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Multi-layer System Architecture Model for the European Super Smart Grid

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ABSTRACT:

Europe is aiming to become the first climate neutral continent by 2050. This ambitious aim is affecting and challenging several industries. Energy sector is one of the largest greenhouse gas emitters and the energy revolution is in action. The amount of renewably produced energy and electricity has increased enormously during recent decades. However, the state of the power networks all around Europe are in danger to form to be the bottleneck of the future development. The grid is in desperate need for attention and investments, to get to the next level of the modern renewable power production. The European Union and the Commission have published several incentives, rules and regulations which are legally binding or encouraging the Member States to evolve their power infrastructures. The grid is required to change to be more flexible, smart and interconnected. Cross-border connections and the utilisation of advanced metering and automation, together with distributed power generation, are the most effective and efficient way to transform the grid operations to this century and beyond. The final goal is to create a European super smart grid, which combines the technological and ideological characteristics of the two seamlessly. Smart grid actions emphasise local distributed generation and smart metering infrastructure with intelligent automation, whereas super grid actions focus on wide-area connectivity and HVDC technology to transport power across the continent. Both therefore support the distributed energy generation, decentralisation and flexibility. The super smart grid is relatively complex system, which can naturally be difficult to comprehend and manage. A new revised and extended architectural model and structurisation are required. The extended model created within this thesis research is based on an existing smart grid architecture model SGAM, but with the addition of super grid characteristics to serve the modern European power network fully. As the grid itself is required to be more flexible, the architecture model's cube-like layered structure enables future development and advancements to be included and extended within.

KEYWORDS: Decentralisation, power network, renewable energy, smart grid super grid, system architecture model

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TIIVISTELMÄ:

Euroopan tavoitteena on olla ensimmäinen ilmastoneutraali maanosa vuoteen 2050 mennessä. Tämä kunnianhimoinen tavoite vaikuttaa ja samalla haastaa useita toimialoja. Energia-ala on yksi suurimmista kasvihuonekaasupäästöjen aiheuttajista. Tämän seurauksena käynnissä oleva energiavallankumous on kasvattanut uusiutuvasti tuotetun energian ja sähkön määrää valtavasti viime vuosikymmenillä. Euroopan sähköverkkojen nykytila on kuitenkin vaarassa muodostua tulevaisuuden kehityksen pullonkaulaksi. Sähköverkko kaipaa kipeästi huomiota ja investointeja, jotta se yltäisi samalle tasolle nykyaikaisen uusiutuvan energian tuotannon kanssa. Euroopan unioni ja komissio ovat julkaisseet useita kannustimia, säädöksiä ja määräyksiä, jotka ovat oikeudellisesti sitovia tai vaihtoehtoisesti kannustavat jäsenvaltioita kehittämään infrastruktuurejaan. Verkon on muututtava joustavammaksi, älykkäämmäksi ja yhtenäisemmäksi. Rajat ylittävät yhteydet sekä kehittyneen mittauksen ja automaation hyödyntäminen yhdessä hajautetun tuotannon kanssa ovat tehokkaimmat tavat muuttaa kantaverkon toiminta tälle vuosisadalle. Lopullisena tavoitteena on luoda eurooppalainen ylikansallinen ja älykäs sähköverkko, joka yhdistää saumattomasti kahden teknologian ja ideologian ominaisuudet. Älykäs sähköverkko korostaa paikallista hajautettua tuotantoa ja älykästä mittainfrastruktuuria sekä automaatiota, kun taas ylikansallinen sähköverkko ideologia keskittyy laaja-alaiseen liitettävyyteen ja HVDC-teknologian hyödyntämiseen. Molemmat toiminnot tukevat hajauttamista ja joustavuutta. Kyseinen sähköverkko on suhteellisen monimutkainen järjestelmä, jota tämä tutkielma pyrkii yksinkertaistamaan ja pilkkomaan helpommin hahmotettavaksi. Tarvitaan uusi, päivitetty ja laajennettu arkkitehtuurimalli sekä rakenteellinen järjestys. Tässä tutkielmassa luotu laajennettu malli perustuu olemassa olevaan älykkään verkon arkkitehtuurimalliin SGAM, johon on lisätty olennaisia ominaisuuksia palvelemaan nykyaikaista eurooppalaista sähköverkkoa. Koska itse verkon on oltava joustavampi, arkkitehtuurimallin kuutiomainen kerroksellinen rakenne mahdollistaa tulevan kehityksen ja mallin laajentamisen.

AVAINSANAT: Hajauttaminen, sähköverkko, uusiutuva energia, älykäs sähköverkko, ylikansallinen sähköverkko, järjestelmäarkkitehtuurimalli

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Abbreviations

°C	Celsius

%	percent
AC	alternating current
ACER	European Union Agency for the Cooperation of Energy Regulators
AI	artificial intelligence
CEF	Connecting Europe Facility
CENELEC	European Committee of Electrotechnical Standardisation
CEN	European Committee of Standardisation
CETO	Clean Energy Technology Observatory
CIM	Common Information Model
CO2	carbon dioxide
DC	direct current
DER	distributed energy resource
DG	distributed generation
DSO	Distribution System Operator
ENTSO-E	European Network of Transmission System Operators for Electricity
ETSI	European Telecommunication Standards Institute
EU	European Union
EV	electric vehicle
GHG	greenhouse gas
HVDC	high-voltage direct current
IEA	International Energy Agency
IEC	International Electrotechnical Commission
km	kilometre
NECP	National Energy and Climate Plan
NIST	National Institute of Standards and Technology
NRA	National Regulatory Authority
PCI	Project of Common Interest
PMI	Project of Mutual Interest
RRF	Recovery and Resilience Facility
RRP	Recovery and Resilience Plan
SGAM	smart grid architecture model
SSG	super smart grid
TEN-E	Trans-European Networks for Energy
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan

1 Introduction

Climate change is the greatest challenge in the time of our lives. The main cause of the change has been the increased level of greenhouse gas (GHG) emissions. Until 2022, energy and electricity sector caused the largest share of the total GHG emissions in the European Union. Since then, the transition towards renewable energy sources such as wind and solar power, a significant emission reduction has been obtained. Overall, the sector has achieved significant results over the past decade with over 40 % reduction of GHG emissions between 2013 and 2023 in Europe. (*Greenhouse Gas Emission Accounts*, n.d.; *Greenhouse Gas Emission Intensity of Electricity Generation in Europe*, 2025)

EU is the global leader when it comes to fighting climate change and revolutionizing the energy and electricity sector. Europe is pursuing to be the first climate-neutral continent by 2050. To reach this aim, new policies, regulations and strategies are to be in action. Accelerated electrification of modern economies has forced the global energy transition to not only make fundamental changes to the energy sources, but also to the grid infrastructure. The electricity grid is in danger to take shape as the bottleneck of the climate neutrality revolution, since the grid is the backbone of the entire power system. To facilitate the large-scale integration of renewable energy, the current state of the grid is not keeping up with the required capacity and volume of transport. Renewable energy sources are known for their intermittent and fluctuating nature, which only accentuates the basics of electricity generation – supply must meet demand. Same type of flexibility is required to be incorporated into all parts of the network to maximize the benefits of renewable energy production. (*European Grids - European Commission*, n.d.-a; *The European Green Deal - European Commission*, n.d.)

Two potential system concepts to shape the nature of a conventional grid, are smart grid and super grid. The concepts, which neither are fully in their idealized forms yet, focus on different areas and problems inside the general grid and therefore they have previously been compartmentalized as mutually exclusive alternatives. Smart grid is a small-scale distribution level solution focusing on modernization of the network with digitalization and automation, while the super grid is focused on large-scale high-capacity transmission connections cross-borders. However, both are system level concepts utilizing various technologies with common aims on increasing the resilience, flexibility and efficiency of the grid. This makes them complementary and coexisting, even though they generally operate at different grid levels, using different technologies and tackling the problems differently. Thus, the need for a comprehensive control system strategy is necessary. (Adnan et al., 2023, 2024; Blarke & Jenkins, 2013)

As a combination of the concepts, a super smart grid or SSG is a complex system which impacts, activates and operates on several different levels of the European grid entity. Naturally, to control such entity, a clear structure and modern hierarchy are required. The traditional top-down hierarchy is not seen as functional anymore, since the responsibility of operations is spread through stakeholders. The model of the hierarchy and the structure of the control system architecture are identified as the main challenges of the final establishment of the SSG, as the technical obstacles are no longer the primary concern. Existing system architecture models and structures principally evolve around only one aspect of the grid system.

To enhance the interoperability, this thesis aims to create a framework for the control architecture of a multi-layer electricity network strategy in the EU area. The system combining both super and smart grid concepts is referred to as a super smart grid (SSG). Ideally, the SSG is a system which is able to transport mainly renewable sourced electricity across wide areas with integrated intelligent monitoring, increased efficiency and decreased emissions. An updated system architecture model integrated with both super and smart grid operations reflect the evolving requirements of the European energy landscape by providing a comprehensive visual model to clarify the system concept.

This thesis research is executed as mixed-method research, combining theory and the construction of the model. To captivate the official and institutional dimensions, a theoretical framework by a literature review including policies, regulations and reports from

The European Union and The Commission, together with research papers from other reliable sources was conducted. A conceptual model of the SSG system control architecture was created, in order to gain more insight and lay the foundation for future simulations and further research.

1.1 Scope

This thesis covers the complexity of a European super smart grid and the control strategy architecture, through EU and national level legislation, objectives and future power system requirements, without forgetting the environmental changes and impacts. Climate change, accelerated electrification and energy transition are the drivers behind EU’s ambitious decarbonisation objectives, which then deliver the need for power system development. Previous studies are some for, and some against the cooperation of super and smart grid elements, thus the exploration of both perspectives expands the viability examination. European Union and Commission regulations and publications are widely included and emphasised in this thesis research, to clarify the background and concrete implementation requirements.

The structuring of the theoretical framework began with the screening of the current state of European power generation, networks and electricity market. This included the examination of energy dependencies, nuclear power controversy, and cross-border interconnections. General energy generation history, habits, systems and sources are included from the European perspective, but more in detail discussion focus is on the electricity generation, systems and sources. To avoid confusion, it is here clarified that the term energy includes electricity and other energy types such as heat for example. Hence the term power referring mainly to electricity in the scope of this thesis.

Overall, this thesis explores and combines the authoritative publications and research outcomes to create a solid architecture model for the future power grid, which can handle additional flexibility and new innovative applications coming. Existing architecture models of modern power systems were also discussed to find the most suitable one for the specific needs of the European SSG. The model structure is intentionally kept relatively simple, yet effective in order to enhance the visualisation of the complex system.

1.2 Structure of Thesis

The research of this thesis is divided into two main parts, which complement and support each other according to the mixed-methods approach. First, a comprehensive theoretical framework is conducted, through a literature review. To accompany this, a new control system architecture model is constructed based on the research question, research gap and literature review findings. The theoretical framework goes through the European SSG development considering past, present and future aspects, together with the analysis of control strategies and hierarchies.

The methodology section defines and elaborates the chosen implementation elements of the thesis. This chapter illustrates the reasoning behind the chosen research method, and the total process of the theoretical information collection and forming of the final model. This leads to the model chapter where, based on the foundation of the literature review, a supportive and complimentary model structure is created, explained and examined.

The results and findings from the model creation and simulations are then covered with discussions about the future aspects of power system development. The viability and possible use cases of the created model are assessed further, with critical evaluation and from several perspectives. The final chapter presents a summary of the research and concludes the complete thesis.

2 Theoretical Framework

To aggregate a solid background and obtain deeper understanding of the topic, a comprehensive integrative literature review was conducted. This theoretical framework presents the relevant European level legislative publications, regulations and objectives together with opposing and supporting research findings around the topic of super and smart grid operations. The integrative nature of the literature review enables the research to go beyond of not only summarizing studies but enhancing the generation of new insights and perspectives. This then advances the development of the future frameworks or improvements.

The theoretical section of this thesis research is built by intentionally introducing and exploring all the major factors and events shaping the European power system to its current form, with the future intentions in mind. This way the broad subject is easier to absorb and comprehend. Each section of this chapter focuses on one topic related to the development of the European SSG objectively.

2.1 The European Energy Transition and Pan-European Network Objectives

The energy sector causes more than 75 % of greenhouse gas emissions in the European Union. Renewable energy, energy efficiency, and energy security are crucial topics to reach European Union's ambitious climate-neutrality aims – the main one is becoming the first climate neutral continent by 2050. The key priority is to ensure that all Europeans have secure, clean, and affordable energy available. To achieve appointed climate objectives, major improvements to the power grids are to be executed momentarily. Therefore, EU has designated various plans and incentives to support diverse cross-border energy infrastructure projects, which enable the creation of a distributed energy system. (*Energy and the Green Deal*, 2022)

When EU was founded, one of the foundational treaties included the proposal of a single internal market and free movement. The key proposal is that people, goods, capital, and services can be traded cross-border between Member States without unjustified restrictions. Free movement of these four constructs form the fundamental of economic freedom in the European Union. The liberalization of electricity and gas markets during 1990s enabled grid interconnections, to create better security of supply and increase competition. Since then, the new objectives such as sustainability and risk-preparedness, have emerged. In order for EU to maintain the fundamental right of the free movement, the ideology needs to be stretched to gain stronger coverage also over the energy and electricity sector, by linking together networks, generation sites, market platforms and all operators across the continent. The goal is to have unified system which is powered by renewable energy and operates on latest technologies, by providing affordable and sustainable energy without any dependencies on external suppliers. To achieve this, there are several past and present impactful factors, which require inquiry. As the share of renewable energy has been increasing tremendously during recent years, the focus has to be moved on towards the power transportation. (*Free Movement of Goods - EUR-Lex*, n.d.; *Internal Energy Market | Fact Sheets on the European Union | European Parliament*, 2023)

2.1.1 Power Generation in European Union Area

Approximately a 46 % share of European Union’s primary energy generation came from renewable sources in 2023. During the same year, 67 % of the total gross available energy was produced by fossil fuels. The share of renewable energy has more than doubled in the past two decades and the expansion is expected to accelerate, due to EU’s climate neutrality objectives. Main energy sources and consumption practises differ significantly. The large amount of fossil fuel-based generation in the gross available energy is explained by the differences in energy infrastructure, policies and investments between Member States. The share of renewables in electricity generation in 2023 for example ranged from over 90 % to even less than 15 % between states. Renewable energy sources cover the largest share of power generation, followed by fossil fuels and nuclear power.

As mentioned, the source variation between countries is a sum of several influencing factors which are generally either geographical, political or economic. (*Energy Statistics - an Overview*, n.d.; *How Is EU Electricity Produced and Sold?*, n.d.)

Renewable Energy Directive was first introduced in 2009, and since then, the share of renewables in EU has been increasing gradually. In 2024 renewable energy share from final consumption in EU was 25,2 %. The new minimum target set by EU to be achieved by 2030 is a 42,5 % share of renewables in energy consumption. The revised Renewable Energy Directive published in 2023 already increased the target from previous 30 %, to the aim of achieving a 45 % final share. All Member States are obligated to contribute to this target. The final consumption includes energy consumed as electricity, transportation, industry and heating. As touched on previously, the differences in renewable energy utilisation between Member States are vast. In 2024 Sweden had the largest share of renewables with 62,8 % out of final consumption, followed by Finland with 52,1 % share. This is primarily due to their large hydro and wind power industries, and the utilisation of biofuels in heating. The complete variation between Member States is shown in Figure 1. (Directive (EU) 2023/2413, 2023; *Renewable Energy Directive*, n.d.; *Share of Energy from Renewable Sources, by Country*, 2025)

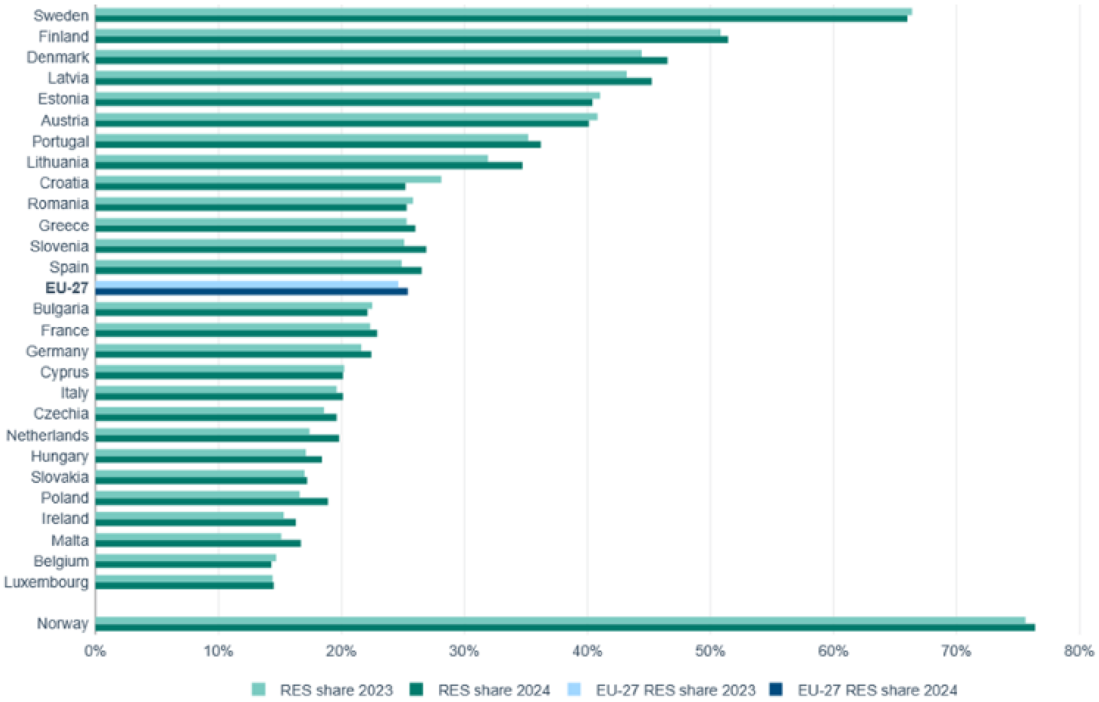

Figure 1 Share of renewable energy in final consumption by country, adapted from Eurostat (2025).

Electricity production has been leading the decarbonisation efforts, and in 2024 the share of 47 % of all electricity in EU was generated renewably. Overall, EU is leading the technological development of renewable energy generation. With net electricity production in EU, the most common renewable energy sources in 2023 were wind power with 18,5 %, hydro power with 13,5 % and solar power with 9,1 %, as shown in Figure 2 below. (*How Is EU Electricity Produced and Sold?*, n.d.; *Renewable Energy Directive*, n.d.)

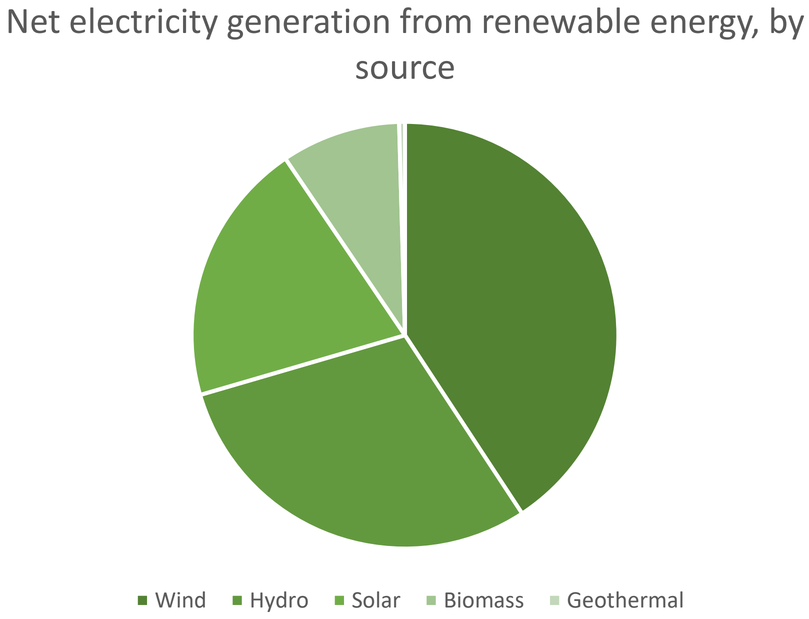

Figure 2 Net electricity generation by renewable energy sources in 2023, adapted from a web article by the Council of European Union (2025).

Natural resources, climate and landscape all shape each individual energy generation palette. When it comes to energy sources, the potential and possibilities are relatively uneven due to the geographical locations, even with renewable energy sources like wind and solar. Northern European countries have longer and darker winters, but the yearly amount of sunlight is around the same level as in central parts of Europe. Generally, coastal areas are more ideal for wind power production. Also, the strong winds in the North Sea for example, are beneficial. This makes Denmark the leading country with the share of primary energy generation of wind power being 56 % in 2024. Other wind power reliant and coastal countries are Ireland, Sweden and Germany, all with over 30 % share of wind power in their total electricity palette. (*Electricity Production, Consumption and Market Overview*, n.d.; *How Is EU Electricity Produced and Sold?*, n.d.; “Wind Energy in Europe,” n.d.)

Fossil fuels play a more significant role in countries and regions with domestic deposit or easy access to coal or natural gas resources. Poland’s largest source of electricity production is coal with 56 % share of the total generation in 2024, for example. For countries like Poland to completely abandon fossil fuels, major changes in attitudes, investments and national policy choices are required, which can take time. Overall, fossil fuels covered 31,7 % of the total net electricity generation in 2023, with the most popular ones being gas (17 %) and coal (11,7 %). (*How Is EU Electricity Produced and Sold?*, n.d.; *Poland - Countries & Regions*, n.d.)

The third largest share of the net electricity generation in 2023 was covered by nuclear power, which underlines the political reasons behind energy source breakdown between Member States. The political reasons clarify and determine what is seen as socially and strategically acceptable or viable. While EU sets the emission targets, the national policy choices reform the actual energy palette, which creates diversity. This diversity can be seen beneficial for different types of expertise and as a great asset from the perspective of energy security inside EU. Historical policy decisions and public opinions have sharply shaped the investment in nuclear power, so that other Member States are strictly against it, while others continue to expand the development of new power plants, as this is seen as a domestic alternative to imported fossil fuels. The net electricity production by the type of fuel is shown in Figure 3. (*How Is EU Electricity Produced and Sold?*, n.d.; *Nuclear Power in the European Union - World Nuclear Association*, n.d.)

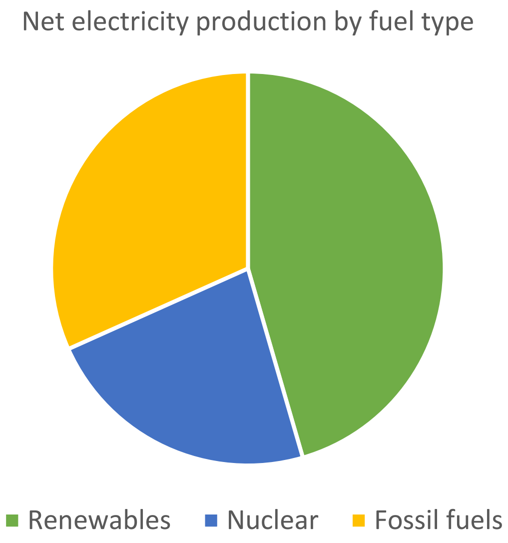

Figure 3 Net electricity production by fuel type in 2023, adapted from web article by Council of the European Union (2025).

The political reasons are rather interrelated to the economic reasons, which define what is realistic and economical. Wealthier Member States are able to make large changes into their energy portfolio quickly, while less wealthy countries must rely on existing infrastructure, which is primarily fossil fuel-based generation, for longer periods, and possibly wait for EU funding to make significant changes towards the climate goals. This also indicates that the industrial structure dominates the job markets and market integration. Energy sector contains several jobs in different fields and retraining and recruitment takes time and effort. (*Commission Continues Action to Lower Energy Bills with New Guidance on Renewables, Grids Infrastructure and Network Tariffs - European Commission*, n.d.; *In Focus*, n.d.)

Energy in EU is used for heating, lighting, producing and transporting. Different transportation activities had the highest energy consumption in 2023 with 32 % of the total available energy. This lifts petroleum products to be the top energy product of the final consumption. However, electricity had the second largest share as an energy product with 23 % out of the final energy consumption, and the share is expected to increase in the future. Most of the utilised renewable energy production is included in the final electricity consumption. The direct use of renewable energy in 2023 was only 13 %, when the real consumption was 25 %, including the generation and consumption of renewable electricity. (*Shedding Light on Energy in the EU*, n.d.)

As mentioned, EU has been working towards a single internal market and free movement, where also electricity and gas are able to flow freely across borders. Therefore, increase in power network interconnections would enhance a more integrated market, where the price of electricity would decrease and converge across all countries. A cooperative and controlled multi-layer strategy with smart and super grid operations, aims to connect all the diverse pieces of the EU’s power puzzle and create new innovations, jobs and better security across the continent. In the context of future European super smart grid, the diversity in power generation and consumption habits between Member States must be identified as an asset to multifunctional expertise and versatile possibilities. The key is that the distribution of generation and responsibilities increase the number of options available. This then naturally increases the efficiency, safety and security of the comprehensive power system.

2.1.2 European Electricity Market

The European electricity market represents the world’s largest integrated electricity market, by delivering electricity to 266 million customers with 11,3 million km of lines and cables across Europe. The integrated market is the best and most efficient way to ensure secure, sustainable and affordable power to all Europeans. The aim is that through common market rules and regulations paired with interconnections, the electricity produced in one Member State, could be transported and utilised in another one. The electricity market rules are being reformed as a part of the European Green Deal, to better match the future development requirements. (*Electricity Market Design*, n.d.)

Reformation of the electricity market rules began with a proposal in 2023, and the new revised rules, Directive 2024/1711 and Regulation 2024/1747, were adopted in 2024. By 2025 the Member States were obligated to transpose the new rules into their national law. The new market rules are focusing on making the market more responsive and resilient. Overall, the market reformation also benefits the larger integration of renewable energy, and supports better protection, stability and predictability of electricity prices, which then contributes to the competitiveness of European industry. All this can be achieved by increased interconnections and communication cross-borders. (*Electricity Market Design*, n.d.)

Wholesale electricity prices have conventionally been linked to the wholesale gas prices, which has caused an increase of fluctuations and quickly evolving market price spikes. Due to these events, EU wants to ensure the independence of European companies and consumers by protecting them from these unpredictable and inevitable price spikes. Long-term contracts like power purchase agreement (PPA) are market-based solutions to achieve this with. (*Affordable Energy*, n.d.; *Electricity Market Design*, n.d.)

The electricity market in Europe is structured zonally, including several designated bidding or pricing areas. Some countries operate as one bidding area and some have been divided into several zones. The bidding zones are areas where the constrains or limitations of the transmission capacity or congestion are not affected, as all actions in most cases happen inside the specific zone. Each bidding zone has one electricity wholesale price. Finland, for example operates as one bidding zone, but in Sweden and Italy, there are in total four different price zones. Generally, the bidding zone borders follow the national borders. (*Bidding Zone Review*, n.d.; Cartaxo et al., 2022)

Electricity market is then the platform where power is traded across the different regions through various participants. The same market rules apply to each bidding zone. The market consists of balancing market, day-ahead market and intraday market. The European electricity market is often divided into several regions across the continent. However, there is no official definition for these regions, so the presentation varies between sources. The division is done to clarify the connections and statistical aggregation. The typical market regions are presented in Figure 4 below. (Cartaxo et al., 2022)

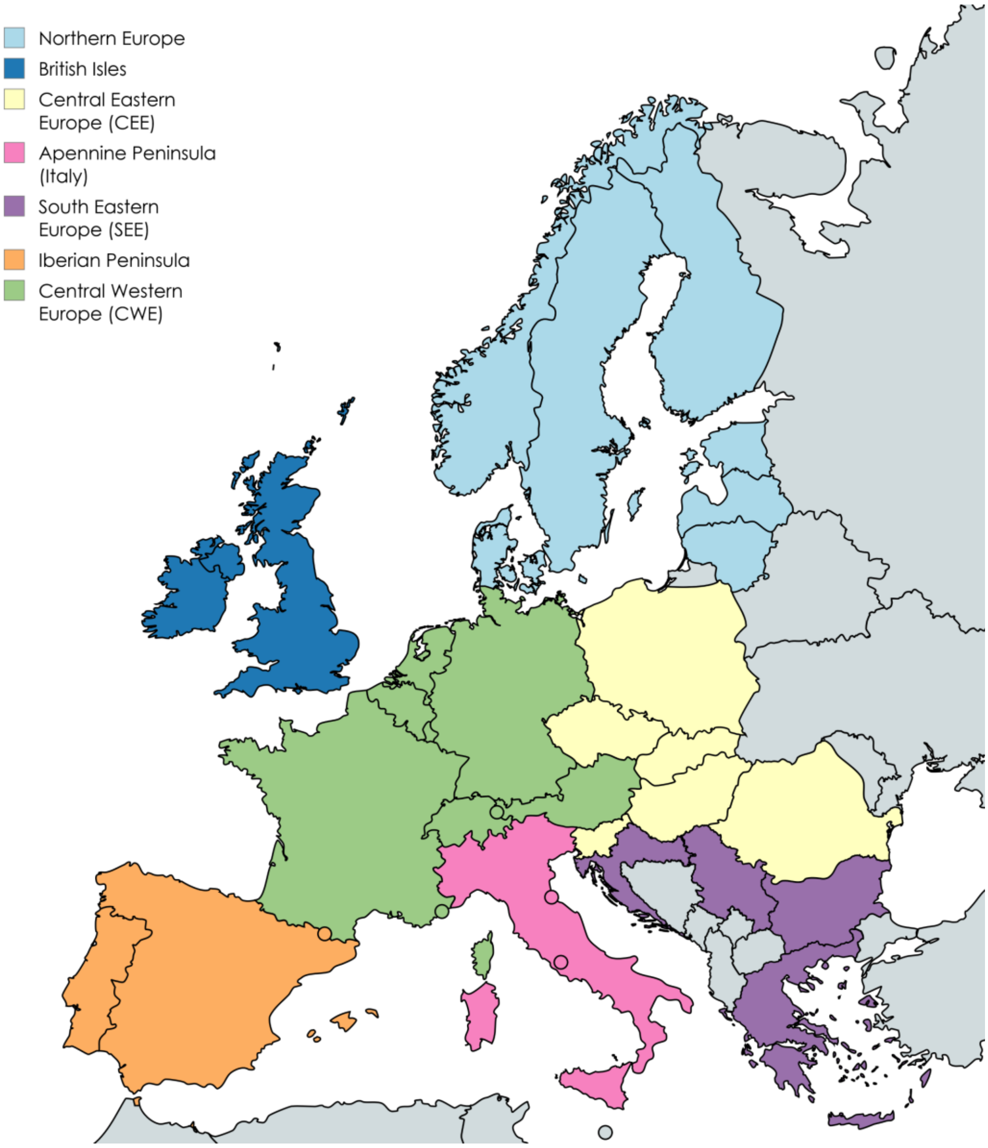

Figure 4 European electricity market regions, constructed based on Cartaxo et al. (2022).

There are Nominated Electricity Market Operators or NEMOs in each EU Member State, and their role is to run the day-ahead and intraday integrated markets inside the Union. A NEMO is basically an entity which operates in cooperation with the TSOs as a market operator in either national or regional markets. The NEMOs are also required to work in coordination within each other, since they are responsible for publishing their resulted prices simultaneously across Europe. NEMOs do not decide the prices, they produce the prices through rules set. According to Regulation 2015/1222 NEMOs must operate with harmony, transparently and equally. (Cartaxo et al., 2022; *nemo_committee*, n.d.; Regulation (EU) 2015/1222, 2015)

If bidding zones are the map and NEMOs the countries on the map, the transmission lines operate as the roads. As with the physical interconnections of the electricity network, the trading happens typically between neighbouring areas or countries. By unifying the electricity market actions in Europe, the physical network system and connections could be utilised to the full potential. (Cartaxo et al., 2022; Directive (EU) 2024/1711, 2024; *Electricity Market Design*, n.d.; Regulation (EU) 2024/1747, 2024)

This brings us to market coupling, which has been recognised as one of the key solutions to achieve the grid reinforcement objectives. Bidding zones can be seen as the invisible element when it comes to market coupling. As a refined approach, market coupling links together multiple electricity markets across various geographical regions with coordinated operation. Market coupling aims to create an integrated, unified and liquid flexible market, which enables efficient cross-border electricity trading, reduces price differences and improves grid stability and security of supply. Several regions inside EU have already been coupled, synchronised or connected, but the larger implementation of such approach is more complex, yet increasingly inevitable in the future. The creation of a European internal electricity market depends on coupling of both day-ahead and intraday prices over the bidding zones. Currently, the day-ahead market is more advanced in the coupling and unification process, with larger number of participants also. A single European electricity market would be better aligned with the physical reality of interconnections and power flows. (Cartaxo et al., 2022; *Electricity Market Design*, n.d.; Regulation (EU) 2019/943, 2019)

The market unification took a huge step forward in September 2025, when the EU day-ahead electricity market transformed from the hourly interval to 15-minute interval trading. Thus, electricity prices are calculated every 15 minutes, which reflects more accurately the short-term variations between electricity supply and demand. The finer granulation gives power systems the much-required flexibility. The aim is to create a single EU level intraday market, where all market participants can operate continuously, promoting necessary competitiveness. These mentioned activities are initiated in the Electricity Regulation (EU/2019/943) and in the reformed electricity market design rules Directive (EU/2024/1711) and Regulation (EU/2024/1747), the latter ones entered into force as a part of the Green Deal Industrial Plan in 2024. (Directive (EU) 2024/1711, 2024; *Electricity Market Design*, n.d.; *EU Electricity Trading in the Day-Ahead Markets Becomes More Dynamic - European Commission*, n.d.-a; Regulation (EU) 2019/943, 2019; Regulation (EU) 2024/1747, 2024)

As the European electricity market is the largest in the world, the architectural and control related challenges inevitably reflect on that. The wide range of rules, incentives and regulations together with the tight cooperation and coordination are all highly appreciated and required actions to ensure the adequate operations. The complexity of the system requires multiple authoritarian entities, since no single central authority can control everything, not the physical grid or the electricity market.

2.1.3 External Energy Dependencies

Energy imports are divided into primary and secondary products. Primary products refer to raw, unprocessed natural energy source, while secondary energy products are refined or converted from the primary sources. The same terms and definitions are used in other energy related contexts. Primary energy products are for example fossil fuels like natural gas, oil and coal and secondary product would be the electricity produced with these sources.

EU’s domestic energy generation is not enough to satisfy the total demand, so making external imports necessary. In 2023 the imported energy dependency rate was over 58 %, including primary and secondary energy products. This means that almost 60 % of the energy required was met with net imports coming from outside of the Union. The dependency rate varies highly between Member States. Most of the imported energy is fossil fuel based primary energy products, used for electricity production, heating, transportation and industrial processes. This chapter takes a deeper look into the primary energy products used in electricity generation. The main imported energy product was oil, primarily used as a fuel in the transport sector, followed by natural gas, which for the most part is used in electricity and heat generation. Approximately 30 % of households inside the Union are heated with gas, especially in the southern parts of the continent. Still over 31 % of natural gas is used for electricity and heat generation. (*Energy Statistics - an Overview*, n.d.; *Where Does the EU's Gas Come from?*, n.d.)

EU has historically been heavily reliant on Russian fossil fuels, more specifically gas and oil. Russia has large gas, coal and oil natural reserves and energy trading was seen as viable way of binding Russia into cooperation with other European countries. The geographical location and vague pipeline network made Russian fossil fuels affordable, which helped European industries to stay competitive in the global market. (Gritz & Wolff, 2024)

Gas was the main fossil fuel in EU's electricity generation scene in 2023, with 17 % share of the total production. Overall, natural gas in EU is used for power generation, industrial activities and household heating. In 2024 the natural gas dependency rate was 85,6 %, so most of the gas consumed has been imported from outside the Union. The natural gas production inside EU has been steadily declining. Romania and the Netherlands have been the largest natural gas producers in 2023 and 2024. (*How Is EU Electricity Produced and Sold?*, n.d.; *Natural Gas Supply Statistics*, n.d.)

In 2021 over 40 % of imported pipeline gas in EU came from Russia. After Russia invaded Ukraine in February 2022, EU has deliberately reduced the reliance on Russian fossil fuels, and the share of imported pipeline gas came down to 11 % in 2023. The overall reduction in gas consumption together with the rapid increase in liquefied Natural Gas or LNG made the drop possible. Before the downgrading to a marginal supplier, Russia was the main importer of all three main fossil fuels – oil, gas and coal. (*Where Does the EU's Gas Come from?*, n.d.)

EU has decided to gradually give up Russian import of gas and oil completely by 2027. This has led Russia to act by intentionally weaponizing the energy supply. The systematic blackmailing and sabotage are about to end under the legislative proposal by the European Commission. In May 2022 EU launched REPowerEU, a recover plan with a roadmap on phasing out Russian fossil fuels in solidarity between all Member States. The roadmap was updated in May 2025, and a regulation was proposed in June 2025 to end EU's dependency on Russian fossil fuels and to phase out the imports completely. The proposal ensures that the energy supply will be kept safe, while avoiding increases in prices or other possible market disruptions. Due to the existing pipeline connections across EU and alternative suppliers in the global or local market, the transition can be done smoothly. The inevitable phase-out will overall enhance and accelerate several EU's action plans regarding, competitiveness, climate goals and affordable energy. Ultimately, the goal is to replace all the imported fossil fuels targeted to electricity generation with renewable energy. (*REPowerEU*, 2022; *REPowerEU – Phase out of Russian Energy Imports - Energy*, n.d.)

In addition, dependence on Russian nuclear power supplies is a worldwide phenomenon. However, the sanctions of nuclear power dependence in EU have gone under the radar, compared to fossil fuels. Inside the Union area, there are several nuclear power plants build and calibrated to operate with fuel elements provided by the Russian State Atomic Energy Corporation or Rosatom. Fourth of all nuclear power plants in the world are connected to Russia. ("Dependencies of the European Union and the World on Russian Nuclear Fuel Cycle Services, and How to Reduce Them," 2025)

In 2023 Russia also supplied 23,5 % of the uranium used in nuclear power reactors in EU. Some of the Member States have independently suspended all relations and dependencies, since EU has yet not been directly targeting Rosatom with sanctions. For example, Finland cancelled projects definitively on building new power plants. Finland has also signed contracts about nuclear fuel supply with the United States based Westinghouse Nuclear together with Bulgaria and Czechia. Currently, there is no active domestic uranium mining, or it is very limited, due to environmental, social and political concerns. In 2024, a Finnish mining company Terrafame started to recover natural uranium as a by-product of the production of other metals. The full capacity of uranium production is to be reached in 2026 with the total output of 200 tonnes a year. A French-owned nuclear company Framatome has also been said to be developing European based nuclear fuel products. However, Framatome has signed a cooperation agreement with Rosatom, to produce nuclear fuel in collaboration. Framatome is intending to supply nuclear fuel, which is produced in Germany, under the license of Rosatom and from uranium and fuel pellets coming from Russia. Generally, nuclear power is overall more sensitive topic than fossil fuels. which creates even more tension to the sanctions and action, with the massive role Russia has over the whole global nuclear industry. And Framatome’s businesses show, that even if Russian nuclear supply would be ruled out with sanctions on Rosatom for example, the connections and motives are deep and complicated. The change takes time and there is not one ready-to-go solution, but many innovative and bold actions and decisions to be made. Terrafame’s approach is a great example of this. (“Dependencies of the European Union and the World on Russian Nuclear Fuel Cycle Services, and How to Reduce Them,” 2025; *Terrafame Has Started Uranium Recovery*, n.d.; Digges, 2025; Ihédate & ihedate, 2025)

The European Commission launched REPowerEU plan with 300 billion euros, with the focus in Recovery and Resilience Facility. The aim is to decrease the dependence on all sort of imports, but especially energy related ones. The funds are targeted towards projects of energy storage, grid modernisation and acceleration of renewable energy deployment. Member States in the need of this type of funding, are required to include REPowerEU as a part of their own Recover and Resilience Plan (RRP). The Recovery and Resilience Facility (RRF) is EU’s temporary instrument when funding new projects and investments. The temporary Facility was formed during the pandemic in 2020 and is active until 2026. (*Recovery and Resilience Facility - European Commission*, 2021; *REPowerEU*, 2022)

After the incidents in 2022, EU’s main fossil fuel importers have been The United States for oil, Norway for gas and Australia for solid fossil fuels such as coal. EU’s energy dependency rate is relatively high, but progress to decrease the number of imports has already been done. In 2024 the total imports decreased over 16 % in value and over 7 % in net mass, compared to the previous year. The total worth of imported energy was €375,9 million euros and 720,4 million tonnes. (*Imports of Energy Products to the EU down in 2024*, 2025; *Shedding Light on Energy in the EU*, n.d.)

2.1.4 Nuclear Power in EU Area

From political perspective, national policy choices reform the differences between countries. A great example of this is the different approaches on nuclear power. In 2023 nuclear power held a 22,8 % share of the total net electricity generation in EU. This makes it the largest single energy source in electricity generation. (*How Is EU Electricity Produced and Sold?*, n.d.)

Germany, one of the most influential of the Member States, phased out nuclear power completely. In 2002 German policy makers made the decision to gradually let go of nuclear power by 2032, but the process got accelerated after the Fukushima accident in March 2011. Originally Germany had 17 nuclear power reactors in action and the last three of these were shut down in April 2023. This led Germany to temporarily increase fossil fuel-based energy generation to meet the demand. Since then, Germany has the largest installed wind power capacity in EU today. (“Latest Wind Energy Data for Europe,” n.d.; *Nuclear Phase-Out*, n.d.; Murray, 2019)

At the same time, France has the second most nuclear power generation in the world and most inside EU. In 2023 65 % of the generated electricity in France came from nuclear power plants, and 54,6 % share of the total generated nuclear power in EU. Other

Member States with large nuclear power production were Spain with 9,2 %, Sweden with 7,8 % and Belgium with 5,3 % out of the EU total. These four countries alone produced 76,9 % of all electricity generated in nuclear power plants inside the EU in 2023. This indicates the vast contrast between some of the countries. (*Nuclear Energy Statistics*, n.d.)

The overall atmosphere in EU with nuclear power is neutral or cautiously encouraging. As referred, Member States hold the freedom to make the decisions regarding integrating or maintaining nuclear power as a part of their own energy palettes, according to Article 194(2) of the Treaty on the Functioning of the European Union. There were in 2023 a total of 12 Member States out of 27 with operational nuclear power plants. However, the Nuclear Safety Directive and Directive for the Management of Radioactive Waste and Spent Fuel, together with common EU rules and regulations, are binding on all Member States. Some states have no nuclear power generation or the interest for it, such as Austria and Denmark, who both have banned the production and development of it completely. Vice versa, there are states that have previously phased out the possibility of nuclear power generation but are since interested in integrating it as a part of their energy mix. Nuclear power accounted for over one third of the total electricity generation in eight of the 12 Member States that operated nuclear power plants in 2023. (EPRS, European Parliamentary Research Service, n.d.; *Nuclear Energy Statistics*, n.d.; OPOCE, n.d.)

France is promoting a coalition of Member States, that aims to create energy sovereignty and to boost decarbonation. This so-called nuclear alliance enables the growth, research, and development of nuclear power inside EU by also improving the movement away from solely fossil fuels. The alliance is focused on creating a solid foundation and framework to scale up the European nuclear industry in order to succeed in the global competition. (EPRS, European Parliamentary Research Service, n.d.)

Overall, nuclear energy holds a relatively large share of the Union's total electricity generation source palette and the interest towards it has been gradually gaining more trust. There are still big questions to answer and problems to find solutions for, referring to the dependence on Russian nuclear supply. EU's approach to nuclear power has been about evaluating the opportunities and challenges in a rather neutral way. This is anticipated, since the Member States have the freedom to choose, but when it comes to Russia's manipulation and ruling the market sector, much bolder actions, guidance and regulations are required.

2.1.5 The European Green Deal and Decarbonization Goals

Europe is striving to become the first climate neutral continent by the year 2050. The European Green Deal is an action plan affecting several policy areas, transforming the European economy, energy and industries. The aim is to promote clean transition with investments in new innovative approaches, clean technology and sustainable infrastructure. The clean transition is aimed at being done by protecting people and maintaining economic security and social fairness. (*The European Green Deal - European Commission*, n.d.)

The direct actions on climate neutrality and reduction of emissions are bound by European Climate Law, which is the legal backbone of the Green Deal. The agreement is to reduce emissions by at least 55 % by 2030, compared to 1990 level and 90 % before 2040. These targets are crucial intermediate steps on the path to achieve final climate neutrality by 2050. (*The European Green Deal - European Commission*, n.d.)

The European Council has stated that the objective of a climate neutral continent is coherent with the United Nation Paris Agreement, a legally binding international treaty, which sets the goal to hold the global average temperature increase below 2°C compared to pre-industrial levels. The Climate Law, published and entered into force in 2021, operates as the framework on how to achieve climate neutrality objectives, and what mandatory changes are to be made in the future to do so. The Commission notices that previous energy infrastructure investments have been insufficient, and changes are required in order to effectively support the energy transition, accelerated electrification and the scaling up of renewable electricity generation. Therefore, the Climate Law promotes the interconnection of the networks in the trans-European energy infrastructure. Relevant stakeholders and authorities are required to work together within given framework to develop connections so that rural and isolated regions are also taken part in trans-European network infrastructure. (*European Climate Law - Climate Action - European Commission*, n.d.; Regulation (EU) 2021/1119, 2021; *The Paris Agreement | UNFCCC*, n.d.)

A high-performance, well-connected and modernized infrastructure network is a crucial base not only for energy, but also for transportation and digital services. Regulation (EU) 2021/1153 of the European Parliament and of the Council states, that all islands, regions and outermost areas need to be connected to enable a smart and sustainable growth with the promised free movement of all goods and people. The Regulation (EU) 2021/1153 also establishes the Connecting Europe Facility or the CEF with the purpose to accelerate the investments, funding and legal matters related. The contribution of the CEF also naturally includes all the actions against climate change with the objectives of the European Green Deal and the Paris Agreement. However, the primary function of the Facility is to create clear and transparent financial support for prioritized infrastructure projects, such as cross-border network connections, which are strategically significant to the whole Union, but Member States might not provide necessary funding alone. CEF could also fund other crucial projects such as discussed smart and super grid development. (*About the Connecting Europe Facility - European Climate, Infrastructure and Environment Executive Agency*, n.d.; Regulation (EU) 2021/1153, 2021)

Alongside the emission reduction, related objectives and regulations include creating measures and monitoring to track progress by governance progress. For Member States this is included in their National Energy and Climate Plans (NECPs). With these existing systems, progress will be reviewed and assessed no fewer than every five years. The

European Green Deal is purposed to be more than just the targets set. Same goes with the Climate Law, one key feature is to strengthen and concrete the adaptation actions to climate change itself. The aim is to create the right kind of enabling environment, which refers to making the conditions to build green transition approachable and attractive. This ideology can be described as the backbone or a catalyst to the multi-layer control strategy for the grid operations. Without the right conditions, this type of system could not be funded, built or utilized effectively. Primarily, European Green Deal sets common goals, which then spawn other official and EU level plans, acts, rules and regulations. Operators in several sectors and industries are then encouraged and ready to implement within these guidelines. (*National Energy and Climate Plans*, n.d.; Regulation (EU) 2021/1119, 2021)

2.1.6 Grid Interconnections

European energy infrastructure is going through major transformations due to climate actions and geopolitical challenges. New interconnections and updates to the conventional grid are finally seen as a necessity for optimal operations. Previous investments have been guided towards renewable energy generation, and the grid itself has been left with less attention. This is now causing the grid to become the bottleneck of the energy infrastructure modernization. Significant delays in grid development, also delay EU's efforts to achieve climate neutrality and decarbonisation of the economy. The grid is the backbone of the system. Strengthening the grid has various environmental and financial benefits. A modern network enables efficient flow of electricity across borders, accelerated electrification and lower clean energy prices. In addition, global competitiveness and security of supply are crucial priorities together with the climate objectives. (*Electricity Interconnection Targets*, n.d.-a; *Grids Package*, n.d.-a)

The lack of regulatory frameworks was recognised as one of the obstacles on the way of grid modernisation. Other related risks were rather socio-economical, than necessary technological. Now there are several EU level actions and regulatory sets created to enhance the development, so European grids can be connected to the continental level.

The European power networks have interconnections and synchronisation between neighbouring regions. The several synchronised regions of different sizes distribute power through AC lines, with interconnected HVDC lines also across regions. The larger synchronisation of European regions enhances the creation of stronger Energy Union and increases safety and security. In February 2025, the Baltic region power networks were synchronised to the largest region the Central Europe Synchronous Area due to the security aspects and future development plans. This was a huge milestone, when strengthening the European cooperation and moving away from external dependencies. (*ENTSO-E Confirms Successful Synchronization of the Continental European Electricity System with the Systems of the Baltic Countries*, n.d.; Hofmann et al., 2020; Zahid et al., 2025)

On 10th of December 2025, EU presented the European Grids Package which operates as the latest policy and legislative framework for the grid development plans and projects. The Grids Package includes legislative proposals to solve the urgent structural issues in the European energy infrastructure in order to create a genuine Energy Union. The Grids Package was created to operate as a wider policy response to update and unify the rules, regulations and binding legislation related. The legislative proposals promote immediate actions, which then complement the Grid Action Plan incentives and implementation tools. The Grid Action Plan, alongside with other Action Plans, identify the practical actions and showcases the roadmap on how and when to implement them. The Grids Package is designed to cross and support several other ongoing acts, for example the strategic driver REPowerEU published in 2022 to ensure the movement away from Russian fossil fuel imports. (An EU Action Plan for Grids, 2023; *European Grids - European Commission*, n.d.-a)

The European Commission presented in May 2025 a guidance document on proactive investments for future electricity networks. The document is directed to both transmission and distribution system operators and to national authorities as a guidance in enhancing the formation of right conditions to the grid investments to reflect future requirements, competitiveness of industry and to promise affordable energy to consumers. Grid investment requirements by 2040 were projected at estimated 730 billion euros for distribution networks and 477 billion euros for transmission networks. All mentioned initiatives are in line with the European Grid Action Plan and the Affordable Energy Action Plan. These proactive investments enable the multi-layer strategy implementation, since the target of the investments is in innovative long-term network development plans. (*EU Guidance on Ensuring Electricity Grids Are Fit for the Future - European Commission*, n.d.)

The Grid Action Plan includes concrete implementation tools to help guide investments towards projects which accelerate the European electricity network modernization. The Action Plan was issued in November 2023 as a part of the European Green Deal incentives. According to the plan, the consumption of electricity is expected to increase by more than 60 % by 2030. As a response to this growth and to the climate incentives, the electricity networks require more flexibility, decentralisation and digitalisation. The Action Plan is targeting 584 billion euros funding to grid development, due to over 40 % of the grids in Europe being over 40 years old. As for European Network of Transmission System Operators for Electricity (ENTSO-E) is investing 700 million euros until 2050 to the same cause, to modernise the conventional grid with intelligent applications and to create more cross-border connections. (*European Grids - European Commission*, n.d.-a; Zahid et al., 2025)

Seven different action focus areas are identified in the Action Plan, to concrete the investment directions and to accelerate the delivery of intentions. Accelerated and effective unlocking of investments and enhancing access to finances is crucial, since the actual grid construction takes time. Time consuming construction is therefore listed as one of the seven focus actions. When the finances are flowing more efficiently towards the high requirement projects, the development and achievement of climate objectives can stay on the planned timeline by also accelerating the deployment of the new projects with faster permitting. (*European Grids - European Commission*, n.d.-a)

Part of the Grid Action Plan and the Grids Package objectives is to make affordable energy matter for all citizens. Therefore, EU published a separate Affordable Energy Action Plan, including eight actions which are mostly carried through already in 2025. The well-functioning connections and markets must be a priority even with high-end projects, and the costs of a modern, digitalized and flexible network cannot in any case fall on the citizens. According to the Commission, modernizing the energy infrastructure is the most cost-effective way to acclaim climate goals. (*Affordable Energy*, n.d.)

The European Green Deal connects to and overlaps with several concrete implementation regulations and plans. Trans-European Networks for Energy or TEN-E is a separate but intertwined EU instrument, which rules the policies for specifically cross-border network connections in a collaborative and solitary way. The first TEN-E regulations were published in 2013 and since then the aim has been to improve market integration, reduce the risks of bottlenecks, and increase healthy competitiveness between EU countries. TEN-E regulations are legally binding for the Member States. The revised Regulation (EU) 2022/869 came into practise with the same aims in 2022, together with updates on the energy infrastructure categories and priority corridors. (Regulation (EU) 2022/869, 2022; *Trans-European Networks for Energy*, n.d.-a)

Every two years since 2013, as a part of the revised TEN-E policy, new Projects of Common Interest (PCIs) have been identified. The fifth PCI list came in action in 2022. However, in November 2023 the European Union created a new delegated list, which included Projects of Mutual Interest (PMIs) together with updated PCIs. The new list was the first to include both PCIs and PMIs, and in the future this Commission delegated list will be revised every two years the next revision in November 2025 and later publication during 2026. PCIs are projects between at least two EU countries and PMIs are projects which occupy EU countries and countries outside the Union. Primarily the projects are implemented together with countries in the Energy Community Contracting Parties and the European Economic Area. The candidate countries are expected to have aligned energy and climate objectives with the EU and be stable and supportive in terms of supply of service in the continent. (*PCI and PMI Selection Process*, n.d.; Regulation (EU) 2022/869, 2022; *Trans-European Networks for Energy*, n.d.-a)

Even though the European power grid is the largest integrated network and the most resilient one in the world, as a continent Europe is relatively small, geographically and politically. EU is mighty but responsible alliance and with the increasing global tension and climate risks, a strong bond between Member States and other European countries is more crucial than ever. Therefore, focusing on every two-year revision of the PMIs will strengthen the alliance and harmonize the energy infrastructure cross-border, which will then increase security of supply and global competitiveness. Overall, PCI and PMI projects support the thematic areas of the priority corridors and chosen energy sector infrastructure categories. (*PCI and PMI Selection Process*, n.d.; *Trans-European Networks for Energy*, n.d.-a)

The revised TEN-E policy includes a total of eleven priority corridors that cover different geographic regions in EU. The corridors respond to the requirement to connect the currently isolated regions in the sectors of electricity, offshore grid, and hydrogen infrastructure. The three priority thematics named are smart electricity grids, smart gas grids and CO2 networks. (*Trans-European Networks for Energy*, n.d.-a)

Many Member States and neighbouring countries have existing interconnections within their electricity grids, but the long-term plan is to expand the network to cover the whole Europe. The plan agrees with the original ideology stated when establishing the European Union - a single internal market and free movement for all goods and people. As stated in the Climate Law, with the sustainable growth strategy set with the European Green Deal, future EU will be a just and prosperous society, with modern, efficient and competitive economy. Europe is a small continent and by strengthening the connections and relations between Union Member States, the security of supply, overall resilience and reliability of operation increases. (Regulation (EU) 2021/1119, 2021)

TSOs all over Europe are obliged to make grid accommodations for the larger integration of renewable energy. By 2024 only five grid operators in Europe had made the promise to have a completely decarbonized network by 2035, even though 13 EU countries have carbon neutrality objectives set to meet by the same year. EU has set the targets and changed related legislations and more of similar actions from the local governments are necessary. Governments and local authorities through political leadership must determine clear incentives and clarified grid targets. (*Grids Package*, n.d.-b; *What Is Stalling Europe's Transition to Renewable Electricity?*, 16:30:22 +02:00a)

Less bureaucracy and faster permitting enhance the implementation of projects. According to ENTSO-E more than 50 % of the projects which are expected and required to be done by 2030 are still waiting on accepted permits. Both ENSTO-E and the Commission's Grids Package suggest a plan to provide simplification and clarification of the dedicated legislation to all decision-making stakeholders of the grid. The relevant rules should be harmonized between all Member States to avoid overlaps with the existing frameworks and to reduce additional complexity. With shorten ruling deadlines to accelerate the permitting process, especially PMIs and PCIs should be prioritized. (*European Grids - European Commission*, n.d.-b; *Grids Package*, n.d.-b)

Another significant note is the attention towards energy and electricity infrastructure planning. The new truly European perspective of unified Energy Union aims to bring out full potential from the existing infrastructure, while developing the grids across Europe. The European perspective indicates the manufacturers and other stakeholders to prioritize the local markets over their global competitive position, due to limited capacity and project delays. The term Energy Union refers to the final product of market and grid unification development. Energy Union is the goal state where the Commission and all Member States work together to meet and go beyond the climate goals in the future. The Commission publishes a yearly report about the state of the Energy Union creation, the newest one published on 6th of November 2025. The yearly report published since

2015, monitors the progress of the key priorities and tracks that the Energy Union Strategy will be achieved someday. Currently, the emphasis is on meeting the climate goals set for 2030, before the focus moves on the larger objectives to be met by 2050. The 10th edition of the Energy Union Strategy being the latest one has a clear statement. There is a lot of progress made, but all the actions are required to accelerate to meet the ambitious but crucial goals by the set timeframe. The Energy Union report observes the European Union as one author but recognises the differences between Member States. Truly European Energy Union is connected, unified and independent. The suggested vision is that Member States realise they depend on each other when delivering secure and clean energy to all. With true solidarity, trust and support the Energy Union ideally speaks with one voice in the global context. (*10th Report on the State of the Energy Union - Energy - European Commission*, n.d.; *Energy Union - European Commission*, n.d.; REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS State of the Energy Union Report 2025 (Pursuant to Regulation (EU)2018/1999 on the Governance of the Energy Union and Climate Action), 2025)

The Energy Union Strategy naturally promotes sharing the funding principles and project costs. Bundling and sharing costs, as well as the bureaucracy between all associated Member States and stakeholders, accelerates the final implementation of the projects. The Grid Package also mentions the aim to create more fairness and benefits among all participants, while speeding up the processes overall. The cross-border projects create benefits for much larger region than the one they are built on. The Member States are required to open their perspective and be more generous and ambitious with cross-border project funding, permitting and implementing. The Energy union is here to strengthen the European Union’s ties with the Member States across the continent. As many projects concern only neighbouring countries, the climate objectives still bind us all. (*10th Report on the State of the Energy Union - Energy - European Commission*, n.d.; *Energy Union - European Commission*, n.d.; REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL

COMMITTEE AND THE COMMITTEE OF THE REGIONS State of the Energy Union Report 2025 (Pursuant to Regulation (EU)2018/1999 on the Governance of the Energy Union and Climate Action), 2025)

The level of interconnectivity between Member States has not reached the level where an Energy Union could be created. The goal was to have 15 % interconnectivity by 2030, which means that each Member State should have cross-border connections with neighbouring countries so that 15 % of the electricity generated would allow to be imported. By 2025 only 14 countries had met the goal, and five countries were above 10 % of the target, which was the original one set to achieve by 2020. There are still eight countries below current and previous targets. If the interconnection projects are finished on time, the increased connectivity is expected to further assist the carbon neutrality objectives set to be met by 2050. (*Electricity Interconnection Targets*, n.d.-b)

Noticeably, European Union and Commission hold together a large palette of different overlapping projects, plans and policies on improving the energy and electricity sector. The updated development of the grid connections comes up in almost every plan and project, together with the digitalization and affordability of electricity, without ruling out the driving force of climate neutrality objectives. The strategies and policies are designed to defend and complete each other in the big picture. The wide-ranging palette creates an accessible environment for new advancements within all sectors inside the framework. This type of regulative but also innovative framework is also the enabler and inspiration for the multi-layer control strategy of combining smart and super grid operations across EU area. The framework processes are still evolving, but all acts are paving the way to the creation of the European SSG.

2.2 Multi-layer Structure Management

The fluctuating and intermittent nature of renewable energy has created a challenge for the grid. During recent years two solutions have risen to solve or improve the performance, since the accelerated increase in renewable energy generation. Super grid and smart grid strategies are viable solutions to improve the efficiency and effectiveness of the renewable energy utilization further in the future. Smart grid has been identified as a local strategy and super grid more of a cross-system with larger continental coverage and increased interconnections. These concepts can be seen as separate systems or as complementary grid actions. In this thesis research, the strategies are seen as supportive of each other, operating in coordination, rather than in isolation. However, this section of the study thoroughly examines the concepts from different perspectives, to gain a profound understanding. Generally, the need for a framework which covers and merges the two concepts is essential. (Zahid et al., 2025)

2.2.1 Super Grid

Traditional grid infrastructure has not been keeping up with the evolvement of the power sector and accelerated electrification of the modern economy. The term super grid implies to a wide-area electricity network which covers multinational areas or even continents. The key to a super grid is to increase connectivity by expanding and conjoining transmission grids cross-borders. New technologies and innovations are in the core of a successful and viable implementation of this sort of grid infrastructure. The leading technology currently being High Voltage Direct Current (HVDC). Ideally, a super grid enables the movement of large amounts of electricity across large geographical areas and long distances. This also connects remote renewable energy generation areas to the populated and occupied areas with high demand. (Adnan et al., 2024; Blarke & Jenkins, 2013; Zahid et al., 2025)

Increased connectivity naturally also increases the safety and security of supply by providing more possibilities for the supply and demand to meet even with unexpected hazardous events or simply with changing weather conditions. In the European context, a super grid enhances the unification of the European electricity market and connects already existing transmission networks. The planned continent-wide grid operates as the backbone of the regional and national grids. This decreases dependency on fossil fuel and imported energy, while increasing security, diversity of supply sources and integration of renewable energy overall. This should lead to more affordable and reliable electricity across the continent. (Zahid et al., 2025)

There are studies both against and with super grid approaches worldwide. An almost utopian idea is to create a grid which would expand across the globe. The benefits of this have been studies, but however, the problems are more political than financial or technological. A more rational idea is to connect the European grid with China or other parts of Eastern Asia with HVDC lines. (Kristina Hojckova et al., 2022)

A continent-wide super grid in Europe would enable the utilization of renewable energy to its full potential. Due to the increased connectivity, the large solar power plants in southern Europe could provide large amounts of electricity during the day and the offshore wind power plants in the North Sea could generate electricity during the nighttime or when the sun is not shining, for example. The produced power could then be transported where needed inside the continental grid with the HVDC cables. This is how the super grid actions address the fluctuations and intermittency of renewable energy, while enhancing the diversity of energy sources. With HVDC the generated electricity can be transmitted for long distances without excessive losses. Essentially, a super grid supports the idea of distributed energy generation and takes it a step further with large-scale approach. (Adnan et al., 2024; Zahid et al., 2025)

As the fundamental part of the system, the lines and cables are required to accommodate all the changing patterns of generation, consumption and transportation. Unavoidably, the network is required to expand relatively rapidly. Reflecting on the European Green Deal objectives of 2050, the grid is estimated to expand with 500 000 kilometres of transmission lines and 3 000 000 kilometres of distribution lines by the same year in the Union area. According to the Clean Energy Technology Observatory (CETO), an additional 7 000 000 kilometres of existing mainly distribution lines are to be replaced by 2050. (*Smart Grids in the European Union*, 2024)

Most of the existing and operational electricity lines globally are AC lines. The popularity of AC lines is explained by the relatively low losses and simple voltage transformation. Historically, AC lines have been more affordable and accessible, due to most power plants generating electricity naturally as AC, so there has not been a need for expensive converters. Therefore, the existing infrastructure and industries are build based on AC. However, as mentioned, the increasing amounts of inverter-based electricity generation, like solar or wind power, the popularity of DC technology is increasing, especially solutions such as HVDC. However, even if HVDC is gaining interest and investments, new AC lines are still required, due to the existing structure of the grid. (*Electricity Grids in the European Union*, 2025; *Smart Grids in the European Union*, 2024)

HVDC system transports electricity by using direct current (DC) instead of more conventional alternating current (AC), with high voltages. This type of system performs exceptionally well with longer distances, due to lower reactive power transmission losses and increased capacity. HVDC enables wider connectivity by connecting distant power networks with different frequencies or stability conditions, as well as connecting offshore wind plants for example. HVDC method is also ideal for underwater cable connections, which makes the overall performance suitable for high demand and large coverage power systems like the European SSG. Several areas in Europe or in EU are already synchronised, but in order to connect all the areas to each other, HVDC can be a key method. As the plan is to transmit electricity by direct current, the system requires HVDC semiconductor devices which convert the generated AC to DC for transmission and then back to AC. (*Electricity Grids in the European Union*, 2025; Neubauer et al., 2025; Zhou et al., 2026)

The materials and substations built for HVDC system cover most of the required costs. However, when comparing the transmission costs by length between AC and DC lines, the compensation of the relatively high costs of HVDC are inevitable for longer distances. With shorter distances, transporting electricity with AC lines is more affordable, since there is no need for substations in each end of the line. A study included in the CETO report Electricity Grids in the European Union from 2025 showed that DC lines are more cost-effective with distances over 300 miles or 482,8 kilometres, but the best efficiency is achieved at over 2000 miles or 3128,7 kilometres. The overall performance of HVDC lines are from hundreds of kilometres to few thousands for distances and with power transmission from hundreds of megawatts to a few gigawatt. (*Electricity Grids in the European Union*, 2025; *Smart Grids in the European Union*, 2023; *Smart Grids in the European Union*, 2024; Neubauer et al., 2025)

DC cables are mainly made of the same materials as more traditional AC lines. Since HVDC cables are meant for long distances, they are required to be viable in underground and undersea conditions as well. Underground cables are mostly made of copper and insulation, as the overhead lines require mainly just steel and aluminium. HVDC lines and cables require less physical material compared to the three-phase AC lines and with the higher voltage level the same amount of material reaches higher transmission capacity. The overall cost of materials has been increasing, but when compared to the total cost of the demanded grid infrastructure update the investment in efficient and mature technologies such as HVDC are worth the costs and will pay themselves back eventually. (*Electricity Grids in the European Union*, 2025; *Smart Grids in the European Union*, 2023; Neubauer et al., 2025)

One major risk for new large-scale innovations is the long lead times. Supply levels for different grid infrastructure projects have increased, which naturally increases the lead times of components manufactured. More uniform and simple implementation of the project run-throughs for the Member States with the EU tendering laws could accelerate the process. However, according to stakeholders and operational parties in the EU job market, the lack of or incompetent workforce are not risks to tackle. (*Electricity Grids in the European Union*, 2025; Neubauer et al., 2025)

Overall, the European super grid is evolving and forming strongly in the future. Large-scale connectivity enables market coupling and engages the EU Member States to each other, eventually creating the unified Energy Union. Thus, the power systems work as one, not as a patchwork of several national grids. This not only promotes reliability and resilience, but also solidarity. The cross-border connections allow the Member States to support each other during different crises. This became extremely visible and important during the recent power supply disruptions.

2.2.2 Smart Grid

Intelligent and smart applications have already been growing popularity with the accelerated technological development in the 21st century. The mature innovations have been spreading across sectors reaching applicability in the electricity grid operations as well. By modern day definition, a smart grid is an information-based bi-directional electricity network which minimizes the costs and environmental impact and maximizes system reliability, resilience and flexibility. The aim is to utilise digital and intelligent technologies to automate, optimize, control and monitor the electricity system between generation, transmission, distribution and end-users bi-directionally. Based on the information collected and the bi-directional operations, the supply and varying demand are meeting effectively and efficiently, while the grid stays stable. (Rodriguez-Perez et al., 2024; *Smart Grids*, n.d.)

Generally, a smart grid links together all grid stakeholders with the use of automation and modern communication technologies to always function as a coordinated system. A real-time monitoring enables quick and effective demand responses with load management. A smart grid is ideally a self-recovering system, which can automatically detect faults and hazardous activities and make the necessary actions to recover without further harm. All this is based on the two-way or bi-directional communication and transportation of power. Therefore, smart technologies fundamentally transform both power distribution and transmission. Grid updates are required to improve efficiency, economy, safety and security. A smart grid gives power generators and users the ability to control the flow of electricity for both ways and therefore to optimize the supply, demand and consumption. The control and communication can be implemented with different devices, sensors and computers. (Blarke & Jenkins, 2013; *Smart Grids*, n.d.)

As a term smart grid does not necessarily illustrate only one solution, but rather multiple applications and approaches with smart characteristics. In conventional sense, smart grid functions resemble and project distributed energy resources or DERs in many ways. However, depending on the context, these solutions can rather be seen as supportive of each other and working in unity to increase efficiency and achieve better results. In the context of European plans and actions towards climate neutrality, smart grid indicates a network of somewhat individual automative and intelligent local solutions, which together enable smart controlling of the grid actions all over the Union area. Smart grid functions, like communication, automation, optimization and self-recovery are to be utilized also as a part of the large-scale power network, so the term does not apply only to small DERs in the context of this thesis, even though DERs play a rather significant role in the future development of the grid. (Blarke & Jenkins, 2013)

Under the European Commission as an in-house project operates the Clean Energy Technology Observatory (CETO), which monitors sustainable, clean and innovative research activities of the EU energy technologies, value chains and markets. CETO targets both mature and emerging technologies with particularly innovative solutions. A series of annual reports concerning the chosen themes published includes a status report about smart grids in Europe. CETO is a common initiative between the European Commission and the Joint Research Centre, which publishes the annual research status reports. CETO was founded by the European Commission in 2022 to tackle the complexity of transition to a climate-neutral Europe. As a part of the CETO annual exercise project, smart or advanced metering infrastructure has become one of the key subjects. There are several acknowledged factors and regulative level drivers behind the support of the updating conventional meters. Smart metering is the main solution to create a smart grid. Smart meters are in the core of EU’s plans on unifying electricity market and network. (*Clean*

Energy Technology Observatory - SETIS - SET Plan Information System, n.d.; *Smart Grids in the European Union*, 2023; *Smart Grids in the European Union*, 2024)

Smart meters have been emerging as important tools to the global digitalisation. Smart meters track the real-time movement of electricity in the grid, what is fed into and consumed from. The smart metering infrastructure indicates that smart meters are used in all parts of the electricity network. The real-time monitoring and tracking of the distribution system enables better visibility and mitigates outages and decreases the reaction time to such hazardous events. Ideally, all electricity end-users are monitoring the electricity prices, and their own consumption and reactions are made accordingly based on the data. This applies to the power generators and all stakeholders as well. With real-time visibility to all actions in the grid, real-time reactions are enabled, and certain changes can be made accordingly as a response to that. With the overall live insight on consumption behaviour, both consumers and generators can moderate their own actions and habits to save not only capital but also energy and resources. (Al Khafaf et al., 2026; *Smart Grids in the European Union*, 2023)

This enhances a greater balance between supply and demand. Data and automation are the key components, as with a larger understanding of all the occurring habits and behaviours can gain new perspective. Smart metering is revolutionizing the historical roles of conventional electricity networks, by blurring the lines between producers and consumers. Smart metering endorses DERs to be a stable piece of the energy and electricity sector together with the overall distribution of the resources while connecting the whole system through communication and automation. In many cases the smart solutions feed the complete system and enable or accelerate future development within several linked parties or functions. The knowledge and insight on each one of the activities in the grid is allowing the network operators to better plan and focus their investments and resources where needed the most. The better management of the infrastructure reduces the operational and maintenance costs. The digitalisation also enables better connection between the TSOs and DSOs. In 2020 there were over 100 million smart meters installed. (Al Khafaf et al., 2026; *Smart Grids in the European Union*, 2023)

The normalisation of smart meters creates room for new innovations such as the development of smart appliances, which are then able to communicate with the electricity meters on their own and adjust accordingly. These possibilities create even more new market openings and increase competitiveness. Only relying on the availability of information is insufficient. The true efficiency of the smart grid system comes from the data utilisation. This is where data analytic and artificial intelligence programmes come to the picture. With the smart characteristics of these functions, all the communication, monitoring and related acts can be done automatically, within the rules set. Integrated artificial intelligent can recognize patterns and learn to react with different occasions. Without the use of AI, the electricity end-users can control the functions manually. In concrete, this is extremely helpful especially with peak hours, when electricity consumption is suddenly higher than expected, or there is a lack of supply for some reason, and in other words – demand and supply are not coherent. The training of AI to do the required controls automatically will enhance efficiency and effectiveness to the full potential. (Al Khafaf et al., 2026)

To create a full infrastructure, there are several Union and national level initiatives on changing the meters into smart ones. EU level regulations and policies are to be requested, since the smart applications support and ease the larger integration of renewable energy due to the automatic reactiveness to the fluctuations of renewable sources as mentioned. The smart meters are required to be equipped with functionalities ruled in the Electricity Directive EU/2019/944. In addition, national authorities need to make sure that the deployment of new meters is done so that the update serves the whole system but also individual consumers and businesses. This requires effective and systematic installation and commissioning. According to the European Union Agency for the Cooperation of Energy Regulators (ACER), in 2021 already 54 % of European households had a smart electricity meter. In 13 EU countries the percentage of smart meter deployment was over 80 % in 2022. Back in 2019 the Commission published a report which studied the benchmarks the smart meter deployment in all 28 Member States at the time. According to the published study, the investment in smart meters is estimated to reach 47 billion euros in EU by 2030, which indicates over 260 million installed smart meters. The cost of a single smart meter installation is between 180 € and 200 €. (Directive (EU) 2019/944, 2019; *Smart Grids and Meters*, n.d.)

Overall, the electricity distribution is regulated by National Regulatory Authority or NRA in Europe. NRA is making sure that each EU Member State is on track with their energy targets. ACER is supporting NRA to supervise the correct performance of all regulatory policies and coordination of the contributions. NRA also rules the penalties and incentives of the DSOs, and now they are also supervising and evaluating the Member States development projects towards smarter grids, together with the integration of renewable energy objective achievements. NRA is therefore ruling the smart meter change in EU. (*National Regulatory Authorities (NRAs) | Www.Acer.Europa.Eu*, n.d.; Rodriguez-Perez et al., 2024)

Accelerating the meter change, EU electricity market made the change from hourly to 15-minute or quarterly trading intervals. Electricity prices are then calculated every 15 minutes hence the growing share of alternating renewable energy. The quarter interval enables more accurate predictions of demand and supply with increasing system's reliability and flexibility. This also benefits consumers, who are now paying more precisely on their actual consumption every 15 minutes. In concrete, the change has meant that all electricity meters were to be swapped into ones which could handle the 15-minute measurement and pricing. The target is to have all meters changed by 2028. All Member States and market areas are gradually moving to the 15-minute interval model. The move was planned to be done in two stages. In the first stage, the imbalance settlement was adapted to the 15-minute interval model and the deadline for this was set to the end of 2020. However, for example the Nordic transmission system operators applied extension to the transition, and the final deployment of the new interval service was made on 22nd of May 2023. The second stage was to change the electricity spot price into 15-minute intervals, which was when the Union's day-ahead electricity market made the change on 30th of October 2025. (Directive (EU) 2019/944, 2019; *EU Electricity Trading in the Day-Ahead Markets Becomes More Dynamic - European Commission*, n.d.-b; *Smart Grids in the European Union*, 2023)

The aim with the new trajectory is to harmonize the market and network in EU, and the standardization of the 15-minute interval electricity market is a great act towards those aims. Together with the meter changes and renewable energy integration, new desperately required investments are on their way. A large amount of the REPowerEU and EU Climate Law investments are targeted to the distribution grid updates, especially to digital solutions. Smart grids and therefore smart metering have been named as one of the priority thematic areas of the TEN-E, with the aim to enhance the integration of renewable energy. Smart Grid Regional Group evaluates all smart grid projects under the TEN-E Regulations. (*EU Electricity Trading in the Day-Ahead Markets Becomes More Dynamic - European Commission*, n.d.-b; *REPowerEU*, 2022; *Trans-European Networks for Energy*, n.d.-b)

2.2.3 Distributed Energy Resources and Decentralisation

Traditionally, electricity has been produced in large facilities far from populated areas. The idea of consumers becoming prosumers, which indicates that they can produce their own electricity and even store it, has been gaining popularity in the past decades. The amount of consumer-scale solar panel installations went through a final increase in Europe since the rise of electricity prices due to the Russian invasion of Ukraine in 2022. The distribution of electricity production across the stakeholders in the network supports the climate neutrality aims but also brings out challenges. Similarly, as smart and super grid innovations, DERs challenge the way to produce, trade, transport and consume electricity. (*Executive Summary – Unlocking the Potential of Distributed Energy Resources – Analysis*, n.d.; *Russia's War on Ukraine – Topics*, n.d.)

DER is initially an umbrella term, which combines distributed generation, storage, electric vehicles (EV), demand response and combined heat and power. The key idea is to spread and connect generation, storage and flexible loads. Ideally, DERs increase flexibility and efficiency, since conventionally power is best to be used where and when generated. However, this does not strictly apply to super grid and HVDC type of applications, which are specifically meant to transport electricity for long distances. To maximize the climate neutrality potential, several innovations and approaches are required, and DERs are a relatively mature and easily adaptable solution, which creates new opportunities to expand the concept concretely to the grid. DER is a great concept already in use, which is meant to be a supplement for the conventional power operations. For example, DERs can be combined with smart grid applications such as smart metering and automation. This enables all generated electricity to be either used, stored or sold to the general grid, so no electricity would go to waste due to the bi-directional lines. The digital management could also enable DERs to contribute to balancing, capacity services and ancillary services. With digital visibility to all operations and opening of the markets, the DERs could possibly help adjust electricity prices and mitigate frequency fluctuations in extreme situations. (Adnan et al., 2024; *Executive Summary – Unlocking the Potential of Distributed Energy Resources – Analysis*, n.d.)

According to the International Energy Agency (IEA), the electricity market and grid infrastructure regulation and design require a transformation, in order to gain full potential from the DERs in the big picture. There has been constant disparity between interests of DER owners and grid operators, due to the inadequate consumer incentives, which has formed to be the restrictive factor in the way of beneficial collaborative operations. (*Executive Summary – Unlocking the Potential of Distributed Energy Resources – Analysis*, n.d.)

The contribution of DERs is to be valued thoroughly and regulations modified so that the services required are integrated into the grid system and electricity market. Policy makers and regulators are required to develop a new market model with established updated rules, roles and responsibilities, which can better accumulate innovative and emerging solutions and resources. The future market and grid designs are to be transformed to be open to small-scale participants to serve and allow the bi-directional movement of electricity between stakeholders. Increased connectivity and open markets enhance competition, system efficiency and resilience. (*Executive Summary – Unlocking the Potential of Distributed Energy Resources – Analysis*, n.d.)

DERs include the concept of distributed generation DG, which implies that the generation of electricity is not only based on one or two resources, but rather on several different types of power resources scattered geographically. In some cases, the distribution of power generation between multiple sources comes naturally or out of convenience. A great example of this is Finland, where the generation system is relatively evenly divided between number of resources. The distribution of generation increases security of supply and safety, since the required energy can be obtained from other sources if one is unavailable for some reason. This is the core intention behind all the grid development and connectivity update requirements. A limited and deliberated number of energy sources and overarching interconnections around the continent of Europe will be the key to climate neutrality success. ("Electricity Generation," n.d.; *Executive Summary – Unlocking the Potential of Distributed Energy Resources – Analysis*, n.d.; *Understanding the Value of Distributed Energy Resources*, 2023)

2.2.4 Network Topology

In traditional or conventional power networks the flow of electric energy is unidirectional. Increased amounts of distributed and renewable energy generation together with the power electronic technology development are forcing the change of grid topology. Super smart grid functions introduce the bidirectional flow of electricity to be the standard across networks. Distributed generation and renewable energy generation are added to the distribution network level, which is designed originally to not have any production on it. The complexity of the future power system forces the network topology to evolve. (Nichita et al., 2013; Prakash et al., 2016)

With radial network topology, power flows through a single path from source to each load. The system structure makes power flow outwards like tree branches. The flow is then unidirectional from the single substation through one main feeder to each load point with distribution transformers to customers. There are no closed loops. The radial topology is simple and affordable to design, operate and maintain, and the structure is mainly used in low voltage distribution level applications such as residential areas or rural networks with overhead lines. The tree-branch-structures vulnerability comes from the fact that if any element or component on the path fails, the power flow stops to that point. Since there is no looped structure or alternative route, the downstream customers lose all supply. However, this is also one of the advantages of the radial network, since the failure on one path will not have any impact on the wider system. (Nichita et al., 2013; Prakash et al., 2016)

The real issue is that radial network topology is planned specifically for passive loads, which has made it a popular choice as a distribution network design globally, since it was also originally planned to operate without any power generation on it. The introduction and inclusion of distributed generation do not serve the purpose of either one. Especially, the fluctuating and intermittent renewable energy generation disrupts the simple radial flow of power and causes voltage instability and various protection coordination issues. This accelerates the reconfiguration of the distribution networks, so that the increased integration of renewable energy is accommodated accordingly. (Nichita et al., 2013)

Ring, round or loop network topology serves the renewable energy generation and addition of DGs in general much better compared to the radial structure. With the ring topology, there are two or more feeders delivering power to the load points. The feeders are connected to each other forming a loop. This is a hybrid between the radial and meshed topology. The ring structure provides two paths for the power flow from substation to each load branch, increasing the reliability of the system in case of a failure, since there is always an alternative route for the power flow. The ring system requires higher investments compared to the radial one, but the reliability of the operation and supply continuity is also much higher. The power and voltage losses are also relatively smaller. As the system is more complex than the radial tree-like-structure, the maintenance is more expensive and arduous. (Ahmad et al., 2018; Prakash et al., 2016)

An interconnected or a meshed network topology has several connected paths between sources and loads. Several loops operate simultaneously and power flows to multiple directions. The structure is similar to the ring topology, but with redundant lines with various alternative routes as organized backups in the case of a failure. This configuration is the most complex, which makes the operation and protection of the system challenging. Generally, a meshed network is configured based on the already existing grid, so the structure is greatly adaptable, since there is no installing of a totally new network. (Nichita et al., 2013)

Network's structure and architecture have major impact on the quality of power, reliability and overall stability of the system. When creating an SSG, it is crucial to understand and consider the performance, benefits, disadvantages and applications of each network topology. Power networks in the future are evolving towards the meshed topology, since the great adaptability, reliability and receptiveness for distributed renewable energy generation. However, transmission and distribution networks serve different roles, and they have evolved with different priorities in the past. (Espejo et al., 2018; Nichita et al., 2013; Yue et al., 2020)

Transmission network transports large amounts of high voltage power over long distances from power plants to distribution networks. The transmission network's interconnections go beyond different regions, countries and synchronous areas, which makes the cross-border electricity trading possible. This means that any failure or instability can possibly result in huge impact across various areas or countries. Therefore, the meshed topology has been utilized on the transmission level. Transmission networks are required to meet N-1 security, which indicates that the loss of any single element will not interrupt the system. There must always be an alternative route or path for the power flow. (Espejo et al., 2018; Nichita et al., 2013)

Distribution networks have traditionally been radial, since the original design is to deliver electricity locally. Therefore, the failures have also been local without necessarily impacting other parts of the system. The radial structure has been efficient and affordable in the past. Due to accelerated electrification and urbanization, the ring structure became more convenient for distribution networks to adapt to. Ring and meshed structures are always created on top of the radial one. As mentioned previously, the distribution network is facing challenges with the integration of distributed and renewable energy generation. (Nichita et al., 2013; Prakash et al., 2016)

Inevitably, the transmission and distribution network topologies are functionally becoming more unified in the future. Distribution networks are becoming more flexible by enabling bidirectional power flow together with active control and monitoring practices. The network is not passive anymore and communication between distribution and transmission levels is crucial and inevitable when reaching to achieve EU’s climate goals. Exchanging data increases knowledge and stability and reliability of both networks. One of the major changes is the unified control philosophy for both transmission and distribution level operations.

2.2.5 Cooperative Control and Coordination Between TSO and DSO

The European Network of Transmission System Operators for Electricity (ENTSO-E) links together 40 transmission system operators from 36 European countries to create the world's largest interconnected grid with secure and coordinated operations. ENTSO-E was created with a legal mandate under the EU Law to support and provide technical and strategical contribution towards the common climate neutrality objectives. ENTSO-E’s mission is to guard the European electricity system by bringing together the expertise of all TSOs and DSOs to ensure a secure, safe, sustainable and affordable electricity system now and in the future. The association connects and mandates authorities and grid operators across and beyond EU. (*Mission Statement*, n.d.)

ENTSO-E also delivers important outlooks of the pan-European electricity systems and networks. The deliver outlooks are short, mid or long-term investigations. The most valuable of the outlooks currently is the long-term one, TYNDP or the Ten-Year Network Development Plan. TYNDP is the base for all European electricity network infrastructure development plans. The plan is revised biannually, the latest revision done in 2024. TYNDP investigates and studies what the electricity system needs in 2030 and 2040. By connecting and complementing national grid development plans, the TYNDP provides European-wide view of how the electricity system is required to evolve. It examines how the cross-border interconnections and transmission together with storage solutions can support the energy transition in a secure and cost-efficient manner. According to ENTSO-E, every euro invested into the grid development projects will translate into more than two euros saved in system costs. The 2024 TYNDP has the same key findings mentioned in several factual connections – the existing network infrastructure projects are not enough. More investments, effort and actions are crucially needed to enable the project implementation in the set timeframe. (ENTOG, 2024; *Power Outlooks*, n.d.; *TYNDP 2024*, n.d.)

To optimize the controlling of the total electricity system and to enable the energy transition, a close cooperation between the TSOs and DSOs is highly valued. ENTSO-E together with the new EU DSO Entity aim to enhance this collaboration. DSO Entity is an association for distribution level system operators around Europe. Established in 2021 the DSO Entity connects and supports DSOs like what ENTSO-E does with TSOs. The legally mandated by the EU Electricity Market Regulation 2019/943, the association aims to attract more investments and interested towards DSO level development plans and projects. The 2022 revision of the TEN-E Regulations acknowledges the increased relevance of DSO level actions such as the smart grids. Previously, several reports and regulations regarding the grid development and energy transition have focused on TSO level implementations. Now the EU DSO Entity is also included in the biannual updates of the TYNDP. (*DSO Entity – Pillar of Europe's Energy Transition*, n.d.; Regulation (EU) 2019/943, 2019; *TSO/DSO Cooperation*, n.d.)

The increasing integration of distributed energy resources (DERs) is significantly changing the network system dynamics. Technical and operational issues can occur more often within both networks. Conflicting control actions, lack of visibility and observability, unsafe utilization of flexibility and inefficient congestion management cause disruption between transmission and distribution systems. Generally, the distribution and transmission system operators are responsible for their own networks, however, the comprehensive charge of the overall system security has been on TSOs. Since many of the DERSs are connected to distribution networks, a new type of interdependency is required, which in the best case of scenario can solve the imbalance between system and local level needs and constraints in a distributed energy resource dominated network. Coordinated cooperation can even enhance the most common grid operation challenges such as congestion and voltage and frequency control. (Gerard et al., 2018; Yoon et al., 2024)

Before the energy transition, the cooperation between DSOs and TSOs has not been seen as a primary solution for mentioned issues, since DSOs have generally not had the ability to engage in any flexibility actions. In many cases TSOs operate directly with the distributed renewable energy generators by providing ancillary services to maintain the system stability. TSOs activate and procure flexibility services from resources connected to the distribution network, without technical validation from the DSOs. This creates a systemic coordination gap. Sharing the responsibilities, actions and production of ancillary services is the next step, since DSOs are no longer passive network operators. By allowing the DSOs to acquire flexibility, they can actively influence the power flows inside their own network. This way the DSOs are able to contract, activate and procure changes in generation or consumption from connected energy generation resources. The technical validation of the connected resources is then done on the distribution level. By accessing overall wider range of flexibility and potential flexibility services, the technical and operational issues can be tackled. With collaborative communication, the unpredictable and possibly conflicting flexibility activities and the consequences are to be minimized. (Gerard et al., 2018; Yoon et al., 2024)

Better grid visibility and observability support the previous statement about cooperation and communication benefits. Even if DSOs are to be more in charge of their own network services in the future, the visibility over transmission systems and their operational actions have been very limited or non-existent. To efficiently and successfully cooperate, DSOs and TSOs are expected to have improved level of visibility and observability over other's networks, since some actions and decisions done by either of the system operators can have an impact on the other. The need for better visibility and observability is linked to the need for improved data exchange between the networks. The existing exchange of information is expected to intensify with the interoperability practices and additional standardization. DSOs and TSOs produce and require different types of data, and the defined roles should be based on that, so that data with higher quality and minimized delays can be shared effectively. A stronger engagement of general standards enhances the system operators to adopt a more systematic approach for the communication and data exchange between them. The related regulatory framework has been included in different international and EU level publications, such as the Electricity Network Codes and International Electrotechnical Commission (IEC) Common Information model (CIM) standards. (*Common Information Model*, n.d.; Gerard et al., 2018; Yoon et al., 2024)

Congestion management, frequency response and voltage control are concrete grid related issues which are expected to increasingly occur with the large-scale DERS integration. Conventional energy management methods have been identified to be somewhat incompetent. As the flexibility, communication and visibility are brought to the next level, the accompanying actions help to work out the existing but now highlighted issues. DSOs and TSOs handle congestion differently. DSOs with DERSs are battling with general line congestion, frequency problems and uncertainty of the power generation. High penetration of fluctuating renewable energy sources together with accelerated electrification seen as the increase in EVs and heat pumps, cause local clustering inside the distribution networks. Besides the renewable energy generation fluctuations, in transmission networks, congestion is caused by lack of transmission capacity, large power transports across wide areas and market-driven activities not being aligned with physical capabilities. (Attar et al., 2024; Gerard et al., 2018; Yoon et al., 2024)

Congestion management is a real-time operational necessity, which can’t be completely avoided with planning. If congestion is not managed appropriately, it can cause voltage violations, protection outages and equipment damages. Traditionally, congestion has been managed through grid reinforcement, by updating components or adding lines to the system. These actions are expensive and time-consuming. There are new innovative and more flexible ways to handle congestion in the future networks, such as market-based solutions. (Esmaeel Nezhad et al., 2025; Yoon et al., 2024)

As an additional ancillary service, congestion management can be implemented through a marketplace. For example, in Finland, the national transmission system operator Fingrid has launched a congestion management market, which is a joined marketplace for both transmission and distribution networks. Fingrid and Helsinki region distribution system operator Helen Electricity Network both utilize the marketplace offers as primary method for congestion management. Currently the marketplace is an experiment between the Finnish TSO and one DSO, but the results and things learned will act as the base for creating a national congestion management market in the future. The experiment is going on until December 2027. Market-based congestion management solutions have more allowance for customization, since they are based on flexibility. (Esmaeel Nezhad et al., 2025; *TSO-DSO Congestion Management Market*, 2025)

To successfully solve the identified challenges and issues, the interactions between TSOs and DSOs is required to intensify in a more standardized and structured manner. While TSOs and DSOs are expected to collaboratively create a set of common European level standard actions and principles to enhance coordination, a certain degree of flexibility and freedom must be preserved to allow individual system operators to adapt the principles to their national circumstances and specific needs. Not all information, activities and practices are to be shared but rather expand the conventional roles of the system operators to be more responsive and resilient. The key is to breakdown the previous control hierarchy and distribute the responsibilities accordingly.

2.2.6 Control Structures

Existing control structures designed for grid purposes are quite conventional, for the complexity of an SSG. The most common one being the hierarchical structure, with primary, secondary and tertiary control levels. This model is the dominant one around the world. The control is centralised around TSOs and synchronous power generation. The hierarchy indicates that decisions are made from top to down. This control system is relatively simple and works well with predictable and synchronous systems. (Suehiro & Namerikawal, 2014)

As mentioned, traditionally in energy networks, the power of control has been divided so that the upper levels have the most responsibilities and concentrated authoritarian power, which then drains downwards. This uneven deviation creates the hierarchical structure of the system. This type of control structure is most suitable for a system with straightforward objectives and operational boundaries. Structures like this are most effective when the system aims stay stable, as each level executes their defined functions with a limited scope. Usually, this also indicates that the interactions between the levels and stakeholders are limited. A diagram of the hierarchical structure is presented in Figure 5 below. The structure and its limitations are too rigid for the flexibility requirements of the SSG. (Ai et al., 2018; Kouveliotis - Lysikatos et al., 2020)

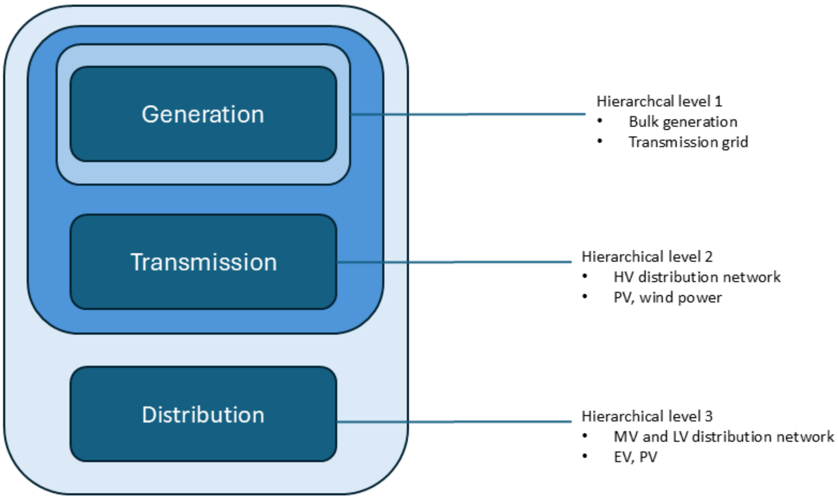

Figure 5 Hierarchical power system control, adapted from Ai et al., 2018; Kouveliotis – Lysikatos et al., 2020.

One of the standardised architecture models, which does not take accountability about the final control hierarchy, is the smart grid architecture model (SGAM). The basic idea of SGAM is that all the related activities are divided into five interoperability layers, which are further separated into domains and zones, according to the hierarchy of the power system. SGAM layers are presented in Figure 6 below. SGAM supports the architectural design approach of the future implementation of the grid, and it is generally utilised to assess smart grid use cases in a technologically neutral way. The three-dimensional model supports system planning and is generally used to outline new smart grid related solutions. (CEN-CENELEC-ETSI, 2012)

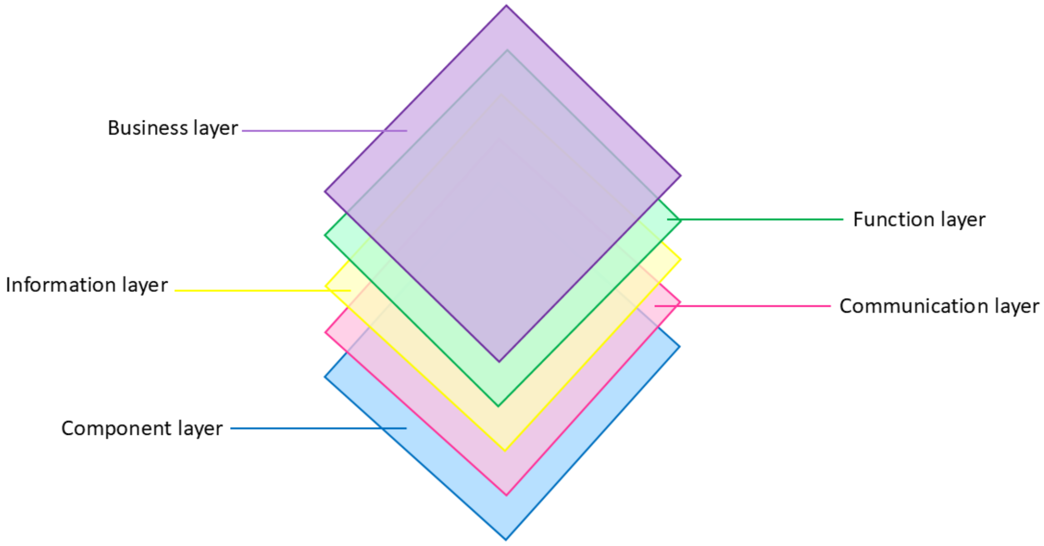

Figure 6 SGAM layers, adapted from Panda & Das 2021.

The cube-like-structure enhances the systematic modelling of the interoperability of all components and stakeholders. The model is designed especially for large and intentionally increasing integration of renewable energy sources. SGAM has great potential and flexibility through the interoperability characteristics, enhancing greater communication, data exchange and parallel development across layers. The different domains and zones address and present relevant smart grid stakeholders and their hierarchy, as seen in Figure 7. (CEN-CENELEC-ETSI, 2012; Panda & Das, 2021a)

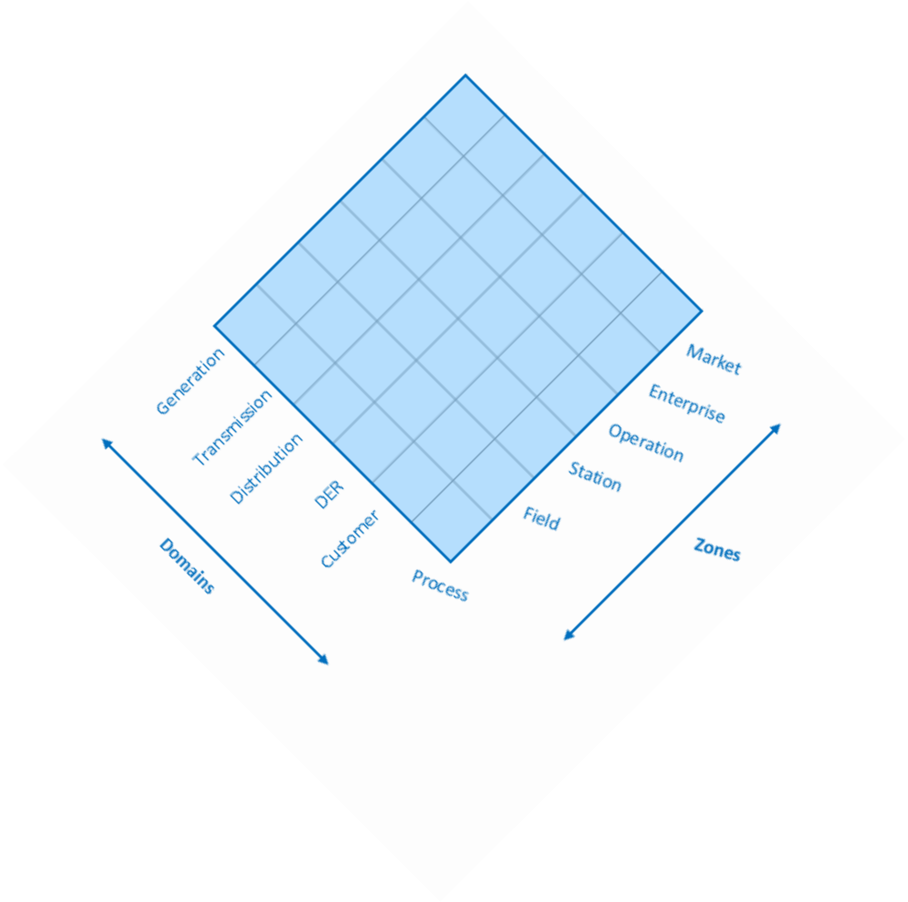

Figure 7 SGAM domains and zones, adapted from Panda & Das 2021.

Multiple previous studies have identified SGAM as the most viable conceptual models, due to the visualisation and clarity created for further analysis, modelling and design. SGAM was created by several European institutions including European Committee of Standardisation (CEN), European Committee of Electrotechnical Standardisation (CENELEC) and European Telecommunication Standards Institute (ETSI). The creation was a response to the European Commission's standardisation mandate M/490 and was done in cooperation with the smart grid coordination group. (Albano et al., 2015; Panda & Das, 2021a)

Similar standardised architecture model is the smart grid conceptual model by the National Institute of Standards and Technology (NIST) from the United States. This model only acts as the reference framework for the future development of smart properties of the grid. It includes relatively strong standardisation and regulation orientation but lacks on with the formal structure and control practices. There are also other architecture models specifically for smart grid applications, but the methods and approaches vary drastically. Through the strong belief and foundation of standardisation, the smart grid conceptual model by NIST is the closest to SGAM. (Albano et al., 2015; Panda & Das, 2021b)

As mentioned, SGAM itself does not take note on the concrete control structure of the power system. However, it has potential and space to adapt the control levels and elements, as the conceptual model gives a clarified and solid foundation to serve all the requirements of future power grids. Based on the SGAM, a control structure could be designed, with the addition of super grid elements. (Panda & Das, 2021b)

2.2.7 Super Smart Grid

A super smart grid (SSG) unifies the capabilities of both super and smart grid concepts as an advanced wide-area electricity network with large connectivity. The system sustains the network infrastructure of several interconnected nations with increasing amounts of renewable energy by also decreasing the production of greenhouse gas emissions. Ideally, SSG operates as bi-directional system providing the exchange of data and electricity, through communication and transmission between the sources, demand and supply. Overall, SSG has been a futuristic concept that has been emerging and coming into form slowly during modern times. The intelligent system is self-reliant with modern communication devices and sophisticated control methods. (Zahid et al., 2025)

As SSG is the combination of two relevant grid concepts, there has been discussion about whether the two concepts are complementary or competing. The differences between super and smart grid basics are certainly acknowledged and considered within EUs development plans, but the comparison of the two as separate strategies has not been seen as necessary. A study published by Energy Policy in 2013 compares the two in detail and identifies conflict of interest with technological and socio-economic topics between the two. The study appoints the concepts as mutually exclusive, with proposed independent strategies for each one. The Energy Policy article identifies the differences between a domestic strategy for smart grids and a cross-system strategy for super grids, and how the authorities and grid operators must comprehend that both concepts are to develop and evolve as united and in parallel. (Blarke & Jenkins, 2013)

However, these developments are to happen in different premises with different integration strategies, without the one concept diminishing the other one's feasibility and viability. The main concern of the article is that even though the two concepts operate and benefit from similar market settings, the competition would not be fair. According to the Energy Policy article, the technologies and characteristics of the super grid are already well-established and more mature, which helps them gain institutional development status with accordable investments. Whereas the smart grid operations include more immature technologies and the market is not as welcoming to this type of innovation. (Blarke & Jenkins, 2013)

Another concrete battle of visions started in early 2000s between Eurosolar and Desertec, two organisations who aimed to pursue the same goal of completely renewable sourced electricity in Europe through different actions. Eurosolar's ideology was to decentralise renewable energy generation by distributing solar power production across European cities, communities and households. Whereas Desertec planned to install large-scale solar power generation sites specifically to deserts or other rural areas. At the time, the two organisations also had different views about nuclear power, and they were heavily criticising one another. Since then, the decentralised vision has gained more popularity, although the ideology behind Desertec's objectives is linked to the super grid operational actions, as the renewably produced electricity would have been transported for long distances from the rural areas to consumers. The battle between Eurosolar and Desertec does not fully reflect the conflicts between smart grid and super grid concepts, but the question between decentralised and centralised electricity production approaches. (Lilliestam & Hanger, 2016)

It is noteworthy to acknowledge, that these differentiating approaches are slightly outdated and since then the technological development as taken huge steps forward and the market has evolved to be more innovative, open and even in the lookout for new applications. The differences between technological applications and operation premises, as well as the similar beneficial market settings, can also be identified as the factors which bind the super and smart grid concepts together. Enough differences, with the same aims and markets can be ideal in the long run for achieving and solving as complex objectives as the climate change. (Blarke & Jenkins, 2013; Zahid et al., 2025)

EU has proven to see the two operating as a combined system with different control strategies, which complement and support each other. This creates more perspective to the future development of all related systems and gives room for new innovations to thrive. Even the Energy Policy article mentions that EU has had dissenting view about the future of electricity networks. For example, the United States of America had a strong belief that smart grids, advanced metering and bi-directional communication are the correct solutions for the modernization of the network. Even though these approaches serve the increased integration of intermittent renewable energy, the resolutions are quite local. However, the US has recently also explored the super grid concept, with the focus being on HVDC technology deployment as a part of the federal grid modernization plans. Long-distance high-capacity transmission lines are required when increasing the amount of decentralized renewable energy. Investments have been targeted towards connecting the three major interconnections, Eastern, Western and Texas. By connecting remote or distant areas which are rich in resources, the full potential of renewable energy can be obtained. The conclusions are same as in the EU. The connections improve security of supply, resilience, and sustainability. Even if the US does not have nearly the same environmental aims as what the EU has set. The motivation to improve the grid in the US is stated to be more about increasing security when it comes to hazardous events and natural disasters. (Blarke & Jenkins, 2013; *Connecting the*

Country with HVDC, n.d.; *Grid Resilience and Innovation Partnerships (GRIP) Program Projects*, n.d.)

This even further proves that both super and smart grid concepts are necessary in the future of electricity networks and that they can operate in parallel. SSG is evolving as a concept strategy to not only being a buzzword, a trend or a utopic scenario, but to be the feasible reference on what modern electricity networks look like. Both concepts have reached maturity and are now vital for the planning of future networks. The motives behind this developmental step might not be the same for all nations or network regions, but the requirements are. The world is more connected than ever, which increases overall knowledge and understanding. The same characteristics are to be incorporated into the context of electricity networks. More connections and data spawn more opportunities and options to contribute, control and optimize all activities related. (Zahid et al., 2025)

As all large-scale innovative projects, naturally the development of SSG infrastructure includes risks and challenges. As the knowledge and information increase through larger connectivity, so does the pain and hardship, or in this case the challenges. As mentioned earlier, the primary complications of the SSG development and deployment are more related to the management of investments and political and socio-economic situations than to the lack of technological competence. The main technological or operational challenges are the proper planning, prediction and preparation of the grid to withstand different contingency issues. Appropriate transmission network topology can mitigate the interconnectivity and instability issues, such as load demand curtailment and ensure the optimized balance of load flow throughout the system. A proactive transmission network planning strategy is growing interest among power regulatory authorities. The topology of the network would be planned so that it accommodates the flexibility of renewable energy generation and is ready to act whenever changes or challenges occur, rather than what the current grid condition in many regions is. Even though the concerns of the load flow balance are named as one of the technological issues with SSGs, the reality is that the current grid capacity is not enough to transport all generated renewable electricity. For example, Finland wasted 400 GWh of renewable electricity due to inadequate grid conditions in 2024. Many TSOs do not even track the curtailed electricity of the costs of it. Inevitably, SSG will face technical issues and challenges, but first and foremost the designed concept is here to answer the covered load flow issues and to enhance a better match between demand and supply. Therefore, it is stated that the related issues remain elsewhere, rather than in technological approaches. In the last resort, appropriate network topology planning is an obligation of the power regulatory authorities. Only three TSOs have taken the transformation of the grid by 2035 as their priority, with the proactive topology in focus. (Adnan et al., 2023, 2024; Blarke & Jenkins, 2013; *What Is Stalling Europe's Transition to Renewable Electricity?*, 16:30:22 +02:00b)

Verbong & Geels (2010) suggests that there are three different pathways, with which the electricity network can be modernized: transformation, reconfiguration and alignment. The pathways are not necessarily mutually exclusive and are based on then recent socio-technical theories. As we can notice, in 2010s the scheme around the grid infrastructure modernization has been somewhat compartmentalized especially about the differences between modernization strategies and approaches. However, not one pathway is better than the others or to be chosen for implementation. All three are primarily portraying the various possibilities of future network infrastructure evolution outcomes. In addition, the pathways describe and include the characteristics of super and smart grid concepts comprehensively. (Verbong & Geels, 2010)

The transformation pathway presents a hybrid model which combines a few large-scale power plants and multiple small local units. With incremental changes the grid infrastructure would enable bi-directional flow on both transmission and distribution levels through smart metering. This pathway is considered as the safest one, as the conventional incumbent operators of the grid recognize the pressure and they want to make more sustainable choices and maintain their power among the grid stakeholders. There is no one crash of changes, but rather gradual and guided integration of new innovations to increase renewable energy generation. (Verbong & Geels, 2010)

The reconfiguration pathway promotes the future development towards a European super grid. This pathway introduces the increase of renewable energy to happen with large generation clusters around the area of Europe and even North-Africa. The widespread generation capacity requires better connectivity and stronger network infrastructure. Through these requirements and motives, the network gradually evolves into a European super grid. With this pathway, the reasoning behind the development requires are related to EU’s external pressure to increase security of supply and global competitiveness. The reconfiguration pathway aims to create a high-tech interconnected international network. To achieve the aims, a more significant hierarchical and architectural changes are necessary, such as new rules and regulations and a more complex control strategy. (Verbong & Geels, 2010)

The third pathway, alignment or more specifically de-alignment and re-alignment, is roughly the most radical one with the idea of disrupting the conventional centralized grid into heavily decentralized. The conventional grid with only a few large-scale generation units would operate as the backup for larger consumers of electricity such as the industry sector, while local cities, neighbourhoods, communities and households generate, store and use their own electricity. These are then considered as micro grids and when necessary, they could operate in isolation or practise exchange of electricity with other similar systems to increase reliability and cost optimization. Unpredictability and fluctuations make the balancing of supply and demand with this type of systems difficult. Therefore, the involvement of advanced metering is seemly, as the monitoring and controlling of the supply and demand can both be done automatically. This helps the micro grid stakeholders to always gain full potential of their system. The alignment pathway de-aligns the traditional centralized and network operator focused grid and tears it a part to realign the power structure of the stakeholders. This new order transposes the power to the consumers or their communities, making them prosumers and the general centralized grid a secondary actor. This then combines seamlessly the decentralized, smart grid and micro grid concepts roughly and radically together as an alternative network development option. (Verbong & Geels, 2010)

The concrete current outlook on the emerging European SSG, is a network system connects different countries with different power generation backgrounds, so that all participants can benefit from each other's expertise. The simplified conceptual diagram in Figure 8 showcases the complexity and connectiveness of the system. (Zahid et al., 2025)

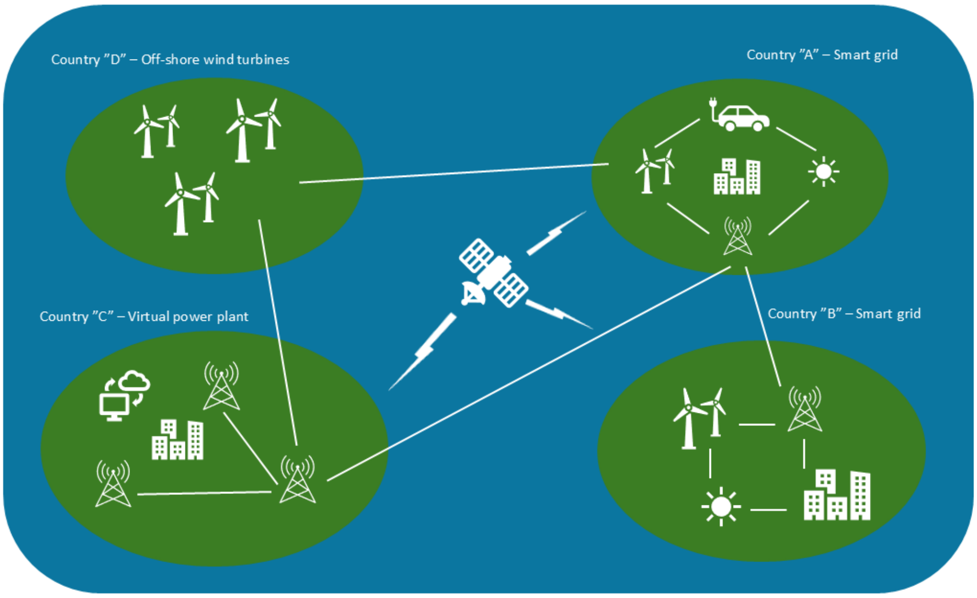

Figure 8 Conceptual diagram of SSG involving four countries, adapted from Zahid et al. (2025).

As noticed, all the named pathways resemble some parts of the SSG system concept. The pathways are a great display of the different power structure changes within the grid stakeholders in each scenario. As the SSG concept is a combination of various factors and developmental innovations involved in the pathways, the importance of a unified framework is inevitable. New rules, regulations and legislations are necessary and will guide the change further. The integration of innovative solutions can be done deliberately, without power structure crashes, if planned accordingly. To simplify, the SSG is based on the background automation and advanced technologies with wide area connectivity. (Zahid et al., 2025)

3 Methodology

This thesis research approach is to conduct a dual study, combining literature review with the creation of an architecture model about the discussed multi-layer control system for the European SSG. The combination of conceptual and computational studies endorses each other and enhances the creation of a wider perspective of the topic. The concrete model visualises the concepts of the theoretical framework and deepens the understanding of the future necessities. This is the main reasoning behind the chosen multi-method approach. The integrative literature review consists of related and existing architecture and control models, together with the EU and the Commission level rules, incentives and regulatory policies. One of the studied architecture models was chosen as the most viable one, and the final model created as a part of this thesis research is based on this model.

3.1 Methods

Concretely, the multi-method research combines the exploration of relevant literature with supportive system modelling. The focus is on the extensive literature review, and in the well-reasoned conclusions. Applied research model is done to support and develop the findings further. The model approach is the combination of conceptual and hierarchical architecture model for the SSG control.

The chosen model implemented, is based on the SGAM structure, with some additions and changes to better serve the European grids in the future. The hierarchical elements of the conventional grid are still somewhat there in the background, but the meshed configuration and bi-directional flows of power and data are changing the comprehensive dynamics. The SGAM was identified to be a suitable one, due to the multi-layered yet connected structure. Traditional hierarchical control system architecture where power and decisions move from top to bottom, are too rigid, as the SSG particularly emphasises the need for flexibility. As the SSG includes several somewhat individual concepts, a wider perspective for the control architecture model is also required. However, the model still needs to be simple enough to not over complicate the system structure. The multi-layer type of ideology fits these requirements, and therefore is the suggested model in this research, based on the literature review and especially considered EU's climate and grid objectives. Same drivers are behind the network topology chosen, which impacts the operational layer of the grid and the control model. A meshed topology was recognised as what serves the SSG and the bi-directional power flow the best. As the regulative background around the subject is comprehensive and strong, the layered structure has space to acknowledge this and has space for future expansion incentivised by new legislation or technological development.

3.1.1 Creating the Theoretical Framework

The purpose of the theoretical framework is to structure and synchronise the literature insights into a coherent system model. This is done by objectively analysing existing literature and alternative frameworks around the related topic, which includes extensive study of the European Union and the Commission level legislation publications, rules and regulations together with relevant articles and previous studies. This improves the understanding of the current state and future aspects of the legislation procedures related. The identification of gaps, challenges and requirements then define the assumptions and design criteria. The foundation of the thesis research is built by studying and undergoing the identified requirements for change regarding climate change, accelerated electrification, energy revolution and the socio-economic and political states.

As the topics of energy revolution, grid interconnections and smart applications are particularly relevant in the current phase of development, there is a huge amount of discussion and research published. Especially in the context of EU and the ambitious decarbonisation goals, there are several intentionally overlapping action plans and regulatory sets and the proper undergoing of them takes time and effort. This is partially the reason for the extensiveness of the integrative literature review within this thesis.

In the research literature, the related topics have been discussed for decades, with interestingly opposing and supporting measures. The processing of these was important to gain understanding about the possible prejudice but also about the risks. Some papers even identify the two as mutually exclusionary. The evaluation of such founding and the argumentation around it is extremely interesting and appropriately challenges and forces to see the other point of view. Super and smart grid characteristics and technologies are studied and represented in academic literature in addition to different occasions and scenarios. Often as a background framework of some more specific research target. The variety of analysed research enhances the absorption of the multitude of possibilities these innovations hold. Many smart applications are mature technologies, just like the smart grid as a concept. Smart operations can have multiple meanings inside the scope, but in the context of electricity networks, the main idea is clear. However, the acknowledgement of external utilisation of the term and technology outside the scope of this thesis is also seen valuable within the big picture. There is room for future discoveries and especially different types of smart applications are already becoming more common in our everyday lives.

Smart applications are also noted in many more EU level publications, compared to the super grid operations. However, the European super grid is generally identified to be implemented through the increased cross-border interconnections and with market coupling in a way. The importance of interconnections has been emphasised nicely in all the EU level publications and incentives directly or indirectly. TEN-E policies and regulations are to enforce the European grid connections and to create a unified Union wide structure of power networks. Also, in the more particular context of distributed generation overall the super grid characteristics are discussed.

Only some academic papers refer to the cooperative concepts with the term SSG, even though the actual conceptual utilisation of both operational technologies would be involved. The publications done by the European Union or the Commission also rarely mention the SSG as a term, even though this is the approach EU is pursuing. To simplify and emphasise the concept cooperation, the use of the term was seen as necessary in this thesis research, since in the end all the future actions and objectives inside the EU context are aimed towards the creation of a such network.

Due to the vast amount of information and publications, the focus scope of this thesis research was targeted to emphasise the extensiveness of the literature review. The gathering, combining and arranging relevant information from various sources formed a clear structure and mission to this thesis. However, to further prove and support the conclusions, a structure model was seen as necessary addition. The gained information requires integrated compiling to answer the thesis research questions and create new conclusions.

The control objectives and structures of power systems are evaluated through relevant sources. This then leads to the structure and architecture of the SSG. Different network topologies are covered together with architecture models, mainly designed for smart grids. The conventional grid hierarchy is studied and a clear need for better communication and cooperation between DSOs and TSOs is identified.

The conceptual framework was created to define the incentives, system necessities, boundaries, key stakeholders and control levels. In addition, the connections and flow of information between different stakeholders and levels was taken into consideration. The framework lays the foundation to the model by presenting the assumptions, findings and design principles in a structured manner. Structuring the concepts systematically from the literature review defines the basics of the system.

3.1.2 Model Design Approach

The core of the SSG control is decentralised physical control, coordinated operational control and harmonious market-based optimisation. The control architecture model includes a large variety of the characteristics, approaches, and factors discussed and concerned in the scope of the theoretical framework. The model aims to implement the desired ideal functions of a multi-layer control system as simply as possible, based on the gained knowledge and design requirements. The existing system designs were studied and analysed, to create assumptions about the current state of the architecture to build the suggested model on to.

From the existing architecture models, SGAM was recognised to be the most influential and potential one in the terms of this study. As SGAM is designed to accommodate smart grids, the elements and characteristics of the design are desirable. Naturally, some additions and changes to the model are required for it to suit the needs of the super grid functions as well. Therefore, the model created complements the structure and elements of SGAM, with the addition of super grid operations and focus on the comprehensive multi-layer connectivity. The layered design separates and presents the different functions of the whole system, so that each element and operation can be examined and taken into account individually, but also within the complete system. This serves the complexity of the SSG and the relevant rules and regulations.

The physical topology of the power network drives the control structure. The SSG system not only includes the physical network topology, but each sector has its own topology, which must be acknowledged. In the scope of this thesis, the detailed evaluation and examination of other than the physical network topology have been marked off, but the other topologies are assumed or abstracted, as a topology-aware control strategy provides efficiency and effectiveness while distributing the responsibilities accordingly.

The topology of power networks can be seen as the underlying base for the multi-layer control architecture. Based on the literature review, a meshed topology approach was chosen, even though the distribution networks can still in many cased have the more conventional radial structure. However, in the context of European power networks, renewable generation objectives and general technological advancements, all power networks will in some point be turned into meshed ones. As the meshed topology is already in use on the transmission network side, the flexibility and security it offers is necessary for the complete system to have.

The meshed connections inspire the connectivity between the different sectors and layers in control purposes as well. Meshed and interlinked topology supports distributed control, as there are certain local autonomy and scaled coordination. Overall, distribution is the key term of the whole SSG and the control architecture, as not one entity can control everything in such complex system.

With the desired characteristics from SGAM in addition with the advanced meshed topology, the created control model aims to concretise and visualise the grid system requirements, in a way that can be further developed into simulations. This type of conceptual models benefits from being a part of a hybrid model with additional test simulations. However, the scope of this thesis was identified to be not enough for such, but there is room for further research and development around the specific topic.

Due to the accelerated technological development, new innovations and additional applications linked to the power system operations have emerged, and the conceptual architecture models have not been updated within the same pace. Therefore, this thesis proposes a control architecture model with the intention of cooperative control, with an extended SGAM inspired framework to serve the European SSG. A clear system architecture enhances future development by providing a usable framework where new innovations are easily adaptable. Decentralised system requires structure to understand and control the actions across the network cost-effectively. Correctly implemented flexibility increases expense savings and decreases the environmental impact. The simultaneously happening global digitalisation, together with fairness and transparency are also to be obtained. These are all key aspects of EU’s future development plans.

3.2 The Control Structure Architecture Model

The cooperative control hierarchy divides the responsibilities between all stakeholders of the grid according to each one’s competence. Well-structured control hierarchy operates as a coordination mechanism in the complex yet flexible system. Certain hierarchies are to be maintained, in order to ensure secure and safe operations. This ensures the system-wide coherence and allocation of responsibilities. The hierarchy is then built according to security, not to power. In the core of the cooperative control is the deviation of power together with the transparency of all actions and communications. Sharing resources, data and information engage all stakeholders together, ultimately creating the European Energy Union. Under the European Union, same rules and regulations commit for the common good.

The extended architecture model includes several interoperability layers with additional connections and control responsibilities. The cube-like layered structure is flexible and comprehensive framework to accommodate the European SSG. The SSG operations and control objectives are mapped based on similar layering as in SGAM, with more conceptual approach. The base layer of the model is the component layer, including all concrete stakeholders and operators inside the European SSG. These are the domains of the model architecture. All the layers are accommodative and supportive levels for the operations of the named components. Each of the layers is presented with specific colouring and operational objectives.

The component layer itself presents the physical distribution of participating operators and components, including applications, grid infrastructure, system devices and equipment. The component layer provides the description of the physical connections between components, as a foundation for the interoperability categories. The interoperability layers are relatively abstract, but the domains, zones, connections and control hierarchies secure them together, so that the model structure is easier to comprehend.

The communication layer addresses the data exchange and data management practises. The layer's primary aim is to provide interoperability between all the physical system components. As with the system complexity, there is no one communication technology used, but rather several ones creating a heterogenous communication system. As one of the key features of the SSG is increase the data sharing between TSOs and DSOs, as well as between customers and system operators, the layer protocols are extended to serve this. The layered model presents the relevant technologies and clarifies the system operability and visibility, by showing how the coordination Is enabled.

As the communication layer defines the technology and practises, the information layer goes deeper into the specific data and information exchanged between operators, and the motivation and necessities behind it all. The aim is clarification and to create common understanding of the used and shared data, which allows the combability and interconnections. As one of the viable features of the SSG is to increase connectivity and data sharing between TSOs and DSOs, as well as between customers and system operators, the information layer protocols are extended.

The function layer describes the required services, functions and relationships with an architectural overview of the structure. It incorporates and introduces the extended operational functions within the European SSG scope. The level of coordination and scale for super and smart grid operations are differentiating, but compatible. This layer can be identified as the most important one in the SSG model, since it presents the operational logic of the system architecture. Without the actions on the function layer, there would just be data, but nothing done with it. This layer makes enables the intelligence of the system.

Arguably the second most important factor is the proposed addition to the business layer, which defines why the SSG functions exist and are necessary. The business layer models the institutional intention through EU's regulatory framework, in addition to the business models and market structures, so the overall business view on the concerned information. With this SSG architecture model the business layer focuses on mapping the policy and regulatory structures, which direct the system from above and beyond. As on the top layer of the model, the EU governance covers and impacts all domains directly and zones indirectly.

4 Multi-layer System Architecture Model

As power systems are becoming seemingly more complex, the thorough yet straightforward modelling of them becomes more important. Through modelling and simulations, the vast systems can be examined, explored or tested part by part beforehand without any excess risks or inconveniences. The SSG system requires structural separation and clarification of system elements and control objectives. A system architecture model enhances the comprehension of the large-scale construction and highlights the future necessities.

4.1 Control Objectives and Performance Criteria

Controlling and directing actions on several levels is complex, but with adaptable regulatory work and structured operations the maximum effectiveness can be reached. In this chapter, the objectives and criteria of the multi-layer control structure are presented. The next chapter presents the concrete model architecture and detailed structure. The core objective before this was to identify all relevant stakeholders, functions and actions inside modern grid systems, with the challenges and opportunities in mind.

Not one entity or authority can oversee all control actions and requirements. Hierarchical control system distributes the power of control and decision making based on the shared data and connections to several stakeholders between interoperability layers, to ensure safe, secure and efficient operations. The multi-layer system identifies the specific qualities of different parts of the system and structures the communication, connections and control actions accordingly.

The primary objective when creating a viable model is to enable proper analysis and design of the system coordination. The aims and goals of the model can be divided between the system objectives and system performance criteria. The performance of the control system architecture model can be assessed by the adaptability. Architectural consistency, with clear separation and mapping of the layers and the correct placement of components and functions are crucial aspects in the performance criteria assessment. The same way, the model structure should be understandable by relevant researchers and authorities, with appropriate governance considered. Overall compliance and completeness at a conceptual architecture level without any operationally critical aspects missing, but with no unnecessary details. The control objectives of each relevant stakeholder should be traceable so that correct functions are linked to correct operations and components.

The system objectives to achieve are more related to the inclusion of certain crucial elements in the context of the European SSG. The primary objective being the integration of super and smart grid capabilities, through preserving the existing smart grid pourabilities with the incorporation of operational super grid coordination, by also avoiding duplication, confusion and conflict. The layered model needs to embed the EU governance inside the system operations, by connecting the operational control to related regulations.

The final objective is to have the model accommodate and implement the flexibility and resilience requirements of the future power networks. The model must ensure to be scalable and extensible in order to evolve with future developments, increasing number of participant actors and changing regulations. The structural and architectural extensions represent the upgrades necessary and the control-aware modelling.

4.2 Extended Architecture Model for the European Super Smart Grid

The extended architecture model is designed to emphasise the cooperation of the SSG, therefore the operational elements presented are mutually inclusive. Each layer present different parts of the grid operations with specific interactions, including both super and smart grid characteristics. The three-dimensional model provides an organized map of the SSG system, with the functions intentionally overlapping each section they effect on. The system enhances the analyzation of different use cases and identification of communication and interconnection gaps. This model is easily modified based on the managed system. As in the original SGAM, there are six zones and five domains. The six zones and their reshaped purposes are explained in Table 1 below.

Table 1 Extended architecture model zones and explanations.

Zone	Explanation	In SSG
Process	Power transformation, physical processes and equipment (generators, transformers, lines, cables, loads, sensors and actuators).	Long-distance power transmission, distributed power generation, HVDC lines across continent.
Field	Monitoring and controlling equipment, local and immediate actions, measurement of system conditions in real-time.	Instability and fault detection, renewable generation output monitoring, monitoring of cross-border flows.
Station	Substation automation systems, HVDC converter control systems, protection coordination.	Local control strategies, more precise controlling of renewable generation, controlling of substations and converters.
Operation	Power system control management over several domains. Virtual power plant management systems, energy management systems, distribution management systems, microgrid management systems, electric vehicle management systems.	Real-time balancing across continent, coordination between TSOs, controlling the cross-border power flows. **The central intelligence of the European SSG.**
Enterprise	Aggregator and flexibility providers, organizational processes, infrastructure and service management, workforce and training management, relation management.	Cross-border forecasting and planning, TSO-DSO coordination, system-wide resource optimization.
Market	Fully integrated European electricity markets, trading, retail market.	Market coupling, power flows are driven by market signals.

The control aspects of the system are divided between the component and function layers. Even with the distributed and cooperative control hierarchy, the real-time controlling is done on the generation domain on the component layer, due to safety and security. Overall, the system hierarchy is shown through the model zones, which represent the level of control from physical processes to economic decision making. It is important to notice, that the hierarchy does not intent to isolate the layers, zones or domains, but rather enable the correct flow of information and control. The domains represent the roles and locations of the power system stakeholders. More precise explanation on each domain is shown in Table 2 below.

Table 2 Extended architecture model domains and explanations.

Domain	Explanation	In SSG
Generation	Large-scale generation, connected to the transmission network,	Renewable and distributed geographically, offshore wind farms, large solar parks.
Transmission	Infrastructure which transports large amounts of electricity across countries and over long distances.	Use of HVDC, cross-border interconnections, balancing of regional differences, demand response, TSO-DSO cooperation.
Distribution	Infrastructure which distributes electricity to end-users.	Large integration of DERs, local power flow management, local demand response, TSO-DSO cooperation.
DER	Distributed energy resources, traditionally connected to the distribution network (rooftop solar, EVs, energy storage).	Demand flexibility, local generation, storage, enhances larger involvement of prosumers, aggregated and actively controlled.
Customer	End-users and prosumers.	Active participation, consumption adjustments, flexibility market participation.

All zones and domains are included in each interoperability layer, where different elements fall on to different locations and hierarchical statuses accordingly. Figure 9 presents the cube-like structure and the order of layers.

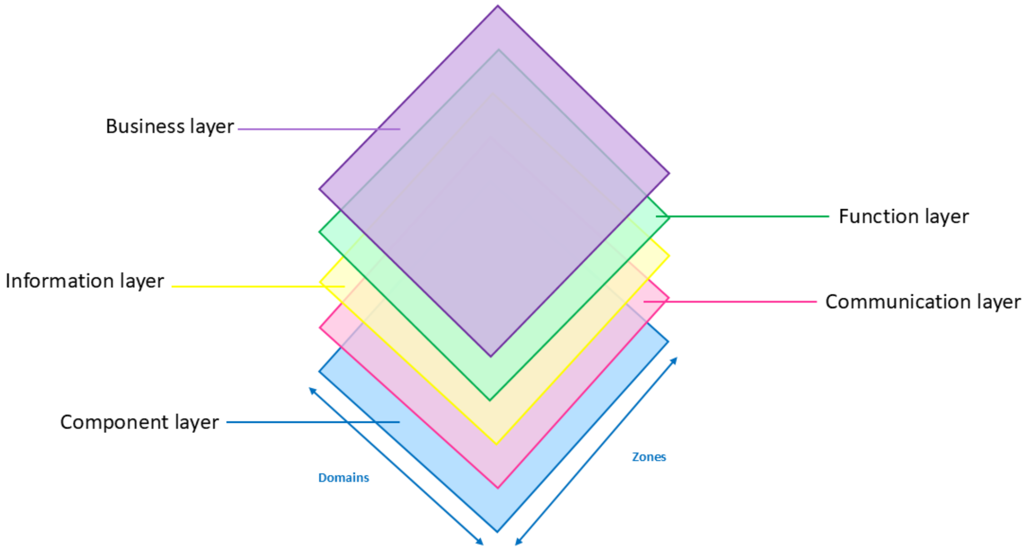

Figure 9 Extended architecture model layers.

Each layer has a designated colouring. The order of layers is the same as with the traditional SGAM. The next chapters go through each extended layer structure and qualities linked to the European SSG.

4.2.1 Component Layer

The component layer's purpose is to present the physical entities and elements of the system. In the case of the European SSG, the component layer consists of the physical hardware, from renewable power generation to control centres and controllers. HVDC infrastructure covers the lines, substations and converters together with the wide-area monitoring systems and automation devices, which enable the efficient and intelligent operations all around the SSG. These devices and systems must reach across layers, in order to cover all operations. The control centres are responsible for the real-time control execution and coordination functions of the operations. From the hierarchical point, TSOs come before DSOs, but to highlight the interoperability and communication requirements they are presented in contact with the operation zone. The real-time automative controlling of the system is to happen on this level, creating the base also for the control hierarchy. Similarly, as with traditional fossil fuel power plants, the level zero control responsibility and protection are on the renewable generation sites.

The component layer creates the foundation of the grid system, with the physical infrastructure. The super grid components are easily adapted to the layered structure. Figure 10 presents the component layer with SSG related hardware.

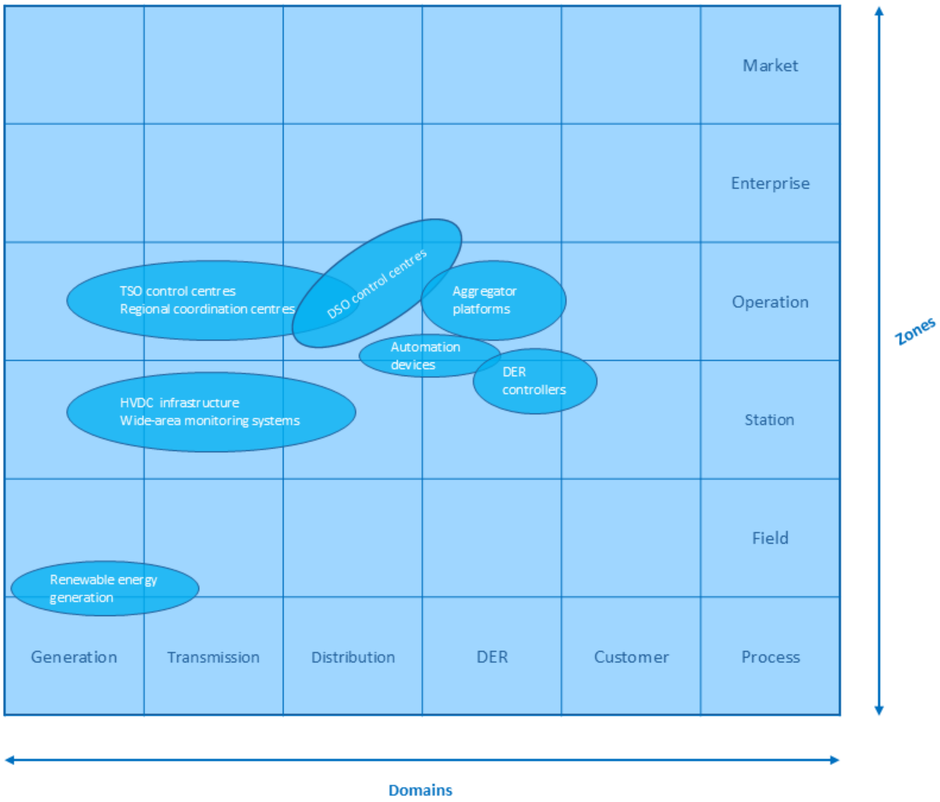

Figure 10 Extended architecture model - component layer.

Aggregator platforms are to be involved in modern grid systems, due to the complexity. They operate as the bridge between the distributed power resources and large-scale grid and market operators. Aggregator platform collects, manages and controls multiple DERs as if they were one entity. The control system of these and the information technology hardware are placed on the component layer.

4.2.2 Communication Layer

On top of the physical infrastructure constructed in the component layer, the communication layer elements can be built on. The purpose of this layer is to show the required connections, and how all components and elements communicate with each other. The aim is to enable real-time communication across the grid. This layer enables the smart grid characteristics with the extended data exchange.

The operational communication happens between HVDC converters, substations and TSO control centres. Through high reliability, this communication link is used to maintain grid stability and to control frequency and voltage. The layer rather represents the connections and links than specific technologies used. However, the most crucial transmission level communication is executed with fibre optic networks, while the distributed resources and smart meters generally utilize wireless communication. The communication layer structure is presented in Figure 11.

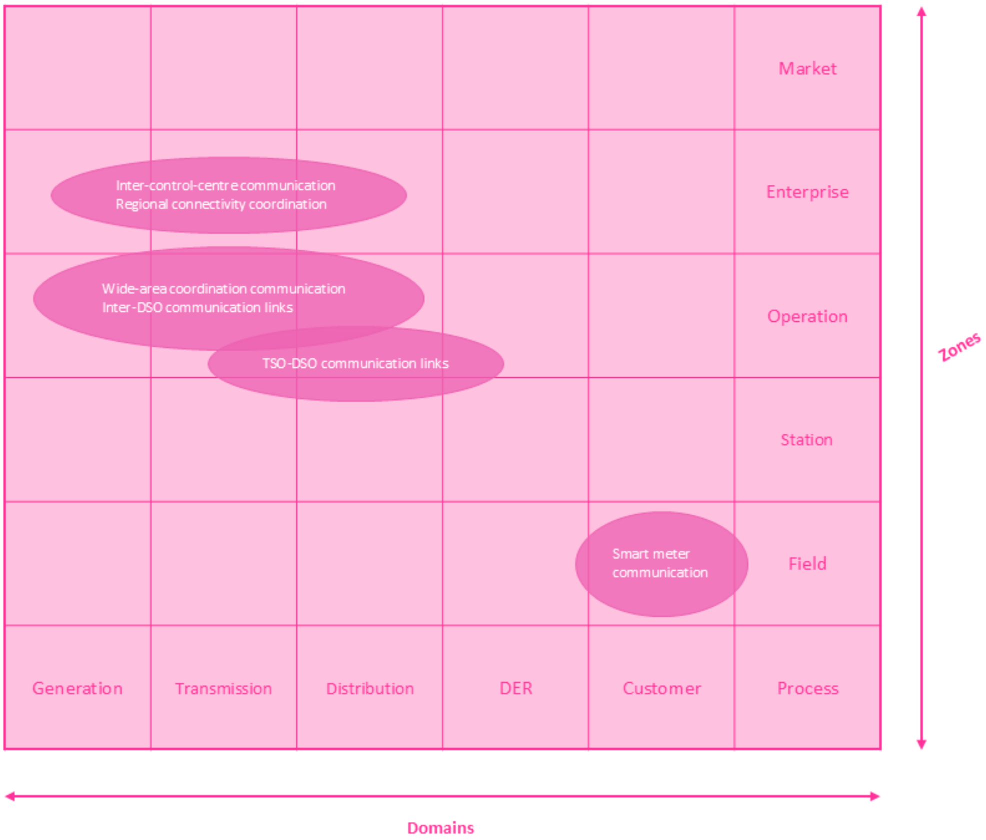

Figure 11 Extended architecture model - communication layer.

The monitoring communication between smart meters, sensors and the wide-area coordination communication enable the real-time grid visibility and enhance early detection of disturbances. The same applies to the communication between TSOs and DSOs, so that the links can be utilized for market forecasting and cross-border coordination. Overall, the SSG relies on safe, secure and interoperable communication across borders and organisational boundaries. Data is in modern structures is seen as value and power.

4.2.3 Information Layer

The information layer then showcases what information is being exchanged through the communication layers links. With the SSG this means measurements, device states, flexibility availability, power flows and aggregated system states. The SSG introduces a new level of data aggregation and abstraction in order to enable cooperative coordination while also maintaining the data sovereignty. The information elements are placed according to the system organisational scope. With this layer, the engaging of customer domain is crucial as the prosumer approach is expanding together with the smart and advanced metering infrastructure. The defined elements are shown in Figure 12.

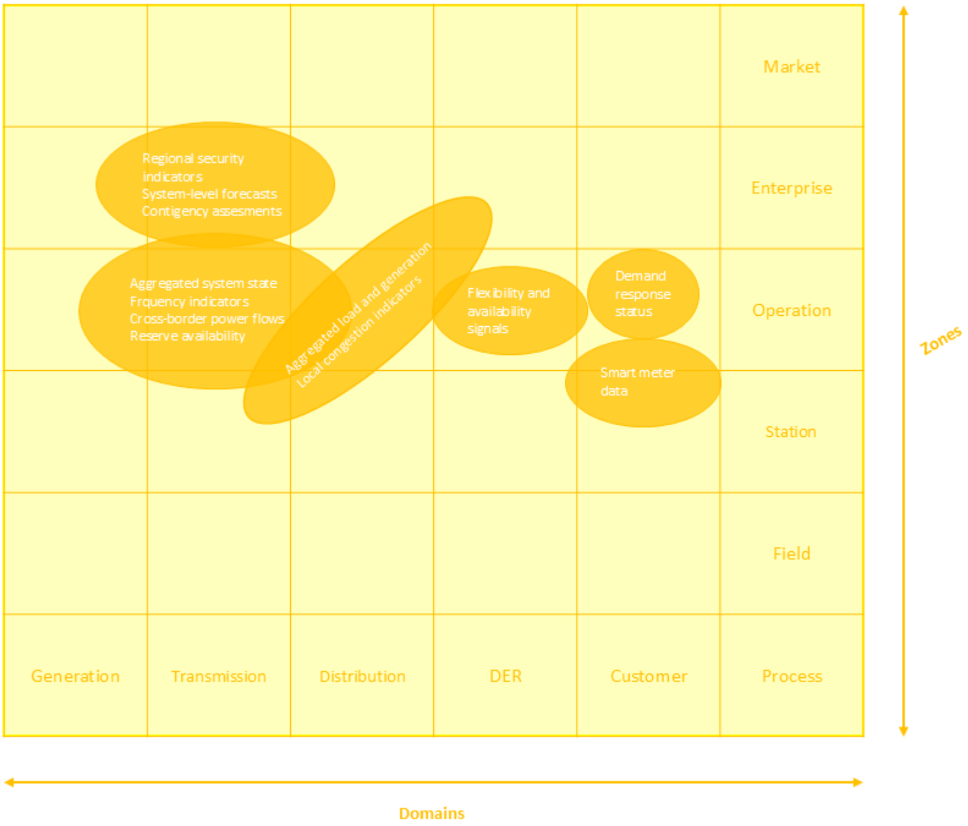

Figure 12 Extended architecture model - information layer.

The operational data includes voltage, frequency, current with power flows and component statuses. The forecasted data is critical for the renewable energy integration. The data includes output predictions, generation forecasts and demand forecasts. With unified electricity markets in mind, the exchange of market data like prices, bids and offers are non-negotiables for the cross-border electricity markets. Flexibility data through aggregators and DERs provide availability and demand response information, which further permits the smart behaviour of the grid.

The main aim of the information layer is to make sure all the European SSG stakeholders share, structure and interpret the data the same way consistently. Data exchange and increased communication are the key elements when coordinating operations across the complex energy system. The physical connections lay the groundwork, and the information components make the system valuable and modern.

4.2.4 Function Layer

The function layer is the most important layer in the SSG context. It creates the operational intelligence and makes the decisions regarding the collected data. Without the function layer actions, there would be data, but nothing done with it. To attain the operational intelligence, challenges such as cross-border coordination, renewable variability and integration of DERs are to be handled. The SSG is to answer and improve all these above.

The function layer turns the information layer's data into actions. The control over element and actions is crucial. Key functions include power flow control, direction and magnitude of power and the power balancing between Member States. The function layer ties together the sole purpose of the SGG creation by being the central enabler of the intelligent actions across the European power system. Cross-border interconnections, increase in renewable generation and digital control requirements together create a complex and highly dynamic system, which the function layer's actions are able to manage.

Real-time or automatic system stability control is a priority function to make the SSG an operational network system. The function layer coordinates frequency stability, voltage control and load balancing adaptively across stakeholders. This increases system reliability and predictability. The high-level control and coordination are also the factors which enable the implementation of super and smart grid characteristics simultaneously in reality. Through these actions, the function layer connects all the grid operators and unifies the actions, meaning, all TSOs are coordinated similarly as well as the aggregators and DERs.

When it comes to strictly super or smart grid characteristics, the function coordination enables the controllability of the HVDC. This indicates that the power flows are actively controlled with functions such as voltage regulation, setpoints and power routing. The grid is no longer passive, which is also seen with the integration of aggregators and increase in DERs. The distribution of such flexibility creates the ability to decrease, increase or shift the generation or consumption of power. However, individual DERs can be relatively small to control or manage directly, and this is where aggregators come into the picture. By combining several small units, they can act as one controllable resource and have interactions with TSOs, DSOs and markets. The function layer enables the formation of virtual power plants. Similarly, the function layer actions enable the grid to become intelligent or smart, when relevant data is collected, decisions automated and coordination of control is adaptive, the system can react dynamically to each occurrence.

With the structure of the function layer, the vertical alignment of elements presents the required operational hierarchy. The layer provides the control logic and coordination functions necessary for the optimal operation of the European SSG. The functions range from local smart grid control to coordination and control functions across the continent. The placement of each function represents the primary operational area and the level of responsibility. Some of the areas are overlapping, which indicates that these functions need coordination across various domains and zones, as shown in Figure 13.

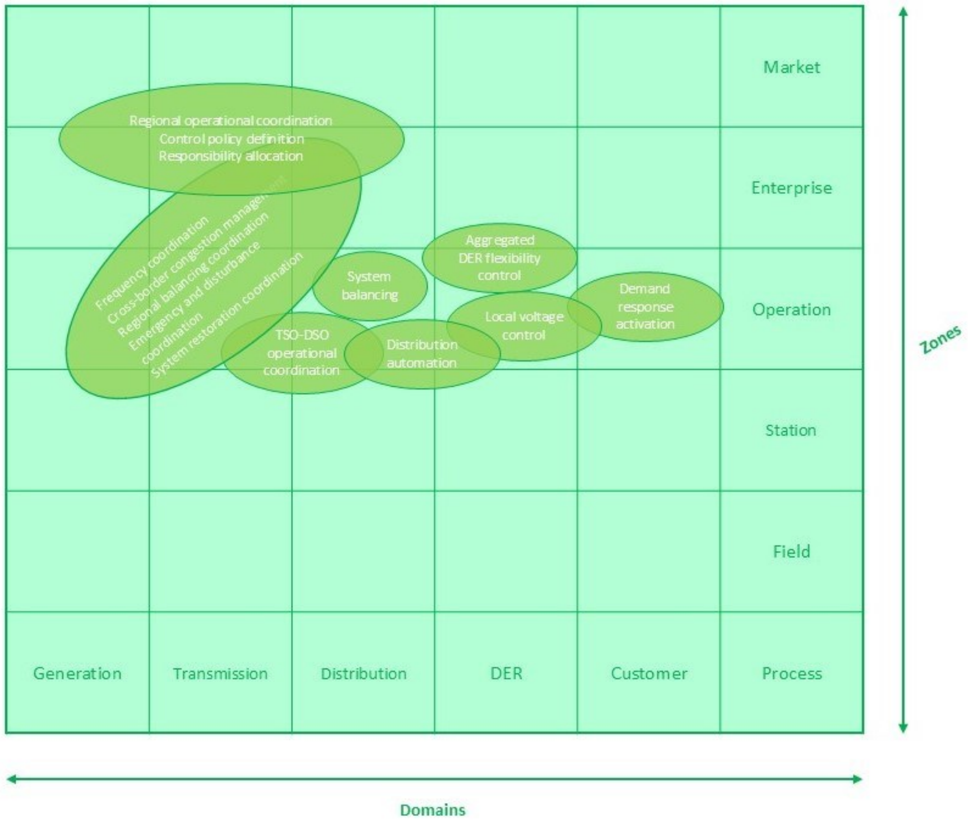

Figure 13 Extended architecture model - function layer.

Overall, the system stability reassurance and real-time reactions to all disturbances and anomalies are the baseline of the operations. With the increased renewable energy integration, congestion management and demand response are also happening through the function layer. Optimal, efficient and stable performance are the responsibilities of this layer.

4.2.5 Business Layer

The purpose of the business layer is to discover the system’s organisational roles and responsibilities, together with the regulatory actions. As the responsibilities are shared among several stakeholders, the elements span across domains engaging the coordinated operations. Coordinated governance structure is necessary due to the complexity of the grid and the inclusion of multiple nations and operators. Figure 14 presents the visualisation of the business layer.

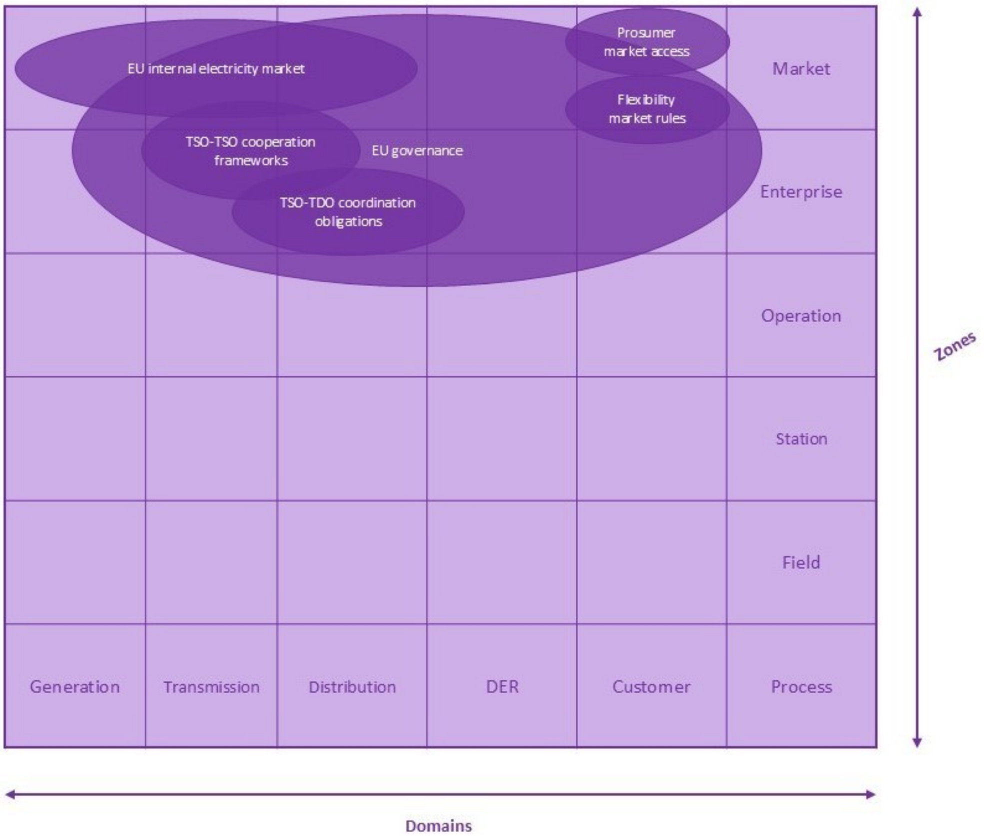

Figure 14 Extended architecture model - business layer.

From business and governance points, the European SSG could be seen to cover all domains and zones in the model structure, as the comprehensive engagement and cooperation is the aim. However, key elements include regulatory frameworks, electricity markets and market coupling. This layer presents the market and operational rules through the EU governance. With the SSG aspects, the market design is updated to better serve renewable energy and further enable accelerated prosumer and aggregator participation.

As discovered through the integrative literature review, the SSG links to several regulatory policies and authorities. The governance structure is formed between stakeholders responsible for all parts of the power generation and network. As EU and the Commission dictate the rules and regulations, each stakeholder entity is responsible for the supervision and execution of the set rules within their own area of actions and expertise. For example, ENTSO-E is the entity responsible for the TSOs and the coordination of the European power grid. Similarly, DSO Entity is corresponding to DSOs across Europe and coordinates their operations. Overall, EU governance covers the market design, energy policy and cross-border regulation.

With the model the EU governance is shown as one figure expanding across all relevant domains and zones, even though most related stakeholders focus on one domain. Mainly, this is done to keep the model structure clearer and simpler, but the governance impact is also intended to be recognised as one source. The expansion of the figure indicates the regulatory complexity and the immense force of EU level legislative work. There are several policies and regulations to follow, and similarly there are several entities to enhance the correct implementation, with several participant operators or countries. The interconnected, intelligent and unified European SSG requires multiple levels of governance to distribute responsibilities and manage preferred outcomes. All mentioned stakeholders operate under and in close contact with the EU and the Commission.

In the extended model the EU governance is to touch market, enterprise and operation zones, as well as all domains. The unified market rules, market coupling, cross-border trading and exchange are all coordinated under EU governance inside the market zone of the model. This also then includes the electricity market design and price formation, which within the SSG can be influenced by the power flows between countries or market areas. The TSO-TSO and TSO-DSO coordination are all covered within the enterprise zone, together with network codes and other operational guidelines. This therefore includes the TYNDP by ENSTO-E as a long-term framework plan. The operation zone is indirectly influenced by the EU governance as the governance does not operate the power grid directly. However, the security of supply rules and regulations together with reliability related standards are shaping the operations of TSOs through the EU level governance, the impact exists. Therefore, the model figure is stretched to touch the operation zone.

Overall, all regulations across nations are to be aligned. The business layer secures the economic viability and coordination through the EU area, by ensuring the system-wide coordination of all operations across Member States and participating countries.

4.2.6 Model Overview

The complete extended architecture model includes all interoperability layers inside the overview. The model provides a structured framework which helps to design, construct, understand and adjust the European SSG coherently. The order of the layers indicates the hierarchy and structure of any architectural concept, where the bottom layer is the physical foundation and the top layer represents the purpose and operational incentives. Basically, the order goes from physical to abstract. Each layer evolves and builds on the capabilities of the previous one, which enables a coherent progression. All layers have their own detailed characteristics related to the European SSG or later to a specific studied use case. The complete model overview including all layers, domains and zones is shown in Figure 15.

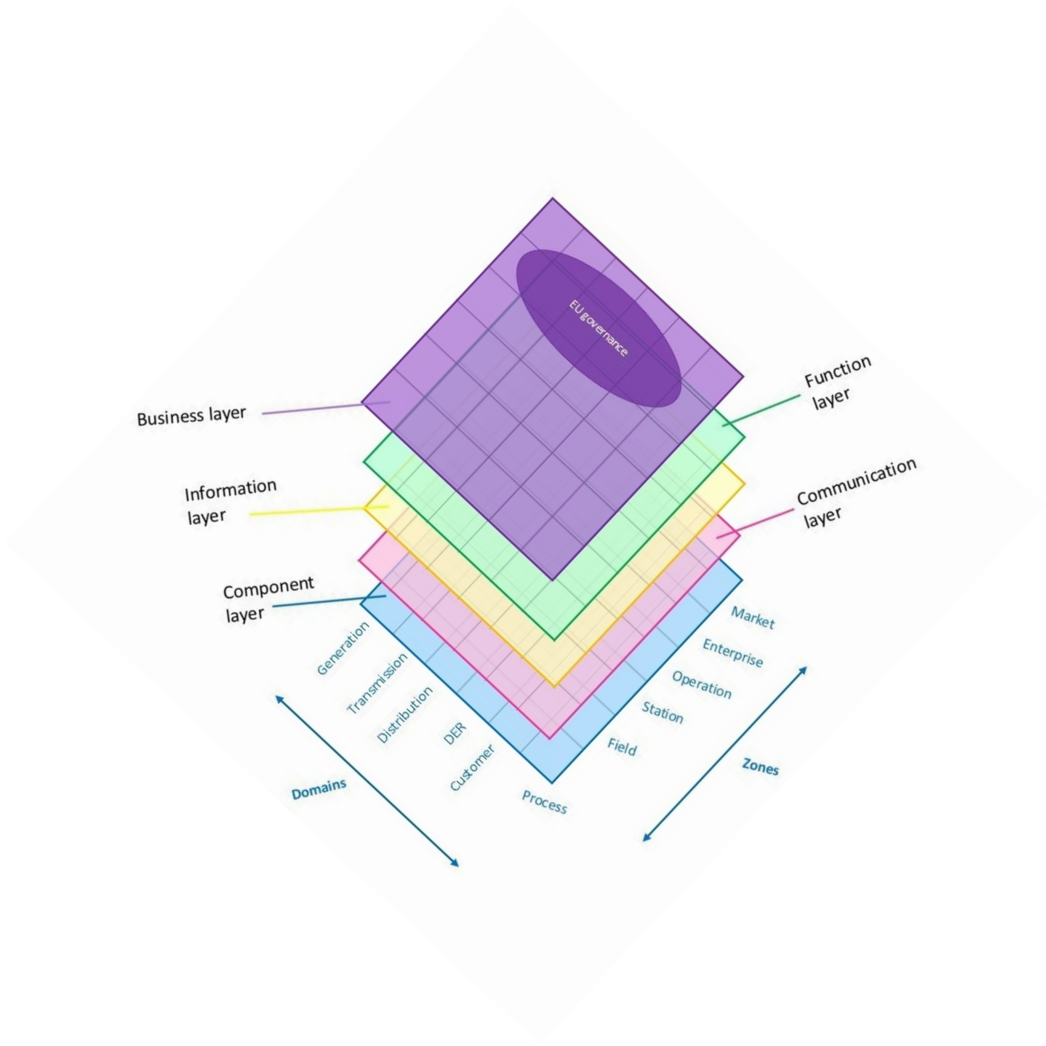

Figure 15 Complete overview of the extended architecture model.

The cube-like structure with overlapping layers represents the layers' capabilities to top up each other, but also that the elements of each layer are somewhat free to move between layers or to cover other parts of the structure as well. This also indicates the larger utilisation of the meshed network topology in European girds in the future. As the meshed structure enables true flexibility and enhances system stability by creating alternative routes in the case of disturbances. Overall, the model structure leaves room for innovation, adjustment and development. The model can be examined through three dimensions and perspectives simultaneously. The dimensions enable compliance and interactions to happen and to be observed as complete. However, every element is allowed to be examined and analysed by its specific the position, control and operation.

The domains and zones remain the same throughout the layers due to the defining structure of the power system. The key is to be able to examine multiple views inside the same system, while only changing the type of interaction. The layers then describe the various perspectives of the same system structure. The permanent placement of the domains and zones potentiates traceability of actions through several layers. This develops the system predictability further and helps to align consequential operations across layers. Therefore, the relations between layers can be mapped for future observations. Overall, the domains provide structure to the grid, zones provide necessary control hierarchy guidelines and layers present the types of interactions going on.

By structuring the complexity of the system, the technical, digital and market aspects can be linked together effectively and efficiently. The system model enhances the navigation of stakeholders and Member States through different grid stages.

5 Conclusions

EU's ambitious climate objectives are shaping the power system markets, structures and ways of operation. New innovations and approaches are necessary. The focus is on unification across Member States, stakeholders and platforms. EU has been the predecessor when it comes to climate actions and by strengthening the collaborative operations. Legally binding targets force all Member States and stakeholders to be involved and participate to a certain extend. However, as discovered through the theoretical framework, the differences in economical states, geographical locations, historical backgrounds and current attitudes shape the execution of set rules and regulations between countries. The achievement of the European Green Deal's goal of climate neutrality by 2050 requires more unified and concrete implementation strategies. This is where the creation of a European SSG comes to the picture. A unified system architecture which forces the power system stakeholders to cooperate with each other on a whole new level. The task is not simple but proven to be doable and the most viable solution in the long run.

This thesis addresses the challenges related to the representation and structuring of the future European SSG. An extended system architecture model is executed to obtain the challenges. The primary contribution of this thesis is to create and propose a cooperative extended layered model, which is based on an existing system architecture model SGAM, which traditionally only includes the smart grid characteristics. The study investigates whether the extended framework can comprehend the necessary increase in integration of renewable energy, interconnections, cross-border power exchange together with the growing coordinated operation across system operators, all actions related to the achievement of the set climate goals.

The theoretical framework conducted through an integrative literature review exposed the extensiveness of the common European regulations and the lack of models including both super and smart grid functions. The integrative nature of the literature study showed all the impactful factors behind the European energy revolution and the regulatory decision making. Europe is a small continent with a long history and great aims to maintain the value of life in the future. The strength and volume of EU governance and the ability to unify practises when necessary was found to be groundbreaking.

The literature review also brought up several aspects and factors to consider when creating the extended model. The main finding was the multi-level complexity of the European SSG system. As the true restrictions are hardly technical but rather economical, operational or organizational. However, these were also found to be the key factors the architecture models were to solve or unpack.

Therefore, the main outcome of this thesis research was to extend the existing architecture model with the addition of super grid characteristics and control objectives. The proposed model enriches the existing model layers. Super grid and smart grid coexist within the same layers, but in different time scales and scopes, interoperating in coordination with each other as one complete system. The super grid and advanced smart grid functions and operations are built on to the existing SGAM inspired control architecture model, so that nothing is being replaced or removed, and new layers to the original structure are not added. The further separation of each layer gives a more detailed outlook on the additional functions and protocols, which deepens the impact of the model. As the structure is flexible, there is room for future additions and adjustments, but the base of the model is comprehensively strong.

The proposed model includes and complies the key factors recognised within the literature review, with the concrete and visual implementation of the framework. The model is kept architectural, to enhance comprehension of the system complexity and the relations between stakeholders. The extended architecture model was seen as a useful tool for the further development of the European SSG, since the model structures the system complexity and ensures interoperability, while connecting technical functions with market mechanisms cross-borders. The additional aim was to portray the value of the architecture-based approach for such power systems, with hierarchical aspects. However, it is to be noted that additional simulations and mathematical formulations with quantitative performance would support the findings and push the development further. This does not erase the importance of the extended architecture model. The SSG is not just technically complicated, it includes structural, economical and organizational complexity.

Ultimately, this thesis research shows the importance of the transition towards the European SSG, as a crucial and mandatory implementation element in order to effectively and efficiently achieve the climate goals. The SSG is not solely about the expansion of the physical infrastructure, but the reconstruction of control, coordination and responsibility, which are the core of system development. Through an extended and revised architecture model the mentioned aspects are strongly represented, creating a coherent and comprehensive framework designed to expand further with the future of European power systems.

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