the grid lines. Thus, under high load conditions, the grid line losses escalate exponentially. Further, if the grid lines operate near their thermal limits due to congestion during high load conditions, they could exhibit a significant line loss. In Europe, grid lines and grid congestion are a common occurrence and has recently become a very pertinent issue due to the faster pace of RES and electrification of society without updating or backing the grid infrastructure creating power quality issues and capacity bottlenecks. At its core, this module uses algorithms to identify the congestion situations within the MV grid infrastructure and adopt commercial flexibility mechanisms to manage it. These algorithms analyse data such as distribution line capacities, peak loads, and voltage levels to identify areas where congestion is likely to occur.

In this case, this software module can contribute to developing the EU distribution grid by recognizing congestion situations. This mechanism of detecting and identifying areas where congestion patterns occur in the grid is critical. It enables the grid operators and planners to pinpoint areas that need attention or where the infrastructure upgrade or modification is necessary to alleviate congestion and ensure grid operation efficiency. Therefore, the module implements the peak shaving processes, and to achieve this, the module leverages on-demand aggregation techniques and coordinating energy usage. This aggregation technique reduces peak demand, which facilitates load balancing and enhances grid stability. Subsequently, this commercial flexibility approach enables the grid operators to utilize the existing grid resources without significant grid investment effectively. In return, it helps to allow better resource allocation and improves the value of the consumers within the EU grid, contributing to its overall development.

This module's crucial aspect is incorporating real-time market information within an ever-changing tariff environment. By responding to market signals, real-time power pricing, and intensive data analysis, this module empowers consumers to make informed decisions about their energy usage. With these advanced features, consumers can adapt their consumption patterns and actively promote efficient energy utilization. In addition, the mechanism adopted by this FLEXIGRID solution enables consumers to curtail or shift their energy consumption during peak loads and take advantage of favourable market conditions. As a result, the module balances the supply and demand on the grid and subsequently reduces grid stress. Therefore, the module's demand-side management strategies to align consumer demand with responding to changing market dynamics play a significant role in addressing congestion issues and alleviating strain on the peak demands. It also emphasizes energy efficiency and consumer flexibility, ultimately supporting the development of a more cost-effective, reliable, and resilient EU grid.

In this particular case, the demonstrations conducted on the Greece demo site with the deployment of this FLEXIGRID solution showcased its capabilities in reducing energy costs, providing peak shaving support, enabling demand response operation, and offering islanding support. The resort where the trials were undertaken, connected to the MV grid and equipped with PV generation, battery storage systems, and smart metering devices, benefited from the congestion management module and energy cost optimization algorithm. As a result, the grid congestion FLEXIGRID solution yielded impressive results in terms of environmental benefits, peak load reduction, and congestion management. Under peak shaving operation, the module achieved an up to 18% reduction in the peak load of the site, relieving stress on the local network during periods of high demand. Energy storage assets play a crucial role in peak shaving due to the uneven load profiles of electricity customers, resulting in high network charges driven by peak demand. By shifting the peak towards low energy rate periods and reducing the peak load through demand shifting and flattening, significant energy cost savings for commercial customers were realized while reducing the need for expensive infrastructure reinforcements in local substations. The congestion management module further supports the network by providing flexibility through the battery's charging/discharging system. This active support improves grid stability and efficiently addresses the needs of the local network. Overall, this FLEXIGRID solution delivers technical benefits such as peak shaving and congestion management and significantly reduces CO_2 emissions and energy costs, promoting sustainable and cost-effective energy practices.

Across the board, CIGRE (2023) has examined a proposal for a real-time control algorithm that combines congestion management and reactive power control in distribution networks, showcasing similarities with the congestion management module found in the FLEXIGRID solution. The proposed algorithm for congestion management is designed with five successive modules to address grid congestion effectively. It begins with the configuration of available flexibility, where potential sources of flexibility within the network are identified and evaluated. The algorithm then moves to bottleneck detection, employing advanced monitoring techniques to identify congested areas or potential congestion risks. The next module determines appropriate control actions based on the detected bottlenecks. These actions could involve adjusting distributed energy resource outputs, coordinating reactive power flow, or implementing demand response strategies. The flexibility dispatch module ensures that the relevant flexibility resources effectively communicate and execute the identified control actions. Finally, the new set points module distribution communicates updated operating parameters to the appropriate devices and systems, ensuring consistent adjustments throughout the network. By combining these modules, the algorithm provides a comprehensive approach to detect, address, and mitigate congestion, optimizing the grid's overall performance.

The proposed algorithm shares similarities with the congestion management module in the FLEXIGRID solution, as both aim to detect and eliminate distribution network bottlenecks by leveraging local flexibility resources' control capabilities to improve grid operation, reduce congestion, and enhance reliability [27]. This demonstrated the replication, applicability, and effectiveness of FLEXIGRID solution at a large scale in a vast EU grid network. Similarly, the congestion management module of FLEXIGRID solution will impact the Ten-Year Network Development Plans, specifically in identifying areas where grid infrastructure investment is necessary or not necessary to allow proper allocation of resources.

3.9 S8: Virtual thermal energy storage model

The Virtual Thermal Energy Storage (VTES) is an advanced software solution developed and deployed within FLEXIGRID projects that aims to exploit the thermal storage capabilities of water heaters or cooling demand and building spaces for achieving optimal flexibility cost-effectively. This FLEXIGRID solution makes it possible to optimize heating or cooling demand effectively without compromising end-users' comfort and disrupting daily operations and routines. The solution takes advantage of occupants' preferences and consumption behaviors to determine the amount of thermal energy to be dispatched and when specific actions are required. The power output of these thermal systems networks, such as air conditioners and water heaters, receives signals from this software to adjust the overall parameters and meet the appropriate thermal requirements.

This model incorporates various optimization techniques software to facilitate an innovative and efficient heating solution. Furthermore, this model deploys both Powers to Heat (P2H) and Thermal Energy Storage (TES) technologies which enable the storage of excessive thermal energy and conversion back to heat when needed. This integration allows for the intelligent management of energy resources and optimizing heating processes within the building. This shows how this solution's adaptability of VTES to multiple network topologies can be implemented in various settings of end-users enabling a wide range of benefits. Therefore, the objective of this VTES solution can be tailored to address specific challenges across the European grids, making it a versatile and adaptable solution.

In the residential apartment at the Croatian demo site (UC6), an advanced FLEXIGRID solution was deployed, including VTES (Virtual Thermal Energy Storage) sensors, a smart metering system, advanced communication infrastructure, and controllable flexible devices like electrified heating and HVAC systems. The key feature of this FLEXIGRID solution is its intelligent coupling of VTES technology with heating systems, creating an optimized solution that blends Thermal Energy Storage (TES) and Power-to-Heat (P2H) technologies seamlessly. This innovative approach considers the thermal behavior of buildings under various usage constraints, such as operational modes and occupancy patterns, as well as the unique characteristics of the building envelope. It enables the system to adapt intelligently to changing conditions and user needs, ultimately enhancing energy efficiency and optimizing the utilization of flexible heating and cooling resources within the residential apartment.

One of the critical features of the virtual thermal energy storage model is its ability to model and simulate the behavior of water heaters and building spaces. This involves capturing relevant parameters such as the thermal capacity of water heaters, the thermal characteristics of the building, and the ambient conditions. By accurately modelling these elements, the software can predict the system's thermal behavior under different scenarios and optimize energy consumption accordingly.

The technical implementation of VTES involves several components and processes. Firstly, end-users' preferences and consumption behavior data are collected and analyzed. This information is used to build user profiles and identify patterns that can be leveraged to optimize energy consumption. The algorithm then determines the optimal periods for demand modifications based on these profiles and grid requirements. Furthermore, the VTES solution can be complemented with advanced forecasting and optimization techniques. For example, weather forecasting can be used to anticipate changes in heating or cooling requirements, enabling proactive adjustments in energy consumption. Optimization algorithms can also be employed to maximize the utilization of renewable energy sources and minimize overall energy costs.

Based on the related applications models conducted shows that the operation of smart thermal energy storage systems in buildings is intricately connected to the support provided by the power system, and microgrids play a crucial role in enabling this synergy [28]. Microgrids are decentralized energy systems that leverage local energy sources for distributed generation and effectively integrate with distributed thermal energy storage systems within buildings. In this technical integration, the VTES solution utilizes decentralized local energy sources such as solar panels, wind turbines, battery energy storage systems and combined heat and power (CHP) systems, which generate electricity to fulfill the power requirements of the building and also contribute to the operation of thermal energy storage systems. These local energy sources provide a sustainable and resilient energy supply, reducing reliance on the traditional power grid and promoting the integration of renewable energy.

Furthermore, by coupling distributed thermal energy storage systems with microgrids, the excess electricity generated by the local energy sources can be directed towards charging thermal energy storage systems, allowing the building to store thermal energy for heating or cooling purposes [28]. This stored thermal energy can then be efficiently utilized to meet the building's heating or cooling demand when needed, reducing overall energy consumption and peak demand from the power grid. Integrating distributed thermal energy storage systems with microgrids also enables load shifting, as the stored thermal energy can be used during off-peak periods when energy prices are lower, thereby optimizing energy costs. Moreover, the VTES solution facilitates demand response strategies by enabling real-time communication and control systems that dynamically adjust the building's energy consumption based on microgrid availability or grid conditions.

In a recent IRENA (2020) publication, the VTES technologies provide distinct advantages by enabling the decoupling of heating and cooling demand from immediate power generation and supply availability [29]. This decoupling allows for increased flexibility and opens up opportunities for greater reliance on variable renewable sources like solar and wind power. By storing excess thermal energy generated from renewable sources during periods of high availability, VTES systems can ensure a continuous and reliable heating and cooling supply even when renewable power generation fluctuates. This reduces the need for costly grid reinforcements that would otherwise be required to accommodate the intermittency of renewable energy sources. Additionally, it emphasizes that VTES is crucial in balancing seasonal demand variations by allowing excess thermal energy to be stored during low-demand periods and utilized during peak-demand seasons. Overall, IRENA findings align with the FLEXIGRID solution that VTES contributes to the transition towards a predominantly renewable-based energy system by improving grid stability, optimizing the utilization of renewable energy, and reducing dependence on conventional power generation methods.

In summary, this FLEXIGRID solution incorporates interoperability features to facilitate the implementation of VTES across different networks. This enables seamless integration with various devices, communication protocols, and energy management systems, allowing easy deployment and scalability. The VTES solution provides a technically sophisticated approach to enhancing flexibility in energy consumption. The VTES optimizes heating and cooling demand by leveraging user behavior, preferences, and targeted device control while ensuring occupant comfort. Its versatility, adaptability, and compatibility with different network topologies make it valuable for addressing challenges in European grids. Therefore, Virtual Thermal Energy Storage (VTES) can enhance the Ten-Year Network Development Plan by addressing key challenges and optimizing the development of the European electricity network. The VTES enhances the TYNDP by enabling the integration of renewables, optimizing grid operations, improving flexibility and stability, utilizing existing assets effectively, and promoting cost-effective system development. By incorporating VTES into the planning process, the TYNDP can facilitate the transition to a more sustainable, reliable, and efficient European electricity network.

3.10 S9: Fuse Platform

Data Spaces represent the next stage of evolution for Digital Energy Platforms, as they aim to create open, federated, and collaborative ecosystems for data sharing. The critical point of data space is storing data at the source instead of the conventional central point. Hence, it will be possible to transfer data through semantic interoperability. In this context, the FUSE platform solution enables Data Spaces. It is an open-source platform built upon open standards and APIs to facilitate the integration of devices at the edge, enabling seamless communication and data exchange between various energy resources. This FLEXIGRID solution has been specifically designed to facilitate the integration of different energy ecosystems and stakeholders while maintaining control over data sharing. This data ecosystems can create the conditions to enable collaboration and competition among diverse participants that depend on each other for mutual benefits. Through the data generated by local and distributed energy resources, FUSE empowers distribution system operators (DSOs) and energy stakeholders to create innovative and value-added services. Moreover, this FUSE platform uses advanced services powered by artificial intelligence to maintain control for data sharing and to offer these added-value services for DSOs & energy stakeholders to improve the flexibility of the European power distribution network.

The integration of data in FUSE is done through the adapters. Adapters act as intermediaries between the diverse range of devices and the FUSE platform, providing a standardized interface for data exchange. Technically, the adapters in FUSE are responsible for handling the data transformation and protocol translation required to establish seamless connectivity between devices and the platform. They are equipped with the logic and protocols to understand the data formats and communication protocols used by different devices and energy resources. When a device is connected to FUSE, the corresponding adapter collects, processes, and normalizes the data generated. This involves converting data formats, aggregating data from multiple sources, and performing any necessary data cleansing or validation. By standardizing the data through the adapters, FUSE ensures that all connected devices and resources are standardized, simplifying the development of services that leverage this data. Furthermore, the adapters in FUSE also enable bi-directional communication, allowing the platform to control and manage the connected devices. This capability is essential for orchestrating distributed energy resources and optimizing their usage based on the requirements of DSOs and other stakeholders. Hence, these components play a crucial role in simplifying the data pre-management process, essential for harmonizing the development of service processes within the platform. Adapters act as intermediaries between the diverse range of devices and the FUSE platform, providing a standardized interface for data exchange which the ENTSO-E can use to investigate how the European power national grid development plans would be achieved cost-effectively and securely.

While at it, FUSE addresses future challenges that aligns with the compliance requirements of frameworks like Gaia-X and IDSA (International Data Spaces Association) to establish a foundation for an inclusive energy ecosystem. Standardizing federation rules for data and services is a crucial aspect which it addresses. This involves defining and implementing consistent guidelines and protocols that enable seamless and secure data exchange between different entities within the ecosystem. It ensures interoperability and harmonization of data-sharing processes. Data security measures, including encryption, access control, and authentication, must be implemented to protect sensitive information and ensure that only authorized entities can access the data. FUSE solution ensures data identification, security, safety, and integrity for data sharing services. With the proliferation of data sources and participants within the ecosystem, it becomes essential to have robust mechanisms in place to identify and verify the origin and integrity of data accurately. Developing connections to data and service marketplaces also presents another challenge for the FUSE platform. These marketplaces act as hubs where entities can offer and discover data and services that cater to specific energy needs. For FUSE to add value and provide tailored solutions, it must integrate with these marketplaces effectively. This involves establishing seamless connectivity, defining standardized interfaces for data and service exchange, and leveraging advanced algorithms and AI capabilities to match the needs and requirements of different stakeholders within the energy ecosystem, which aligns with critical elements of European data strategy which have immense contribution to the European Green Deal [30].

Thanks to this data-driven platform, the FUSE solution enables the identification and organization of the European ecosystem among the ENTSO-E, which is essential for designing relevant use cases on both national and cross-border scales and help on their ambitious plans which aim to help manage the transition towards decarbonizing and modernize the distribution grid to achieve the carbon neutrality as these endeavours require sector integration and close cooperation among all actors as facilitated by the FUSE solution. Moreover, the solution aims to enable energy efficiency, sector coupling, and the integration of renewable energy sources into the European electric system. Through participating in GAIA-X, energy stakeholders with clear governance within this ecosystem, the energy sector's digitalization and adoption can be eased and accelerated while optimizing the European energy system and enhancing its competitiveness. Therefore, through leveraging data-driven solutions, the FUSE solution helps address valuable use cases within the energy sector. These use cases can lead to the developing of new services for European citizens and companies. The solution optimizes the European energy system, improves flexibility, and integrates renewable energy sources. It supports the efficient planning and development of electricity infrastructure, as outlined in the TYNDP, to meet the increasing demands for decarbonization and energy transition.

The eligibility of the Projects of Common Interest (PCI) under the Ten-Year Network Development Plan (TYNDP) initiative is determined through system needs and cost-benefit analysis. Where possible, the analyses rely on scenarios based on official EU and Member State data sources and aim to provide a quantitative basis for investment planning and infrastructure development. In this context, the FUSE solution, a data space platform, plays a crucial role in shaping these scenarios. The platform contributes by offering valuable data and expertise that feed into the development of the scenarios. as it helps ENTSO-E to keep the costs of transforming the energy system as low as possible and implementing an appropriate set of investments which is essential to enable better market integration and lead to competitive power prices. Therefore, the FUSE platform helps the ENTSO-E to understand the energy system and its future for infrastructure development with integrated data from various sources. Overall, by contributing data, this FUSE solution assists in shaping the scenarios better to capture the uncertainties and complexities of TYNDP infrastructure development. This, in turn, improves the accuracy and reliability of the analysis conducted for TYNDP and PCI eligibility determination supporting their development.

4. FLEXIGRID ENVIRONMENTAL PROTECTIONS CONTRIBUTIONS

4.1 Overview

Integrating smart grid technology, such as FLEXIGRID project, into the power system is crucial in decarbonizing the power grid and promoting sustainable development, thereby contributing to overall environmental protection in numerous ways. The primary benefit of FLEXIGRID are the ability to enhance the flexibility of the distribution grid, enabling the seamless integration of large quantities of intermittent renewable energy sources and improving electricity storage. This newfound flexibility allows for efficient management and balancing of the intermittent power supply generated by solar and wind energy sources. By integrating a significant amount of renewable energy into the existing grid, FLEXIGRID will significantly reduce dependence on high carbon-based power generation, substantially reducing greenhouse gas emissions and actively supporting the global transition towards carbon neutrality.

Implementing various digital technologies solutions in FLEXIGRID project significantly enhances the reliability, security, and efficiency of the distribution grid within the EU. These advancements enable the distribution grid to continuously meet the optimal capacity to balance power supply and demand. By effectively matching electricity supply and demand in real-time, the distribution grid facilitates the seamless integration of distributed energy sources, enabling a bi-directional flow of electricity based on generation time and market trading. Consequently, with improved reliability, security, and efficiency, the grid becomes an attractive option for renewable energy sources, surpassing fossil fuel power sources and leading to grid decarbonization. This decarbonization process will not only help to reduce emissions but also mitigate the escalation of extreme weather events that often disrupt the grid's operations.

The FLEXIGRID solutions encourage optimal electricity utilization, particularly during peak hours when electricity prices are higher. Through implementing energy efficiency measures, the overall electricity demand is reduced, subsequently lowering the operational costs of energy. This reduction in power demand alleviates the need to rely on high carbon-emitting power generators to meet energy demands. Consequently, the distribution grid can prioritize utilizing the most cost effective and environmentally friendly energy sources, thereby promoting environmental protection.

This chapter focuses on the considerable and diverse environmental benefits of FLEXIGRID solutions across its eight Use Cases. These Use Cases have significantly and comprehensively contributed to environmental protection, tackling crucial challenges like climate change and ecological degradation. Furthermore, these Use Cases perfectly align with the Ten-Year Network Development Plan (TYNDP) 2020 scenarios, which upholds Europe's dedication to mitigating climate change and achieving climate neutrality by 2050. In this regard, FLEXIGRID is crucial in addressing environmental concerns and charting a path toward a more sustainable future. By actively mitigating these challenges, FLEXIGRID helps in environmental protection.

4.2 UC1: Secondary Substation upgrading for higher grid automation and control

The demonstration of upgrading secondary substations for enhanced grid automation and control, Use Case 1 (UC1), was conducted in San Vicente, Spain. This Spanish demo site consisted of four substations, Bretoña, Madepi, Toranzo, and Villabermudo, which were used to validate the FLEXIGRID algorithms and controls. Additionally, a residential building was selected as the location for installing the smart meter to test its functionality.

The Spanish demo site for Use Case 1 of FLEXIGRID project incorporated 6 solutions (S1, S2, S3, S4, S5, and S9) encompassing various functions and features. These solutions comprised the introduction of a new Smart Secondary Substation, the implementation of the Energy Box, the utilization of feeder mapping equipment, the incorporation of TDR fault location systems, the integration of flexibility algorithms, self-healing and forecasting algorithms, and the deployment of feeder protection relays. These comprehensive solutions aimed to enhance grid automation, communication, flexibility and control specifically within the MV/LV distribution grid of the demo site.

Use Case 1 in the Spanish demo site, incorporating the above stated FLEXIGRID solutions along with their respective functionalities and features, emphasizes the automation of existing substations and the effective management of high penetration of distributed energy resources (DER) areas. This use case facilitates real-time information exchange within the regional distribution grid by enabling remote control and smart monitoring of the substations. Moreover, it possesses the capability to aggregate consumers' demand and supply, thereby serving as a gateway for prosumers. This integrated approach aims to optimize the automation and management of DER areas, providing a robust platform for integrating large amounts of renewable energy sources such solar, wind, biomass etc.

The previous old-style substation lacked the capability to withstand large integration of large amounts of renewable energy sources. Therefore, retrofitting this substation with modern equipment and software through the UC1 to facilitate the integration of the high levels of renewable energy sources within the Spanish distribution grid linked with the demo site settings. This means that the Spanish distribution grid within the vicinity of the UC1 upgrade is flexible enough to accommodate a high volume of angry renewable systems into the distribution grid network with functionality issues such as protection controls. As a result, a high amount of DES, particularly the RES, will be integrated into this MV/LV distribution grid. Furthermore, it presents an opportunity for energy communities and solar prosumers to increase their connection to the local distribution grid. Compared to conventional fossil-based energy generators, renewable energy sources emit little or no harmful greenhouse gases or pollutants into the atmosphere. Subsequently, the additional significant amount of RES will reduce the need to use high-carbon-emitting power plants to meet consumer demand. Reducing high carbon emitters and integrating large amounts of RES reduced the carbon footprint on the UC-1 distribution grid system.

The upgrade of Secondary Substations plays a crucial role in improving the overall efficiency of the grid system, leading to a reduction in distribution grid losses. These losses are a significant challenge and can account for a substantial portion of the energy supplied to the grid. By reducing distribution grid losses, the pressure on the amount of energy supply needed to meet the demand is alleviated. This means that the existing energy generation capacity can be utilized more effectively without the need for additional power plants. Consequently, there is a reduced requirement for high carbon emitters, such as fossil fuel-based power plants, which are typically powered by fossil fuels and contribute to carbon emissions resulting in lower carbon emissions and more sustainable energy infrastructure which contributes toward climate protection.

The upgrade of the four Substations in this UC1 serves as a mere demonstration, representing a small fraction of what an actual MV/LV distribution grid entail. Such grids can cater to hundreds of Secondary Substations, some of which may require periodic special attention. The introduction of automation and remote-control capabilities with self-monitoring features has revolutionized the efficiency and reliability of these grids. For instance, on UC1, the new smart transformer was able to perform on-load self-commutation to the proper values. This advancement significantly minimizes the resources needed to reinforce these crucial grid nodes, including time and fuel. Implementing remote control systems for updated Secondary Substations dramatically reduces the necessity for physical mobility, leading to a substantial decrease in fuel consumption related to extensive travel. Consequently, the demand for fossil fuels diminishes, resulting in a positive environmental impact by lowering carbon emissions.

Including advanced substation controls and protections, such as protective relays, in the UC1 demonstrates a commitment to environmental protection. These upgraded Secondary Substations possess self-monitoring and control capabilities that mitigate environmental hazards commonly associated with outdated facilities, such as explosions and fires. These hazards can cause extensive damage, pollution, and various environmental stresses. By implementing these advanced features, the UC1 significantly reduces the occurrence of such hazards, thereby safeguarding the environment in the surrounding area served by this Spanish distribution grid network. Therefore, the enhanced safety measures provided by the upgraded Substations contribute to a cleaner and more secure environment, minimizing the risk of environmental damage and pollution.

In a nutshell, FLEXIGRID Use Case 1 exemplifies how upgrading secondary substations for enhanced grid automation and control impacts climate protection, including increasing the integration in several ways, including integration of a more considerable amount of Distributed Energy Sources (DES), which predominantly consist of Renewable Energy Sources (RES) which facilitates the transition to a more sustainable energy mix. Moreover, reducing the reliance on high carbon emitters, such as fossil fuel-based power plants, thereby lowering carbon emissions and mitigating climate change impacts, enabling pro-consuming, reducing fuel consumption for travelling during periodic distribution grid maintenance and minimizing various environmental hazards and risks leading to a cleaner and safer environment.

4.3 UC2: Protections functions operating with large RES share penetration in the distribution grid

Use Case 2, of FLEXIGRID involves implementing advanced protection functions in strategically selected substations within the Spanish demonstration site. This particular Use Case addresses the challenges posed by a significant penetration of renewable energy sources (RES) in the distribution grid. To achieve this, two innovative solutions were deployed: the S3 protection system designed to handle high-RES integration and the S9 software module responsible for the location and self-healing capabilities. The primary objective for this Use Case 2 was to enhance the protection systems and operational algorithms of high-voltage (HV) and medium-voltage (MV) distribution networks, particularly in grids with high RES penetration.

Moreover, this Use Case is designed to tackle the challenges associated with incorrectly detecting faults in the existing protection systems, particularly when a significant proportion of renewable energy sources (RES) is connected to the grid using power electronics. For instance, the UC2 deployment of the CIRCE fault locator could determine fault location with known faults in the MV grid of Luena/Toronzo. Unlike the transmission network's protection systems, the distribution grid's conventional functions heavily depend on fault current magnitudes. High RES penetration of the distribution grid increases the levels of fault current to the existing protective equipment of the power system. Subsequently, the increment of fault current effect makes the distribution grid more vulnerable, creating a huge potential risk of reliability drop and affecting the overall security of protection systems.

Therefore, to overcome those issues, Use Case 2 deploys advanced FLEXIGRID protection functionalities, which improve the operation and faults characteristic features for the Spanish distribution grid. These advanced protection schemes change the distribution protection system configuration. It improves the protection coordination between the MV and LV protection systems, fault location, isolation and service restoration through self-healing. Moreover, it hence the radial nature of the power distribution systems since the RES cause the power to be bi-directional rather unidirectional [31]. These functions were deployed on UC2, where the feeder relay was installed on the primary MV substation to detect faults in the MV feeder by opening the upstream breaker. It also performs the reclosing of the mentioned breakers, thus enhancing its security and dependability. Consequently, with all these FLEXIGRID protection strategies implemented in Use Case 2, the overall operational protection system of the distribution grid and reliability is significantly improved. Thus, it’s possible to integrate a high amount of variable renewable energy sources penetration without compromising the integrity of the distribution grid.

While addressing these concerns, Use Case 2 aims to enhance the flexibility of power systems, enabling a substantial increase in the number of renewable energy sources (RES) connected to the distribution grid. A crucial aspect of this is the implementation of bi-directional power flow within the distribution systems, which facilitates net metering and supports the integration of RES. Moreover, advanced protection schemes in the grid promote prosumers, further boosting RES penetration levels. As the rate of RES integration rises, the distribution grid benefits from an increased supply of clean energy. The exponential growth of low-cost energy from RES helps reduce reliance on traditional fossil fuels that cause adverse effects to atmosphere. Consequently, this substantial reduction in carbon emissions contributes to a cleaner environment.

By implementing self-healing capabilities on the distribution grid, the uninterrupted power delivery to consumers is significantly improved. The integration of protection algorithms facilitates fault localization, isolation of affected areas, and restoring power to unaffected regions. Additionally, this solution enables power islanding, thereby reducing power blackouts and enhancing the efficiency and reliability of the grid. The environmental benefits derived from such efficiency improvements are noteworthy. For example, when a power fault occurs, the self-healing capabilities ensure fewer areas are impacted within a shorter time. As a result, standby fossil fuel power generators are utilized less frequently, leading to a reduction in carbon emissions.

In summary, Use Case 2 on implementing protection functions in the distribution grid with significant penetration of renewable energy sources (RES), which is crucial in enhancing environmental protection. Enabling a higher integration of RES and ensuring the safe and reliable operation of the grid, the protection functions deployed by the FLEXIGRID contribute to a cleaner and more sustainable energy ecosystem. The fault localization, isolation, and swift power restoration capabilities reduce the reliance on backup power generation, which often relies on fossil fuels and emits carbon emissions. Additionally, the self-healing capabilities, including power islanding, enhance grid resilience and minimize the environmental impact of disruptions. Ultimately, the implementation of Use Case 2 not only improves the efficiency and reliability of the distribution grid but also significantly reduces carbon emissions, contributing to a greener and more environmentally friendly future.

4.4 UC3: Holistic energy system optimization & emulation for commercial and residential customers

Use Case 3 was the Greek demo site at Makryammos Bungalows Resort-IOSA, Greece, which was the testing ground for a comprehensive energy system optimization and emulation project targeting commercial and residential customers. This Use Case involved the implementation of four FLEXIGRID solutions under a single application, each with its unique role. Firstly, the S4 solution was the integration of the Energy Box. The S6 software module was also deployed to provide accurate forecasting and efficient grid operation. Furthermore, the S7 software module was utilized for congestion management within the system. Lastly, the S9 solution FUSE platform was integrated into the Use Case. All these systems, processes and algorithms solutions were installed along the medium voltage (MV) grid network to manage local energy generation and usage effectively. Together, these solutions contributed to the holistic optimization of the energy system, catering to the needs of diverse customers at the Greek demo site.

Under normal network conditions, Use Case 3 optimizes local energy systems to minimize energy costs for commercial and residential consumers. This holistic approach to energy system maximizes resource efficiency. Consumers can lower their energy costs by reducing energy demand through improved utilization. Adopting energy efficiency measures leads to decreased power needs for the same functions, thus reducing carbon emissions and contributing to the fight against climate change. For instance, the implementation of UC3 facilitates the continuous monitoring and evaluation of the economic advantages stemming from deploying renewable energy sources (RES) and energy storage systems at the demonstration site. To assess these installations' impact, we measured the site's actual electricity consumption, which was then compared to its electricity demand. We converted these savings into energy cost reductions by quantifying the electricity savings resulting from the operation of photovoltaic (PV) panels and battery storage. This analysis allowed us to gain insights into the extent of cost savings achieved and the reduction in CO2 emissions.

On the other hand, under abnormal network operation conditions such as fault and blackout the critical loads power supply is provided from locals' renewables coupled with battery storage operating on island mode within the structure ownership of the prosumers or community energy systems in the commercial and residential consumers. As an example, a deliberate islanding scenario, or artificial blackout, was orchestrated at the Greek demonstration site. This was done to evaluate the battery's capability to supply power to critical loads using the energy stored from the local PV generation. Thus, the Use Case demonstration possesses an emulation capacity that facilitates the evaluation of different business cases under various ownership and operation regimes. Therefore, it can simulate different scenarios, considering factors like energy tariffs, regulatory policies, and investment models. This enables commercial and residential customers to explore different ownership and operation models for their distributed energy resources infrastructure, helping them make informed decisions about the most cost-effective and sustainable approaches that are favorable to climate.

Unlocking the potential of distributed energy resources helps the customers be more proactive and prompts new players to enter power markets, such as aggregators who pool together small-scale resources and act on their owner's behalf. Therefore, the electricity market, such as generators, trading in among others, is not limited to only large and centralized utilities. It also encourages prosumers since consumers can produce their electricity with the most effective and sustainable technologies available according to their needs and preferences, creating bidirectional electricity flows within the distribution grid network. Thus, creating opportunities for new power systems in the distribution networks, such as solar PV and battery storage systems. An integrated and open electricity market creates a competitive and dynamic environment that supports the growth of renewable energy. It promotes innovation, cost reduction, and market-driven pricing while giving consumers more choices and encouraging investment in renewable energy projects. These factors significantly contribute to an increase in the deployment and adoption of renewable energy sources, which plays a positive role in environmental protection.

Integrating automated control mechanisms in the energy systems enables effective management and coordination of distributed energy resources, leading to significant environmental benefits. The system optimizes the utilization of available resources by providing real-time monitoring and control of renewable energy generation, battery storage, and energy consumption. Through dynamic adjustments and operational optimizations of components like solar panels, wind turbines, and battery systems, the system minimizes reliance on fossil fuel-based power generation, reducing greenhouse gas emissions and combating climate change. Additionally, by actively managing and balancing energy flow, the system promotes energy efficiency, avoiding wastage and lowering overall power requirements. This intelligent utilization of resources and emphasis on sustainable energy supply contributes to protecting the environment by reducing environmental pollution.

The demonstration of Use Case 3 yielded remarkable outcomes, showcasing a remarkable reduction of up to approximately 30% in carbon emissions, as reported by the project's responsible partners involved in the Greek Demo deployment. Indeed, a 15% reduction in carbon emission on average was recorded for the trials' duration (July 2022-May 2023). The 30% reduction expressed above corresponds to high PV production/medium consumption season (April 2023). Within the last months of the evaluation and after further development of the solutions the average savings were 20%. This outcome demonstrated the environmental advantages derived from the robust coordination of the operation of on-site activities carried out. The success of this demo highlighted the Use Case's efficacy in mitigating harmful greenhouse gases, emphasizing its potential for promoting sustainable practices and addressing climate change. Thus, it stressed the immense potential of scaling up these innovative solutions. Therefore, by implementing such a project on a larger scale, the impact could be substantial, contributing significantly to achieving the European Union's targets. Furthermore, scaling up the deployment of this solution holds the key to addressing climate change effectively and advancing the EU's ambitious sustainability objectives.

4.5 UC4: Microgrid congestion management and peak shaving

Use Case 4 occurs at the Greek demo site and similarly to Use Case 3, it utilizes the same four FLEXIGRID solutions (S4, S6, S7, and S9) deployed in the previous Use Case. The main objective of integrating these solutions in Use Case 4 is to address two key challenges: peak shaving at the substation level and congestion management in the Greek microgrid. Implementing these four FLEXIGRID solutions, the Use Case aims to reduce network charges and losses by effectively shaving peaks in electricity demand at the substation level. It is achieved by reducing the electricity consumption during the high demand period by either dispatchable DES on the generation side, deploying battery energy storage systems, EV and encouraging end-user participation, such as utilizing local energy resources, demands response in among others. The implementation of FLEXIGRID solutions in this specific use case focused on peak shaving operations, aiming to reduce the peak load of the Greek demon site. Through the utilization of FLEXIGRID modules, impressive results were achieved, with an estimated peak load reduction of up to 18%. This reduction played a crucial role in alleviating the strain on the local network, particularly during periods of high-power demand. Thus, peak shaving enables the power demand of the local distribution grid not to exceed the power supply capacity from the local energy resources, therefore, saving the distribution operators from not procuring additional power from the market to meet the peak load, more often this additional power is mostly sourced from fossil fuel at a very high cost with high carbon emission factor.

Additionally, integrating these solutions in this Use Case enables congestion management at the substation level, providing active and reactive power support to the upstream distribution network. Grid congestion management is an effective strategy to address distribution network transfer capabilities issues that occur at some point, primarily due to DES's excessive power supply and bi-direction due to their nature of production profiles, location, and inflexibility. Therefore, deploying congestion management mechanisms is critical in addressing the most common challenges caused by DES and increasing flexibility on the grid distribution network. Increasing the flexibility of the local grid will subsequently reduce the distribution generators' adverse effect, increasing their effective integration into the distribution grid. This helps stabilize the overall output from variable renewable sources, ensuring a more consistent, reliable and sustainable energy supply. Therefore, reducing the limitations and negative impacts of the DES on the grid lines and Substations to meet the power quality requirements and needs, the distributed energy sources will outperform and become highly prioritized over the traditional power systems based on fossil-fuel generation. As a result, the share of fossil fuels will be significantly reduced from the energy mix in the distribution grid network.

In addition, the peak shaving processes and congestion management, at a local distribution level with support from commercial customers as an aggregated resource, enables development of value and importance of using market information in evolving tariff environments. This decrease in peak load not only ensured a more stable and reliable power supply for the Greek demo site and its surrounding areas but also led to cost savings. Typically, peak demand charges are associated with higher electricity prices, so reducing peak load has a direct positive impact on expenses. This approach recognizes that electricity tariffs can vary based on time of day, season, or overall grid demand. Understanding these market dynamics, consumers can strategically manage their energy consumption through implementing energy efficiency measures to operational efficiency and optimize cost savings. Conserving these valuable resources, consumers contribute directly to the sustainable management of finite resources and help minimize the negative environmental effects of natural resource extraction and processing consequently, improved air quality is achieved, leading to a healthier environment for both humans and ecosystems.

The commercial approaches of peak shaving and congestion management in this Use Case create a mutually beneficial scenario for the grid supply and demand side. Customers experience reduced energy costs and potential tariff incentives for their participation. Simultaneously, the grid system gains advantages from the aggregated flexibility of commercial customers, which aids in maintaining a balance between supply and demand, enhancing grid stability, and facilitating the integration of renewable energy sources. For instance, during the trial at the Greek demonstration site, various simulations were conducted to assess network conditions conducive to the provision of demand response services by the flexible devices deployed on-site. These services aim to support the effective management of network congestion. Therefore, aligning the interests of consumers and the grid, these approaches encourage a more sustainable and efficient energy system that benefits both parties, ultimately contributing to a more resilient and sustainable energy environment.

The Greek demo site under the two Use Cases demonstrates multi-objective optimal dispatch of distributed energy resources in a microgrid. Various achievement was realized, including but not limited to the successful integration and operation of RES, demand response mechanisms, Battery storage systems, and incorporation of the EVs on the microgrid. Using these active and reactive dispatch DERs enabled the entire demo to minimize the reactive power charges for a microgrid, reducing distribution line power losses and voltage regulations. It improved the overall power quality, maintaining the integrity of the distribution infrastructures towards strengthening the network utilization. As much as the aggregated dispatch DER has numerous economic benefits to consumers and power distributor operators, it also has environmental benefits. The systems improve the utilization level of renewables efficiently, supplying power for the load within the region, storage, and flexible demand that minimize peak demand, improves energy efficiency, and substitutes fossil fuel power generators, while the EVs enable the decarbonization of the transport sector through electrification. Therefore, the benefits mentioned above show that the DERs can mitigate climate change impacts, helps to shield against the effects of extreme weather events, and improve energy security while playing a pivotal role in the net zero journeys.

4.6 UC5: Coordinating distribution network flexibility assets & protections schemes in urban district

The Use Case 5 demonstration was carried out in an MV distribution network as the location for the Croatian demo site; this Use Case focused on coordinating distribution network flexibility assets and protection schemes in an urban district. Initially, the operational topology of the network was set up as a radial network with unidirectional power flows, accompanied by a simple and effective protection scheme. However, as the presence of distributed generation in the MV distribution systems increased, it significantly impacted power flow and voltage conditions. A transition to a more complex meshed network architecture is necessary to mitigate these effects and adding the flexibility to existing MV distribution grid systems and thereby enabling more integration of variable RES power. This adaptive protection mechanism increases the grid's resilience, reducing downtime and enhancing the reliability of electrical service delivery. Reconfiguring the topologies in the Koprivnica urban district grid results in improved energy efficiency, enhanced reliability, and increased operating efficiency. These benefits collectively contribute to minimized energy waste and a reduced adverse environmental impact.

Use Case 5 encompasses three FLEXIGRID solutions: software modules (S5, S6) with optimization models and an open-source platform, S9. These FLEXIGRID solutions components come together to form a comprehensive platform that enables optimal and flexible distribution network operation through utilizing of flexibility services for provision of distribution level ancillary services including network voltage stabilisation, balancing, congestion management, peak reduction and N-1 criterion this allows for efficiently utilizing existing transmission and distribution lines, minimizing the need for expensive network expansion and reducing the associated environmental footprint. Further, the provision of flexibility for distribution network are expected to be rolled out at high scale due to their impact of increasing penetration of intermittent renewable energy sources facilitating a gradual phase out of the coal-based power generations hence lowering greenhouse emissions.

Implementing the new protection reconfiguration mechanism is poised to bring about notable changes in the operating and fault behaviours of the medium-voltage district distribution system. This innovative approach can consider the dynamic nature of power system parameters during transient events, thus ensuring safe and reliable operation concerning voltage and current variations. Consequently, this advancement increases the capacity for hosting renewable energy sources within the district distribution network. Moreover, introducing loop configurations enhances power flow in the distribution system, significantly reducing losses. Therefore, through optimizing the power system's transient response and improving overall distribution efficiency, the new protection reconfiguration mechanism holds promise for environmental benefits. It facilitates the integration of renewable energy sources, such as solar and wind, into the district distribution network, thereby promoting clean and sustainable power generation. The ability to accommodate higher capacities of renewable energy contributes to reducing dependence on fossil fuel-based generation, decreasing greenhouse gas emissions, and helping mitigate the adverse impacts of climate change.

The solution's modules utilized in this Use Case have been successfully implemented in a similar project, and DYMASOS (which dealt with switching states of distribution networks). These solutions have been applied to European Union (EU) distribution systems. Implementing these solutions has positively impacted the future of the EU's distribution grid network. It has led to improvements in overall operational efficiency, facilitated the integration of high renewable energy sources (RES) into the distribution grid, and provided end users with opportunities to explore various flexibility services that reduce the overall energy cost. Thus, the successful deployment of these solutions of similar nature in the EU has resulted in significant advancements in the distribution grid network. It has optimized the operational performance of the grid, enabling utilities and grid operators to efficiently manage power flow, maintain grid stability, and meet the increasing demand for renewable energy integration. By leveraging various solutions meant to improve the distribution network, the EU has been able to maximize the utilization of renewable energy resources, reducing reliance on conventional energy sources and promoting a greener energy mix. In a nutshell, deploying these solutions in the EU's distribution grid network has proven beneficial in multiple aspects. It has improved operational efficiency, facilitated high RES integration, and empowered end users to explore flexibility services that ultimately reduce the overall cost of energy. These advancements pave the way for the EU's more resilient, sustainable, and consumer-centric energy future.

The enhanced flexibility of the protection system setup improves reliability and contributes to environmental protection. Utilizing information provided by devices deployed along the grid, such as the SCADA system, and considering the results of supply, reliability, flexibility service provision, and the resilience of the distribution network, protection schemes can be optimized to ensure efficient and sustainable operation while minimizing the environmental impact. The enhanced flexibility of the protection system setup improves reliability and contributes to environmental protection. Utilizing information provided by devices deployed along the grid, such as the SCADA system, and considering the results of supply, reliability, flexibility service provision, and the resilience of the distribution network, protection schemes can be optimized to ensure efficient and sustainable operation while minimizing the environmental impact. Therefore, optimized distribution network operation reduces greenhouse gas emissions, lowers energy waste, and contributes to a cleaner and more environmentally friendly energy system.

4.7 UC6: Virtual Energy Storage for urban building

The sixth use case involves implementing virtual energy storage for an urban building. This activity occurred in a residential apartment equipped with a smart metering infrastructure, advanced communication infrastructure and controllable flexible devices such as HVAC and electrified heating systems located in the Croatia demo site. This residential apartment was equipped with advanced communication infrastructures that allowed for the seamless transmission and reception of signals related to flexibility activation. This was made possible by deploying two FLEXIGRID software solutions: the S8 virtual thermal energy storage module and the S9 FUSE platform. These software solutions enabled the integration of devices at the edge by effectively utilizing locally available data and connecting with other distributed energy resources, heating and cooling loads.

The Use Case achieves a smart heating solution that combines thermal energy storage (TES) and power-to-heat (P2H) technologies. This solution will utilize models, techniques, and optimization algorithms developed within the FLEXIGRID project to ensure the efficient and optimal integration of TES and P2H, resulting in effective energy management for heating purposes. The Use Case facilitates the efficient operation of electrical devices in the distribution network and plays a crucial role in minimizing energy waste and reducing the environmental impact. By introducing flexibility services from a third party, the traditional market dynamics are disrupted as they actively engage in ancillary services such as demand response programs, energy storage systems, and load-shifting techniques for network users in urban districts. These ancillary services, including peak demand reduction, effectively lower the overall electricity consumption and decrease the need for additional generation capacity. As a result, emissions within the Zagreb urban district MV distribution grid ecosystems are significantly reduced, leading to improved environmental sustainability in the Zagreb urban district.

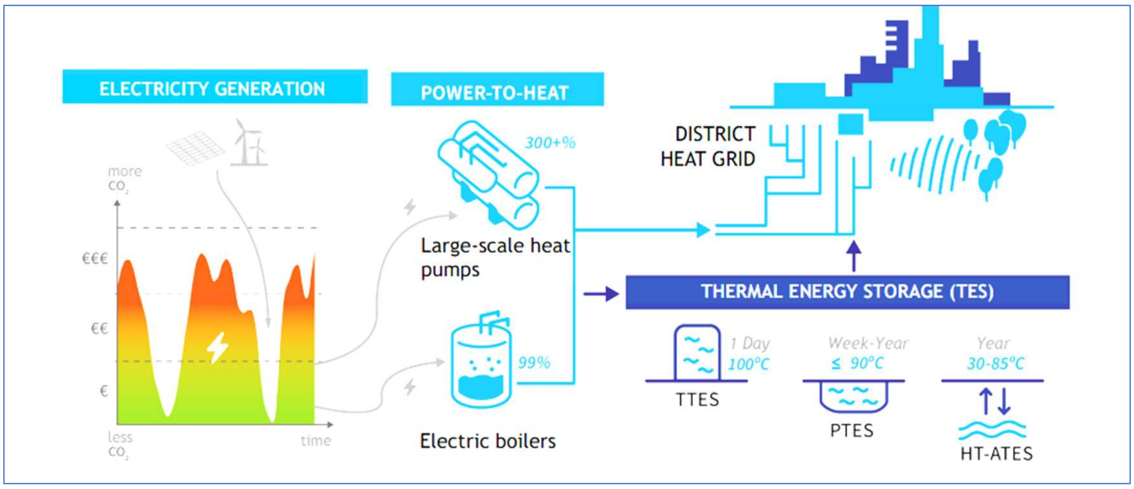

Figure 10: Simple demonstration of TES + P2H technologies Application

Source: (Scholten and Delft, 2023)

In the current era of decarbonizing power systems, the application that combines thermal energy storage (TES) and power-to-heat (P2H) technologies is highly valuable, particularly in Europe. This application addresses the challenge of managing excess power generated by distributed energy resources (DER) at the end-user level within the distribution grid network. The excess power is efficiently stored by converting it into heat, which can be utilized later when needed. This innovative solution is especially beneficial during excessive power supply to the distribution grid network. Storing and utilizing the excess power as heat helps relieve stress on the power grid. Additionally, during peak demand periods when power supply is scarce, this model serves as a demand management strategy, providing a reliable heat source without relying solely on the grid. This contributes to a more efficient and balanced power system while supporting the decarbonization efforts in Europe. As a result, combining thermal energy storage (TES) and power-to-heat (P2H) technologies, increases the self-consumption of renewable energy sources (RES), such as solar power [32]. Increased self-consumption of RES reduces the dependency on electricity generated from fossil fuels, leading to a cleaner energy mix. This shift towards low-carbon or carbon-free energy sources is vital in mitigating climate change and promoting sustainable development. The solution's modules utilized in this Use Case have been successfully implemented in a similar project, such as 3Smart (which focused on developing AC optimal power flow, OPF modules)

In addition to increasing the self-consumption of renewable energy sources, the Use Case also takes advantage of price variations in the electricity market. The storage system is optimized by utilizing electricity when the prices are low and storing it for use during periods of higher prices. This approach allows consumers to benefit from unpredictable price changes in the energy market. The Use Case utilizes communication software and devices to gather real-time information about energy trading variations to achieve this. These software solutions and devices enable the system to monitor and track real-time electricity market prices. The system can make informed decisions on when to consume or store electricity by having access to up-to-date information about price fluctuations. The cost savings derived from the optimized energy storage utilization strategy and price variation can be allocated toward financing these renewable energy investments. Therefore, by increasing their generation capacity through renewables, consumers can further reduce their dependence on the grid and potentially generate surplus energy that can be fed back into the district grid. On the other hand, it enables them to sell their excess renewable energy to the grid, further contributing to the transition towards a more sustainable energy system.

In addition, this Use Case utilises the dynamic building thermal inertia to reflect the behaviour of buildings under varying envelope characteristics including building materials, insulation and windows properties and other usage constrains such as building operations and occupancy. Basically, these factors influence the internal heat generation and heat transfer within the entire building and can use to determine thermal response of building. Moreover, these models optimise the coordination and utilisation of thermal energy storage (TES) and power-to-heat (P2H) towards get the minimal amount of heating or cooling needed in the building without compromising the comfort of occupants. Therefore, it ensures that heating and cooling operations are precisely tailored to the building's needs. This leads to reduced energy consumption through demand response, efficient energy management, intelligent load management, and thermal inertia utilization which eventually lowers energy bills and overall energy savings without compromising the comfort of the occupants. As an example, on the Croatian demonstration site trial, the validation and testing of an optimization algorithm took place. This algorithm necessitates flexibility services from an end-user, particularly during unexpected events. This rigorous testing phase was a crucial step before proceeding with its full-scale implementation in an operational real-world network. Furthermore, activating an end user's flexibility will mitigate and lower the maximum demand, commonly referred to as peak load, within the monitored network. Additionally, in extreme conditions, when power lines become overloaded and voltage levels surpass or fall below predefined limits, controllable loads will be used as a preventive measure to avert network issues that may arise.

Developing comprehensive parametric models for thermal storage equipment, such as water heaters, leads to energy efficiency and environmental protection by enabling better control and optimization of their operation. These models capture important thermal properties, including capacity and discharge rate, and electrical response characteristics, such as response time, power/energy consumption, and ramp-up/down times. Therefore, several benefits are realized by incorporating these parametric models into energy management systems. Firstly, the models provide a detailed understanding of the thermal storage capacity of the equipment, allowing for accurate estimation and control of energy utilization. This means the equipment can store and release the appropriate amount of thermal energy as needed, avoiding unnecessary energy waste. From an environmental perspective, the energy efficiency achieved through optimized operation and control of thermal storage equipment directly contributes to environmental protection. Thus, this Use Case help mitigates greenhouse gas emissions associated with energy production by minimizing energy waste and reducing overall consumption. Integrating renewable energy sources into the district network also leads to more sustainable and clean energy systems.

4.8 UC7: Dispatching platform for MV generation

The Use Case 7 focuses on implementing a dispatching platform for medium-voltage (MV) generation. This platform was tested in the MV and LV distribution grid, which receives power from the HV/LV Sarentino substation in the Italian demo site. Similar to Use Case 1 in Spain, this Use Case aims to enhance the Secondary Substation of the future (i.e., solution 1), particularly those designed for remote, isolated areas. Apart from showcasing replicability, this Use Case highlights the operating flexibility and adaptability of FLEXIGRID solutions under diverse conditions. In addition to the hardware mentioned above, this Use Case leveraged on other three FLEXIGRID solutions, namely S6, S7 and S9, to fulfil its operational requirements. Use Case 7 demonstrates the applicability of FLEXIGRID solutions in decarbonizing electrical grids across Europe and in areas like grid islands that heavily rely on fossil fuels to meet their electricity demand. These regions need help with the complexity of their grid infrastructure and various economic factors that force them to continue using fossil fuel generators. Additionally, the reliance on fossil fuel generators is driven by economic factors such as limited access to alternative energy resources or the high costs associated with transitioning to cleaner energy sources [33]. These factors make it difficult for grid islands to shift away from their dependence on fossil fuels and transition to more sustainable energy systems. However, as can be seen, this Use Case offers a promising solution to address these issues. Therefore, they ensure that they integrate renewable energy sources more efficiently despite the grid infrastructure's complexity in these areas. They reduce the heavy reliance on fossil fuel, which is environmentally unfriendly.

Moreover, in this Use Case, different generations of smart meters were deployed, enabling real-time data exchange between control signals and medium voltage users. These smart meters recorded the behaviours of the MV distribution network and facilitated the development of new strategies for managing active users, including active and reactive power control. This data-driven approach played a crucial role in improving the distribution network's operational efficiency. Thus, an efficient network enables better resource utilization and minimizes losses, thereby reducing the pressure on grid operators to exploit natural resources to meet supply and end-user demand extensively. By optimizing the grid's performance, efficiency measures contribute to conserving the environment and promoting sustainable energy practices.

One of the critical frameworks developed in this Use Case is a dispatching platform. This platform was designed to manage congestion along the MV distribution lines and ensure voltage or frequency stability for the distribution operators. Through continuously monitoring the network conditions and analysing the real-time data from smart meters, the dispatching platform could identify areas of congestion and implement appropriate measures to alleviate them. This proactive approach helped prevent potential bottlenecks and disruptions in the distribution network. Consequently, adopting high amount of distributed energy resources share, which generates clean energy, will significantly increase along the distribution grid network. Thus, this development holds immense importance in climate mitigation efforts and fostering sustainability within the power sector. The power sector can play a pivotal role in building a greener future by embracing such technological frameworks and transitioning towards a more sustainable energy mix.

Usually, the frequency modulation of conventional power plants and substations tends to be slow, and their response signal has hysteresis. This dispatching platform also plays a vital role in the modulation of HV and MV power production plants and primary substations, especially with the increase in variable DER, which results in energy imbalance of the power grid and fast frequency modulation speed and adjustable capacity in a short period. Thus, this dispatching platform for medium voltage generation enhances monitoring and control of this production side by balancing the power systems and increasing coordination between power production and consumption. The supply side adapts its power output by responding to real-time fluctuations in power demand and grid conditions. For instance, in this particular case, deploying the dispatching platform in the Sarentino locality had significant implications for the power production resources and the distribution grid. This platform facilitated the seamless integration of fully and partially repowered resources with the distribution grid. By leveraging real-time data, the dispatching platform played a crucial role in optimizing the power flow, balancing the load, and ensuring the stability and reliability of the distribution grid, specifically in Sarentino area. Therefore, this flexibility in power generation leads to enhanced grid stability, improves overall efficiency, and facilitates the seamless integration of renewable energy sources, such as wind and solar power, reducing reliance on fossil fuels and lowering greenhouse gas emissions.

This platform plays a role of power systems management in monitoring electrical network quantities such as voltage, power factor, current, and other useful power parameters such as active and reactive power at the point of connection with the end users to the external grid, which helps to determine the quantities and quality of the electricity supply in the distribution systems which is useful to not only the DSOs but also the TSOs as it helps to identify the disruption events and determine the energy consumptions on a real-time basis as well as knowing how it can affect the service life and performance of the load or equipment's used by the grid operators. This function holds great significance as it enables grid operators to monitor consumer power consumption practices and assist them in managing their power and energy usage. Additionally, it empowers end users on the MV grid to adopt energy-saving measures, such as controlling equipment performance and current behaviors, to prevent adverse power quality situations like overcurrent. Overall, this function empowers grid operators and end users to manage and optimize their power and energy usage actively, leading to increased efficiency, cost savings, a more sustainable energy system, and ultimately reducing the overall amount of carbon emitted into the atmosphere hence contributing to lowering the effect global warming which is a threat to the environment.

The forecasting algorithms within the dispatch platform serve crucial functions by controlling and monitoring the operational aspects of the grid network in real time and for future planning. These functionalities are essential in the grid network, enabling grid operators to dispatch power resources effectively. Accurately predicting future energy demand and supply patterns, these algorithms empower operators to optimize resource allocation, ensuring the grid's reliability and efficiency. With the ability to forecast energy consumption and generation, grid operators can make informed decisions regarding power generation, transmission, and distribution, leading to improved grid stability and reduced operational costs. It, therefore, not only helps to optimize the use of resources that directly affect the environment but also helps to reduce other indirect resources, such as manual labor, which contribute substantially to adverse environmental effects.

4.9 UC8: Mountainous valley grid operating in island model

The last Use Case 8 was carried out in the mountainous valley site of the Italian demo. The Use Case studied how the electricity grid in the valley could operate independently like an island without being connected to the main power MV network. To achieve this, the Use Case adopted two FLEXIGRID solutions, namely S1, a secondary substation of the future specially designed for remote, isolated areas and S9, the FUSE platform. These FLEXIGRID solutions ensured that a portion of the valley's electricity network could operate independently, made possible through active power control capabilities. In this Use Case, the power sources used were hydropower plants in the valley. The goal was to evaluate whether these hydropower plants could generate electricity and supply it to the local grid while not connected to the main MV network.

Therefore, operating the power plant in island mode encourages the development of decentralized energy resources. Usually, islanded power systems often leverage local energy resources, such as solar, wind, or biomass, readily available in the area. This promotes the efficient use of local resources, reduces dependence on external energy sources. Thus, reducing the dependence on a centralized power grid network, these decentralized systems can enhance energy security, promote local economic development, and enable greater integration of locally available environmentally friendly renewable energy sources. Subsequently, these clean energy sources produce electricity without the need for fossil fuels, thus reducing greenhouse gas emissions and air pollution.

These hydropower plants operating in island mode generate and supply electricity within the valley without needing the long-distance centralized distribution network. It, therefore, reduces power losses that occur in the distribution network. It is essential to mention that a large amount of power losses in the power system occur within the distribution grid network. Thus, shortening the MV distribution distance network will substantially lower the distribution power losses over power distribution at vast distances. Reduced distribution power losses lead to more efficient utilization of generated power and less energy wastage. This effective use of energy enables the optimization of available resources in power generation and supply which directly contributes to environmental protection.

In addition, power plants operating in island mode provide significant benefits to remote and isolated areas with unique and fragile ecosystems. Adopting these distributed energy resources (DER) approach, the Use Case minimizes the reliance on large-scale power infrastructure developments and long-distance distribution lines. This approach helps reduce adverse environmental impacts, such as deforestation, wildlife disturbance, and habitat disruption, which would occur when constructing large-scale power projects that span across multiple regions conserving natural ecosystems.

Furthermore, this use case emphasizes the development of forecasting algorithms to predict power fluctuations in advance, voltage profile, and power balancing controls. It is essential for maintaining a stable and reliable electrical system that helps optimize the use of available energy resources, minimizing energy waste and ultimately reducing environmental impact. In summary, power plants operating in island mode contribute to a cleaner and more sustainable energy system by utilizing renewable energy sources, minimizing transmission losses, enhancing energy resilience, supporting decentralized energy systems, and preserving the environment in remote or isolated areas.

5. CONCLUSION

In conclusion, the European grid network has played a crucial role in supporting the European member states' development, stability, and progress. Over time, the network has evolved from a centralized and inflexible system to one adapting to the changing energy landscape. The shift towards decarbonization and decentralization of the power market has prompted the transformation of the European grid network, making it more future-proof and capable of integrating renewable energy sources. However, the current network still needs to improve, such as congestion and inefficiencies, due to the increasing share of variable renewables and outdated infrastructure. To address these issues, there is a need for further development and modernization of the grid network, including investment in digital, the adoption of smart grid technologies, and the improvement of distribution network efficiency. The future European grid network is envisioned to be more flexible, active, and capable of accommodating bi-directional power flows, with a strong focus on sustainability, cost-effectiveness, and responsiveness to changing market requirements. By doing so, Europe can achieve its climate goals, ensure a reliable energy supply, and enhance the grid network's flexibility, reliability, resilience, and economic efficiency.

The FLEXIGRID project offers a comprehensive set of innovative hardware and software solutions that contribute significantly to developing and implementing Europe's Ten-Year Network Development Plan (TYNDP). These FLEXIGRID solutions address key challenges faced by the European power grid, such as integrating renewable energy sources, optimizing grid operation, congestion management, and sharing data. By leveraging on the advanced hardware components like the secondary Substation of the future, smart meters with feeder-mapping capabilities, and protections for high-RES penetration and software solutions, along with sophisticated software modules, enable grid operators to accurately forecast energy generation and demand, virtual thermal energy storage mechanism, facilitating the integration of renewable energy sources and ensuring efficient grid operation. The advancements in technology and functionality brought about by FLEXIGRID project align with the plan for the ENTSO-E for the TYNDP in the European power grid network, positioning it for further development and advancement in line with European policy and regulation.

In addition, FLEXIGRID project and its various Use Cases contribute significantly to environmental protection. Use Case 1 upgrades the secondary substations for enhanced grid automation and control, enables the integration of a substantial amount of renewable energy sources, reduces reliance on high carbon emitters, and lowers greenhouse gas emissions. Use Case 2 focuses on implementing advanced protection functions to handle the challenges of high renewable energy penetration, ensuring the safe and reliable operation of the grid while reducing carbon emissions. Use Case 3 optimizes energy systems for commercial and residential customers, promoting energy efficiency, renewable energy integration, and reducing carbon emissions. Use Case 4 addresses peak shaving and congestion management, reducing network charges, improving grid stability, and minimizing reliance on fossil fuel-based power generation. Use Case 5 highlights the importance of coordinating distribution network flexibility assets and protection schemes to enhance grid resilience, reduce downtime, and enable the integration of renewable energy sources. Use Case 6 introduces virtual energy storage for urban buildings, facilitating the efficient use of renewable energy, reducing grid dependence, and promoting a cleaner energy mix. Use Case 7 focuses on implementing a dispatching platform for medium-voltage generation, optimizing resource allocation, enhancing grid stability, and supporting the seamless integration of renewable energy sources. Lastly, Use Case 8 demonstrates the benefits of operating power plants in island mode, utilizing local energy resources, reducing power losses, and minimizing environmental impacts. Collectively, these use cases contribute to environmental protection by promoting renewable energy adoption, optimizing energy management, reducing emissions, and conserving natural ecosystems.

In a nutshell, FLEXIGRID project has demonstrated its commitment to transforming and modernizing the European distribution grid to meet the challenges of a rapidly changing energy landscape. Through its Use Cases deploying hardware and software innovative FLEXIGRID solutions, the Project has showcased the potential of advanced technologies, intelligent solutions, and optimized strategies to promote renewable energy integration, enhance grid resilience, and reduce carbon emissions. Moreover, the FLEXIGRID project has paved the way for a cleaner, more efficient, and sustainable distribution network. The Project's substantial contributions to environmental protection, energy efficiency, and renewable energy adoption are crucial to achieving a greener and more resilient energy system in Europe and beyond. FLEXIGRID is an exemplary model for other regions to follow as they navigate their energy transition journeys, especially in the distribution network.

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7. ANNEX

Table 1: Summary of the FLEXIGRID solutions deployed on each Use Case per demo site.

		UC1	UC2	UC3	UC4	UC5	UC6	UC7	UC8
	Solution(s)	Secondary Substation upgrading for higher automation and control	Protections functions operating with large RES share penetration in the distribution grid	Holistic energy system optimization & emulation for commercial and residential customers	Microgrid congestion management and peak shaving	Coordinating distribution network flexibility assets & protections schemes in urban district	Virtual Energy Storage for urban building	Dispatching platform for MV generation	Mountainous valley grid operating in island mod
S1	Secondary Substation of the future	√						√	√
S2	Smart meters with feeder-mapping capabilities	√							
S3	Protections for high RES penetration	√	√						
S4	Energy Box	√		√	√				
S5	Software module for fault location and self-healing	√				√			
S6	Software module for forecasting and grid operation			√	√	√		√	
S7	Software module for congestion management			√	√			√	
S8	Virtual thermal energy storage module						√		
S9	FUSE platform	√	√	√	√	√	√	√	√