Electrical Grid readiness for the European Energy Transition

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Preface

The basis of this research stems from my love for the Environment, my faith in the possibilities of the Human endeavors, and the European ideal of Unity, a participation of Uniqueness. The execution of it has been possible only due to the support of my supervisors, who helped me by focusing the scope, by sharing their knowledge, and allowing me to learn from my own mistakes.

I firstly need to thank my parents and my family as an all. They provided infinite care, support, and love, along this entire master and the journey before it. I know that sometimes they could not understand completely or follow my developments, but I could not have reached these timely and important results without their steady presence behind me.

To my fellow master comrades and my dear flatmates, you made my experience in Deft. Your different origins, the cultures you brought with you, enriched me and, as a consequence, made me humble. I have grown as a concrete person, as an idealistic human being, and as a conscious citizen of this planet we all call home. Thank you! I look forward to improving our Home alongside all of you.

I want to thank my dear friends who I had to say goodbye to for most of these two years. Even if at distance, they kept me aligned with the best version of me, remembering me to put energy and effort not only in changing the World but in understanding and loving those who I have the privilege to meet in Life. I'm blessed to have them in my life because they give value to it.

And finally, I need to thank every one of my supervisors for the immeasurable inspiration they provided with their mere presence. From Prof.ir. Mart van der Meijden I've discovered that you can wok for a large organization, alongside difficult colleagues, but still preserve your uniqueness and your trust in the next generation. Dr. Daniel Scholten showed me the reach and depth that a professional at a relatively young age can achieve. And lastly, but not least, Prof.dr. Kornelis Blok encapsulates the ability to listen and pay respect to everyone who is in front of you, regardless of her/his knowledge, even at the pinnacle of your own career. Thank you all.

Gilberto Dalla Pozza
Novoledo, 31 July 2020

Summary

Europe's power system is facing a problem of flexibility in its path towards decarbonization. The two most prominent electrical sources for the energy transition, wind turbines and photovoltaic panels, are inherently uncontrollable. The mismatch between production and demand leads to stability issues.
Unlocking of flexibility through grid interconnections between countries can help in this system evolution. The planned rollout of such transmission corridors is still inadequate to meet the challenge. As the cheaper option for electrical investments, this thesis investigates how much interconnection is necessary by 2040 in Europe to allocate a Paris compatible power system and if it is possible to achieve it.

Instead of proceeding with a new, ad hoc, modeling system, and a resources-intensive set of simulation, the method employed was based on a collection of authoritative and prior works.
The elaboration of the energy scenario was based on 4 different agencies, from which Paris compatible outlooks were gathered and combined. The reference number is 60% of electrical energy provided in Europe by 2040 from a combination of wind turbines and photovoltaic panels. The total amount of electricity will increase from 3300TWh to 4200TWh because, despite improvements in energy efficiency, electrification will require more energy produced in the electrical grid.

After that, a combination of 12 modeling studies was examined to produce a relevant grid outlook for 2040. Most of the time these peer-reviewed works were not in line with the energy scenario explained previously, so their calculated capacities would have been necessarily scaled in proportional weight. In the end, along the main bottleneck borders of Europe, proposed 2040 levels of capacities have been confronted with the present planned ones.
The main findings are that the increase from planned to needed is on the order of one and a half times, especially for sea crossing interconnections.

The real challenge then stems from the difficulty of executing said infrastructure expansions. Through conversation with experts in the field, the issues of public opposition, joint planning, and environmental constraints have been highlighted. Ten years seems the minimum amount of time for the completion of a transmission project.

As such, together with the reference grid capacities for the European grid, the thesis suggests timely planning and execution of these electrical upgrades, starting in 2024, using early stakeholders engagement as a main preventive measure against hiccups, innovative route solutions to avoid sensible naturalistic zones, or difficult terrains, and uprating when the other two approaches cannot be applied.

Contents

Chapter 1

Introduction

Decarbonizing the Electrical Grid is like changing all components of an airplane, mid-flight, without having it crash down.

1.1 Problem Context

1.1.1 European Vision

Climate change is the defining crisis of our time, but we are far from powerless in the face of this global threat. The European Union (EU) is stepping up efforts and plans to tackle it, becoming in the process the leading actor on the world stage concerning this issue [60].

The production of Greenhouse Gasses (GHG) has many origin sources: the combustion of fossil fuels (CO2, CH4); changes in land-use and agricultural practices (CO2, CH4, N2O); burning of biomass (CO2, N2O); manufacture of cement (CO2); from cattle farming, disposal of household waste in landfill sites and rice cultivations (CH4); refrigerants, propellants (in aerosol applications) and solvents (CFCs, HCFCs); creation of nylon, nitric acid (N2O) [95].
Between all these, the power sector is producing the largest share of GHG [47]. For this reason, decarbonization of the production of electricity is one of the priorities of countries worldwide and the EU in particular.

Renewable energy is energy that is derived from natural processes (e.g. sunlight and wind) that are replenished at a higher rate than they are consumed [25]. This kind of source of energy, Renewable Energy Source (RES), have been regarded as the main driver for active decarbonization of the power sector [70] [51]. Measures of energy efficiency have also the important role of reducing the need of energy production in the first place [57]. In order to promote effectively and timely the energy transition towards less polluting sources of energy, the EU has ruled different set of policies, the most relevant for this research are the 2020, 2030 targets [84], the Clean Planet for All package [46] and the European Green Deal. This last piece of legislation is still in a phase of elaboration at the time of writing, and due to the global health and economical emergencies caused by the Covid-19 disease it is poised to be majorly reformed or absorbed in the pack of reforms to face the epidemic effects [36].

In the "2020 targets", the role of RES has been highlighted with the mandative requirement for the EU as an all (and its member states as well) to reach a certain level of production of energy through RES (20% for the EU and a target for every single countries depending on their starting points). With the horizon of 2030, the target has been revised up to 32% of the energy used coming from RES. These targets refer to the total balance of energy in the EU, while in the power sector itself the share of RES is considerably higher (to compensate for the heavy dependence of the transport sector to the fossil fuels).
The Clean Planet for All strategic vision promotes an 85-100% reduction of GHG production from the energy sector by 2050 and thus nearly complete decarbonization of the power sector [51]. With the

Green New Deal, the target is climate neutrality of the entire block which necessarily entails net-zero GHG emission in electricity production [22].

1.1.2 European Electrical Grid

Physical Layer The European Electrical Grid comprises: the generation plants and units, the transmission infrastructure which operates at high voltage, the distribution grid operating at a lower voltage, the connected loads, the interconnection with countries in the block and foreign nations.

41 is the number of countries directly involved. These comprise the entirety of the EU and, electrically speaking, the countries more connected to it: Albania, Andorra, Austria, Bosnia-Herzegovina, Belgium, Bulgaria, Switzerland, Cyprus, Czech Republic, Germany, Denmark, Estonia, Spain, Finland, France, Greece, Croatia, Hungary, Iceland, Ireland, Italy, Lithuania, Luxembourg, Latvia, Malta, Monaco, Montenegro, North Macedonia, Netherlands, Norway, Poland, Portugal, Romania, San Marino, Serbia, Sweden, Slovenia, Slovakia, Turkey, the United Kingdom, and Vatican City. This block of countries will be referred from now on as the EU++ group, Figure 1.1.

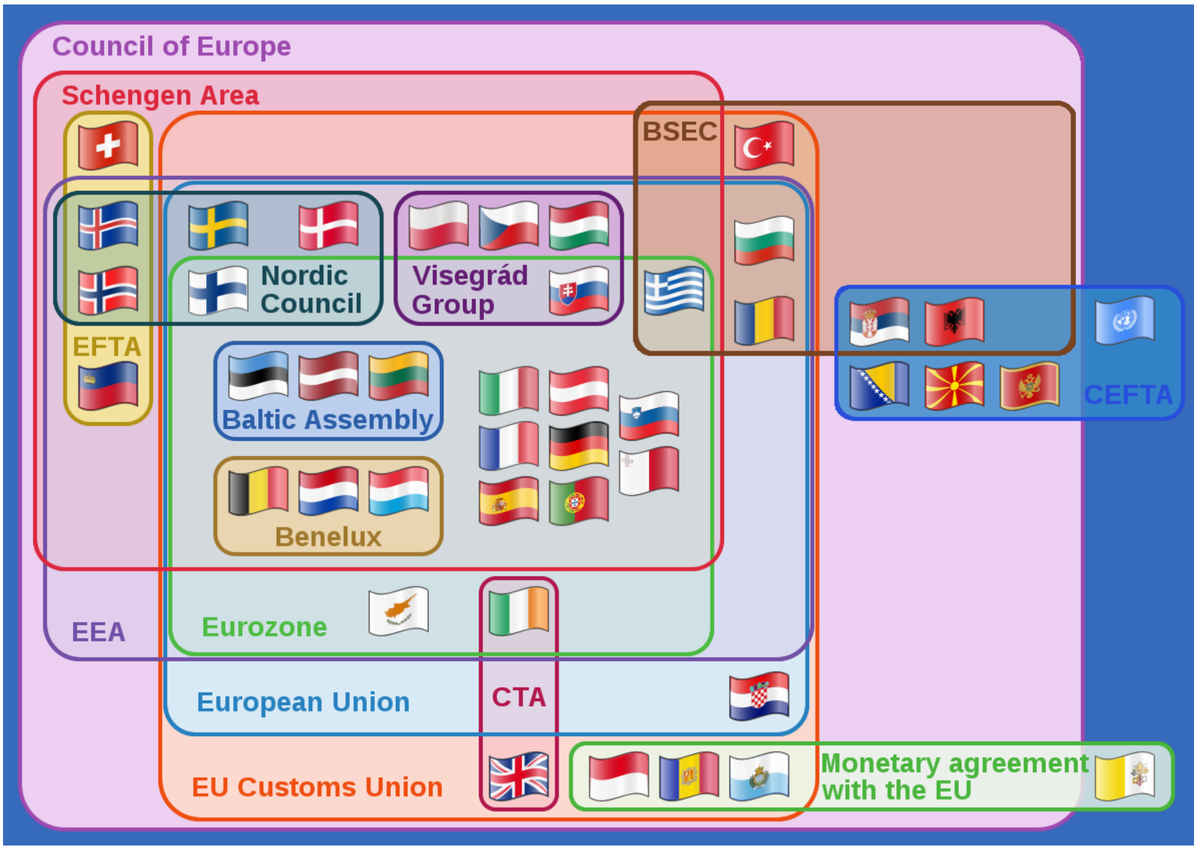


Figure 1.1: Euler diagram of European Countries Involved in the study

The entire region is made of 5 synchronous areas all operating at 50Hz (Iceland and Cyprus are the only two countries disconnected to one of these areas) as shown in Fig.1.2. The total end users in this system are more than 530 million and the amount of energy at play is in the order of 3300 GWh [45].

Due to the overmentioned figures and facts, the overall European Electrical Grid is the largest of the World.

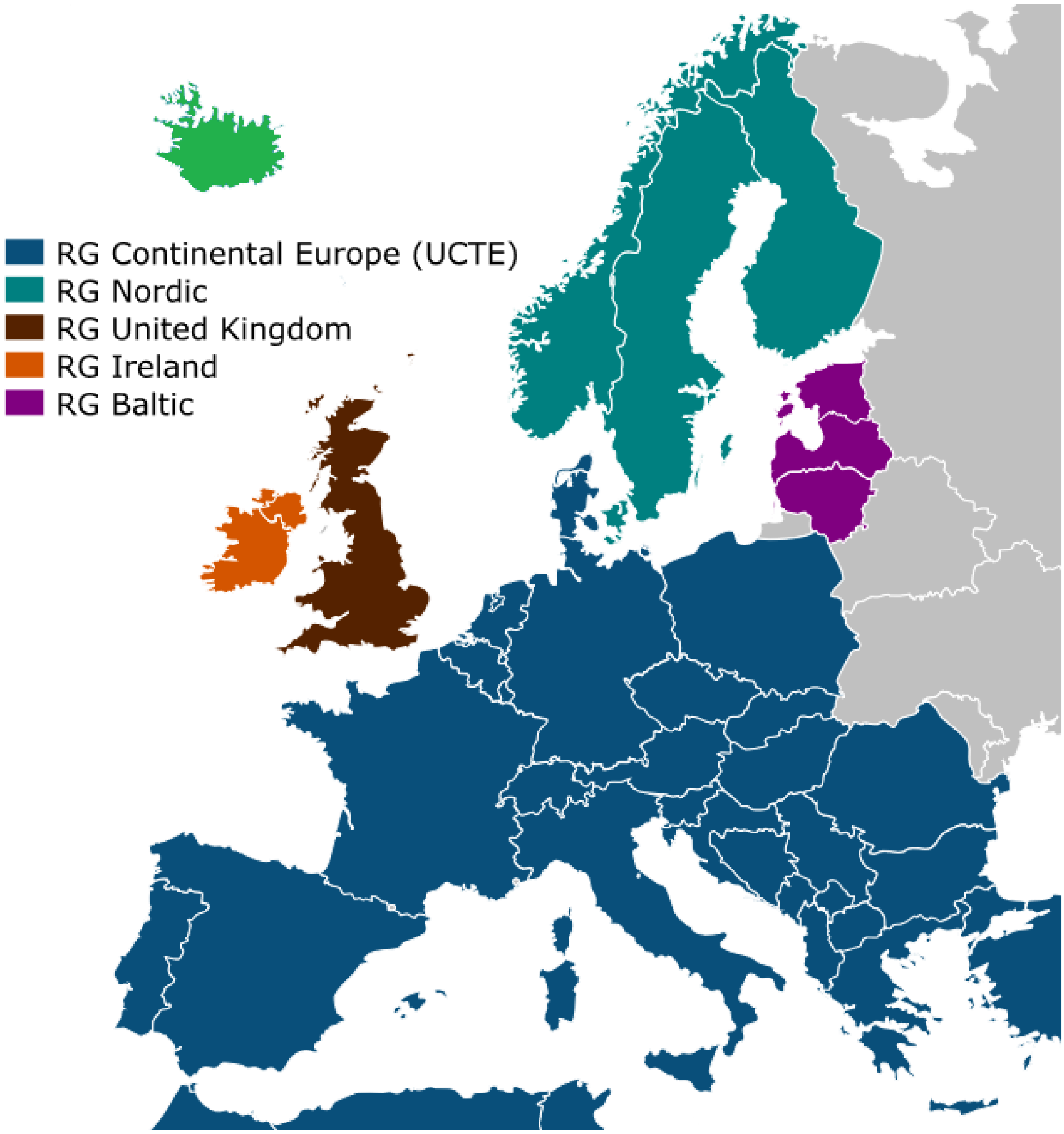


Figure 1.2: Subdivision of the EU++ group in synchronous areas

Market Layer The dispatch of energy production is based on the "Day-ahead market" and the "Intraday market" [30].
Market wise, the EU++ is undertaking a transformation towards market coupling, based on competition between producers in the block that stem from the liberalization reforms initiated in the early 2000s.
The goal of the market coupling is the lowering of electricity costs and the elimination of price differences between countries through the harmonization and integration of the previously mentioned markets across borders [92].

2006 marked the beginning of the integration between national markets with the Trilateral Market Coupling. At the moment, 19 countries of the EU, comprising 85% of the European electricity consumption are integrated into the Multi-Regional Coupling (MRC). In this process, the allocation of cross-border transmission capacity is combined with transnational electricity trading.
The forefront innovation in this field is the 2015's Flow-Based Market Coupling institute between France, Belgium, Germany, and the Netherlands, in which the allocation of capacity transmission takes place

at the same time as the price clearing [72].

Responsibility Layer Who is in charge of the European Grid? Who decides the investments necessary to provide the security of supply?

In the classical centralized view of the electrical grid, the end-users are generally served by the capillary distribution grid. The owner of these sets of infrastructures is called Distribution System Operator (DSO).
Their role, up until now, is to manage the flux of power from the higher voltage grid towards the load. Recently, and especially in the future, the flow that they have to supervise is increasingly more bidirectional due to the presence of small, distributed, energy sources (e.g. rooftop Photovoltaics (PV) panels) [10][98].
The size of this actor's area of influence is regional, for instance, Bulgaria is covered by 3 DSO while France is served by 5 of them (these cited DSOs are those who reach at least 100000 users). The size of a country does not directly entail the number of DSO in a country.

One level above stands the Transmission System Operator (TSO). Their responsibility is upon the high voltage grid that facilitates the movement of power flux from the region of production to a zone of demand. Contrary to the mostly radial and circular architecture of the distribution grid, TSOs manage a complex meshed web of Alternate Current lines and, now more than ever, Direct Current connections [40].

The region covered by these Operators is comparable to the European countries. Only Germany, the United Kingdom and Austria are served by more than one TSO. Due to their inherent monopoly nature, these operators are highly regulated in Europe to provide the highest level of quality of service to the citizens and entity requesting electricity [67][76].

The coordination, trust, and collaboration between TSO have been increasing steadily in the past two decades. The present form of this coordination is the 2008 established association called European Network of Transmission System Operators for Electricity (ENTSO-e), which now represents the 43 TSO of the EU++ block, see Fig.1.3[44].

The key collaborative activity that takes place in the ENTSO-e is the biannual creation of the Ten Years Network Development Plan (TYNDP), which pulls together the plan of the local TSO for the drafting of the only pan-European grid development map. The Association provides long term generation adequacy forecasts, network codes, and transparency inside the European electrical sector [40].

1.2 Problem Description

The modern electrical grid is characterized by the structure and national thinking of the mid-20th century [30].

The production takes place in centralized large capacity plants, the majority comprised of thermal units that employ fossil fuels. The demand for electricity is fairly predictable at a system-level and for this reason, the production plants can be categorized in baseload plants, intermediate-load plants, and peak plants. Baseload plants are characterized by low marginal cost, are the most used plants and their flexibility is limited. The peak plants conversely have higher marginal costs, cover the limited hours of high demand with their flexibility. The balance of power between production and demand is assured through reserve balance: a range of power from production plants available to the TSO to compensate short time horizon mismatch. Lastly, thermo-plants use control mechanisms to assure voltage and frequency stability by adjusting their working point [76].

The flow is from a small number of plants, towards the load close by. The flow is unidirectional, and the frequency of the system is preserved by the huge inertia provided by directly coupled rotating mass in the generation units [30]. This past vision of the electrical system is not suited to respond adequately

Figure 1.3: The TSOs of the EU++, together with their interconnections [44]

to the challenge of the climate crisis and the changes it requires. For once, the thermal plants need to ditch the source of fuel which they had relied on for more than a century. Secondly, the electrification of the transportation and heating sector (which usually relies on petroleum products and gas) entails an increase in electricity demand and a possible disruption for the actors in the sector of the predictable load they are used to. Thirdly, and most importantly, the technology of the new variable Renewable Energy Source (vRES) isn't the best match for the electrical system as described in the section above.

These vRES can be considered, in the first approximation, the present wave of solar PV modules and Wind Turbines. Their output cannot be freely controlled in the same way as thermo-plant or a hydroelectric dam. It depends instead on the availability of the natural flow they depend on; it is thus defined Intermittent. As a consequence, the Residual Load Curve is more volatile, harming the economic incentives on which the classical power system is based on [69]. The output can only be curtailed, up to complete shutdown. The production is thus only predictable and subject to the uncertainty of weather forecast. The interconnection between the source of energy end the grid is mediated by power electronics which in the current gross market of RES technology don't provide the necessary synthetic inertia to safeguard the frequency of the grid [70].

To solve the challenges posed by this energy transition, the electrical grid needs Flexibility [63]. It can be provided in four main ways:

- **Flexibility from the supply side** It is created in two ways: through curtailment of Renewable production, and production from the more flexible power plants.
  Curtailment can be sometimes the least cost alternative to reduce RES production [66]. Present-day Cycle Gas Turbine (CGT) have the capability to follow the fast dynamic of vRES production. The economic incentives for a system entirely based on variable renewable and CGT are still lacking due to the high marginal cost of CGT and virtually none for vRES [63].

- **Flexibility from the demand side** Smart grid and demand response are solutions in which technology, economic incentives, automation, and behavioral science combine to allow the load demand to follow the aleatory production [19][61]. A base form of demand curtailment and retribution is already at play in today's grid [30]. A full-scale implementation of these solutions has to cope with the basic principle of electricity as readily available commodity and the actual response of costumers to price signals.

- **Flexibility from large scale energy storage** The foundation of this solution is the creation of an energy buffer that can disconnect the instantaneous production from the load, allowing in this way flexibility on time domain. No single silver bullet technology can respond to this kind of challenge because of the different time horizons to cover and services provided to the grid. Short-time flywheel systems have a very different time span than a CAES system [61]. Hydrogen provides distinct services compared to a supercapacitor [61]. The R&D in the sector, following the example of PV and wind turbine technologies, is moving fast to improve the performance and bring down the costs [100].

- **Flexibility from transmission interconnection** Solar intrinsic variability is characterized by a diurnal cycle, wind's annual. The weather patterns that impose a more erratic production is constrained in the Synoptic scale (1000km and/or days to a week). This means that by pooling resources together from a larger area the stochastic variation can be even out. Transmission of power over long distances and across borders allows the unlocking of flexibility necessary to allocate cheap renewable energy produced where there is demand and the costs are higher [63][75].

These four main solutions are not, and should not, be considered mutually exclusive. Where an extensive transmission plan between two zones would result to be too costly, a solution of local storage could be more efficient. Where the demand response cannot be economically efficient, building overcapacity RES to then curtail it in the moment overproduction can be a viable solution.

What we can infer is the constant presence of a trade-off between these solutions, based on the technology improvements, economic opportunity, and public acceptance.
This web of choices is constrained by the different levels of stakeholders involved, the urgency of the climate crisis, and the inertia of the system.

The actors range from policymakers setting goals and enabling advantages for specific technologies to lobbies for special interests, from knowledgeable citizens requiring a fast change to those who prioritize a different kind of investments, and from operators that have to cope with a more challenging grid to the industry regime dealing with this fluid environment.
The urgency can push to compromises that could promptly reduce some CO2 emissions instead of waiting for new developments, speed up the rate of adoption of certain technology above the sector's standards or lead to sub-optimal decisions that cause lock-in situations.
The inertia is simply due to the massive infrastructure at stake, the long-term type of investments and the consequent conservative decisions made over this system.

1.3 Research Objective & Research Question

It is inside this vast and fascinating field, in the merge of technology, economy, policies, and behaviors, that this thesis takes place.
The research is directed towards the necessary reduction of the impact of the electrical sector. More specifically, the thesis will deal with one of the four previously mentioned ways in which to provide flexibility to an electrical system in which a high share of vRES is present: Flexibility unlocked from transmission interconnection.

Europe, compared to other macro-regions in the world, benefits already from a well-developed and connected transmission system for electrical energy but it has to be improved. Due to its forged political unity, population density, and relatively small states, a much more interconnected grid is feasible and desirable.
This thesis will thus narrow its focus to the European electrical grid, as an example of development

for the rest of the world. More specifically, we will look at the expansion of interconnectors between countries. Looking at the internal bottleneck of single countries is generally outside of the scope of this project due to the already accumulated expertise at the national level on this subject. Nonetheless, examples of internal grid constraints affecting the cross-border exchange will be present, together with specific nation focus due to their specific location or condition.
The final boundary will be the time frame. Generally, the long term goal of the EU concerns 2050 as final deadline to reach carbon neutrality. Beside the 2030 targets there are not so many points in between. This study will not look at just the outcome, it is more interested in the process that can push the adoption of RES as soon as possible. For this reason, we will examine what has to be done to reach the 2050 goal, by 2040.

As such, the main research question becomes:

> *How to enhance the contribution of flexibility in the European power system to reach rapidly a decarbonized electricity production through cross border interconnection by 2040?*

The other 3 forms of flexibility are not going to be discussed with the same level of detail and attention but are always going to be considered part of the solutions. This main question will be tackled with sub-questions. The first one, and principal, regards the actual infrastructure necessary. The second one, and more marginal, reflects on the issues and possibilities of the grid expansion

1. What is needed in terms of electrical infrastructure expansion to cope with a 60% share of vRES by 2040?
2. Can it be realized?

The result of this investigation is going to be a framework of interconnection capacities, that exposes the most troublesome bottlenecks in Europe. This analysis will allow the actors in the sector to create a more coherent and farsighted plan of action.

1.4 Research Design & Methods

To assess the required transmission capacity between countries solid data are necessary. The starting point is the generation mix and the load trend in the envisioned future. An **Energy Scenario**.
We can already see how the first step introduces a first, and broad, variable parameter. Depending on the type of future scenario the resulting requirements for the grid will be necessarily different (Will decentralized PV panels uptake the majority of energy production? What about worldwide carbon tax or emission credit schemes?). The relevant date are retrieved from authoritative sources.

Then, the calculation for the necessary **Grid Layout** in a specific scenario is usually carried out in integrated and optimized simulation software. The number of variable parameters explodes here with: the scale of space and time used, the number of country considered, the modeling of the power flow, the number of energy carried considered, different power plants, the variable load profile, the specific technical requirements, characteristics, economic aspects of each power plant, the learning curves for different technologies, the policy introduced by the government and the variability of the climate.

The computational and preparation complexity of the simulation needed for entire Europe, without undue simplification that would reduce the insights, exceed the scope and the time constraints of this thesis. For this reason, no autonomous simulation will be carried out over the subject matter. On the contrary the method is to take the results from other simulations. This decision will allow a comparison between different authors, avoiding particular limitations or oversight in their calculation.

Attention will be placed on the process of **Interconnectors** development. From the individuation of the need to its completion.

Finally, through the means of person to person interview, the perspective of experts in the field of electrical infrastructure will be brought in for the development of a cohesive framework and the definition of best practices to recommend. This is a fundamental passage in order to bridge the gap between academia and the actual implementation, between the aspiration and hypothesis of the theoretical world and the reality of taking difficult decisions in the work-space.

The goal of achieving a faster energy transition will insinuate itself in all the aforementioned aspects of the thesis research.

Chapter 2

Literature Review

We will forever be know by the tracks we leave behind us. - Dakota Saying

In this chapter, the employed literature is explored. The method with which it was founded and selected is explained and summarized in one flow chart scheme.
Consequently, an initial analysis of the various scenarios for Renewable Energy Sources growth and development is carried out. Then, different simulations analyses are briefly compared between each other's and their assumption are confronted with the previous studies and the current literature. Near the end of the chapter, leading studies that influenced this thesis are addressed.

2.1 Methodology for literature research

Two concurring methods are intertwin with a feedback loop to create a general strategy. First, the definition of search engines (Google Scholar, Scopus, e Elsevier) and related keywords to the thesis topic (RES, Forecasts, Electricity, Grid Infrastructure, EU, 2030, 2040, 2050, North Sea, Curtailment, wind, PV, biomass, flexibility, Demand Side Management (DSM), storage, acceleration infrastructure, etc.). Google was also used to find special reports of the ENTSO-e body, the EC or the most recent development over EU law, e.g. the debate and resolution concerning the 70% rule for interconnections.

Once the academic search engine returned different findings, a process of scanning and evaluation took place to reduce the overwhelming number of matches. The abstract, if present, has been read and confronted with the most up to date information in the sector (e.g. a study from 2010 over the storage outlook in the EU, even if well done, results completely outdated when looking at the assumption of the research). Alongside with the abstract, the number of mentions has been an interesting factor to contemplate to assess the relevance of the paper.

With this consideration at hand, the different papers where picked or discarded. An attention regarding the balance between opinions and stands have been always present to avoid possible personal biases, e.g. to avoid the confirmation bias over the possibility of reaching the 2030 and 2050 targets and goals, papers from the "European Wind Energy Association", in which, necessarily, wind is regarded as the go-to technology to successfully navigate the energy transition, are confronted and paired with articles from Professor Vaclav Smil, which propose a much drier and conservative view of the eventual energy transition.

The other source of References for this project has been the suggestions from the 2 supervising professors and the experts in the field: during the weekly meeting or over mail, their direct knowledge, read articles or published works have been fundamental to enrich the thesis with a broad scope and at the same time fixed anchors to which come back for guidance.

Connecting these two methods, a feedback loop allowed me to increase the sources in what is called the "snowball effect". During the reading of an article some references are mentioned concerning useful data or assumption, if the data presented was founded useful and relevant a new research using that information or directly the referenced paper was conducted, reconnecting with the steps of the first method. A model of the process is expressed in Fig.2.1 .

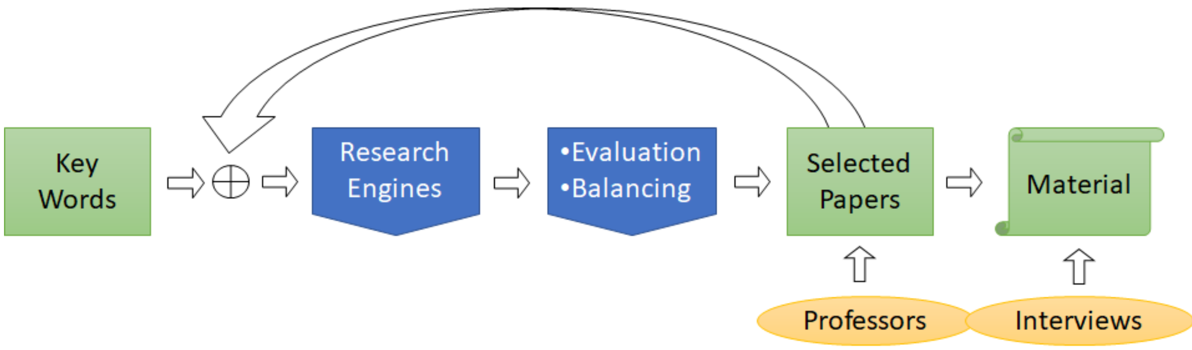


Figure 2.1: The method of research is summarised, with the feedback loop highlighted with the overarching arrow

As can be imagined, this global method of literature review has led to an exponential growth of different branches which had to be periodically chopped off to focus on the main research question.

2.2 Studies over EU RES expansion in the power sector in the coming decades

To formulate the Energy Scenario for the thesis research a baseline has to be found and considered. In this case, the most updated source on the European continent is the most valuable. The European Commission releases a biannual report for every MS. Unfortunately, even the 2020 June edition updates data up to 2018 [32]. The 2019 situation for Europe is thus assessed with reference to the most recent report from the think tanks Sandbag and Agora Energiewende [13]. The Thesis is concerned with the future outlook for the EU++ region. More precisely, a future that sees the power sector reducing the emissions of GHG and complying with the Paris accord.
This kind of scenario is not a foregone conclusion. Different authors come to various conclusions, especially if different assumptions are taken into consideration.

For instance, Heide [56] models a 100% Energy Europe using only solar and wind. This research looks only into the natural availability of these resources, concluding that the future of the European Energy can come from a combination of 55% wind and 45% solar for power generation. The need for storage equivalent to 1,5-1,8 times the monthly load is calculated for vRES as only sources, and the balance of wind and solar results much more in favor of wind in case of other controllable sources considered in the mix.
Looking to just a natural potential a fair assessment is impossible. Moriarty makes a point over the number of filters that are present between the raw energy potential and the effective usable share [70]. There are firstly geographical constraints to consider (deep sea, icecaps, high mountains, forests, natural reserves, and for some technology urban centers). Technical constraints are of course at play in reducing the potential (efficiency of energy transformation and power delivering through long distances). Important to consider is also the parameter of energy return on energy invested (EROI), which could be too low for some technologies. There are inputs of energy needed for manufacture, erection, maintenance, operation, and decommissioning for every power plant. The sum of these amounts should be quite smaller than the average lifetime output, only net energy (the difference between output and input of energy) can power the other economic sectors.

To select the most appropriate scenario elaborators, these have to be widely recognized as authoritative and relevant to our focus of research. **Least-cost options and policy development are the two main parameters that entail the results of an Energy Scenario**.
Partisan visions, such as the ones provided by the Wind Europe (ex EWEA) [49] and the Solar Power

Europe [93], are not considered. Their obvious involvement with the RES development cannot provide an objective outlook of the respective technologies. Even if it provides an interesting perspective to this analysis, the work of de Llano-paz et al. on the mathematical model that analyses technologies according to a cost–risk binomial will be left aside [31]. In this field, a 5 years old study starts to became quite outdated. On top of that, in its risk assessment, the public perception is not considered. One relevant notion is the effect of the dependency on the European continent to foreign hydrocarbons, which yearly drains 3,1% of its GDP. A variegated mix of RES would thus reduce the risk associated with vulnerability to foreign disruption for the power sector and retain capital in the European area.

For these reasons, 4 different sources have been selected for the thesis research because of their in-depth knowledge of the two overmentioned parameters.

- **European Commission** As the source of Europe wide policy on climate and energy, it has an honorary spot. It is the source of the 2030 goal for the GHG reduction and RES expansion. The scenario EUCO3232.5, which is used as a base for impact assessments and the negotiations of the legislative acts proposed under the EU 2030 energy and climate policies, is used in this thesis. Developed in November of 2019 by E3-Modelling, a Greece based consulting company, this simulated scenario has already built-in it the reaching of the previously mentioned goals. The modeling tool applied is the PRIME model (Price-Induced Market Equilibrium System). It simulates the entire energy system of Europe considering demand, supply, prices, investments, behavioral components of microeconomics, and engineering constraints. This scenario is used to set the 2020 levels of EU's power production.
  To extend this scenario "A Clean Planet for all" has been reviewed, and the baseline outlook for the power sector has been used for the definition of the long-term European vision up to 2050. This proposal, issued in November of 2018, is a set of documents analyzing different options for long-term policy in the energy sector. On top of the baseline scenario, 8 envisioned options reach levels of GHG reduction ranging from -80% to -100%. Only the baseline allowed for a comparison of variable RES, for this reason, it is combined with the EUCO3232.5 to provide the outlook for the next 40 years according to the EC.

- **IEA** The next source of relevant forecast and foresight scenarios is the International Energy Agency (IEA). This intergovernmental agency was selected for its comprehensive scope in all fields of energy maturated in 40 years of experience. For these reasons, IEA is regarded as the most authoritative figure in the energy sector worldwide. The World Energy Outlook (WEO) is its main report, released annually. In it, the policies implemented by the nations worldwide are modeled and the results are returned for reflection and evaluation. In the past decades, the agency has started to put significance on the feat of sustainable development and, more recently, decarbonization of the energy sector. This new perspective is reflected in the 2019 WEO reports, which presents not only two reference outlooks for enacted and proposed policies but also one in which the energy sector complies with the Paris Accord.

- **IRENA** Another set of studies considered is the one formulated by IRENA in 2018 and 2019. IRENA is the International Renewable Energy Agency. With 161 countries adherent, it is the largest intergovernmental organization that focuses specifically on a sustainable energy transition. It promotes the widespread adoption and use of all forms of renewable energy, provides full support in knowledge sharing, and policy recommendations. These are the two main reasons for its selection.
  The first one provides an in-depth economic analysis of what is feasible to develop with the European renewable potential. The work was carried out in consultation with Member State through several workshops and sectoral webinars. This study directly confronts the reference case of the EU with a scenario, called REmap, which exploit all the additional option to use the European renewable potential. The second report, issued the following year, expands this finding and elaborates on the REmap for Europe and the entire world, up to 2050. It states that the REmap comply with the objectives of the Paris Agreement.

- **ENTSO-e** Finally, the report elaborated by ENTSO-e has been necessarily considered. The TYNDP starts with some future scenarios for which the agency is preparing itself. Since the outlooks are prepared jointly with the experts in the field, this document can assess the probable future envisioned by those who have a grasp of the real European energy world.

To summarise, the Scenario outlooks have been retrieved from the most authoritative sources that produce a comprehensive assessment on the basis of policy implementation and technology economics. In Chapter Two, the selection of the relevant scenarios for this research will be based on the fulfillment of the Paris Accord goal.

2.3 Grid Outlook Framework

The scientific attitude towards improvements is based on trial and error. For small systems it is normally possible to create a mock-up version, try some changes to its functioning, evaluate the results and then implement the desired changes into the original one, or into directly a new version of it.
In the case of inserting RES technologies in the complex physical constrained electrical grid, testing directly on it is not a viable option. One of the core aspects of a wide electrical grid is its necessity to stay operative as much as possible, avoid any disruption of power provision and any damage to the system itself. Due to its large nature, it is also unfeasible to build a mock-up version of a continent-wide system just to assess how it could react to different scenarios.
This is the main reason why modeling and simulation are integral to grid development. The law of nature governing the electrical, mechanical, and magnetic aspects of the grid are described through equations and clusters of basic modules. The complexity that arises from this operation demands computer assistance, to resolve these systems of equations, constraints, and problems of optimization.

To produce a relevant grid outlook in this thesis, a confrontation of previously developed models and simulation is carried out. The selection of said studies is of capital importance. Unfortunately, in contrast with the previous section on energy outlook, there aren't authoritative studies on the European Grid development beside the TYNDP. It could be more accurately described as an internal report of a firm, that develops a strategy for its own operation.
There are many studies on the electrical grid of Europe or its MS. The selection of other studies is based on three basic factors:

1. The oldness of the report. In this field of simulation, the innovation is rapid. Methods and assumptions taken years ago cannot be considered updated right now.

2. Space consideration. The vastness of the area modeled and the refinement of resolution.

3. Timespan. The behaviors to simulates are quite different. On one hand, the short-term variation of power generation, consumption, and flows determines the stability of the system (PSAT) [84]. On the other, long-term balances on the month's scale or the annual one determines the change of operation and investments (ODS & IDS) [84].

Regarding the first variable, a hard limit of 2010 as the oldest possible simulation was set. With this being said the oldest selected was from 2011 and the most recent was published in 2020. With the average of the selected studies being published in 2015.
Considering the EU++ region, by selecting only those who comply with this strict definition, only the work of ENTSO-e would have been selected. For this reason, the first parameter has been selected more flexible: at least 90% of the load in the EU++ area should be considered in the modeling (e.g. the omission of Malta and Cyprus wouldn't affect the yearly total energy consumption of more than 0.3%). On the other hand, the refinement has been decided to be at least countrywide. Sub-national division (a.i. creating more nodes for each MS) would provide more insights but are generally non-common.
Thirdly, the maximum time refinement for the stability simulation is selected to be one hour. This ensures at least the capturing of the daily variation for solar and wind power generation. It is also in line with the electrical market as it is right now. On the other hand, the timespan of the simulation needs to be at least a year, and not a week or some months. Many models manage to optimize the grid expansion by looking at the single year bottleneck, but the multi-year or even better multi-decennial simulations would reflect the time evolution of needed grid expansion.

By using these reasonable parameters 12 recent simulation studies for the European Electrical Grid Infrastructure have been retrieved, see table 2.1. Between all of these, the study from Jaehnert et al. investigates only the Nordic countries around Norway. It has been considered nevertheless for its thorough consideration and modelling of the hydro-power potential of the region.

As it is explained in chapter 3, the selection of the results from these simulation depends on other two factors: the share of vRES modeled in their respective scenarios (or conversely the amount of CO2 emission reduction from the 1990 level), and the level of demand considered for the European block. These two final parameters are used to compound the weighted average of suggested interconnection capacity, in order to comply with the envisioned level of vRES by 2040. This calculated average would provide a more balanced assessment, reducing the effects of arbitrary assumption or data restriction in every single study.

Authors	Year	Model	Purpose	Methodology	Model Horizon	Area Covered	Time Resolution	Spatial Resolution	Production Power Plants
ENTSO-e (TYNDP) [40]	2018	Own	ODS & S	SM	20 y	EU++	Hourly	Regional	Solar, Wind, Hydro, Nuclear, Gas, Coal, other RES, other fossil fuel
ENTSO-e (e-Highway) [37]	2015	Antares	ODS & S	SM	35y	EU++	Hourly	Sub-national clusters	Solar, Wind, Hydro, Biomass, Nuclear, Gas, Coal
Brown et al.[11]	2018	PyPSA-Eur-Sec-3	ODS & IDS	OM (linear)	1y	EU++ - Cyprus -Malta	Hourly	Country	Solar, Wind, Hydro, Gas
Schlachtberger et al. [89]	2017	PyPSA	ODS & IDS	OM (linear)	1y	EU++ - Cyprus -Malta	Hourly	Country	Solar, Wind, Hydro, Gas
Becker et al. [8]	2014	Own	IDS & S	OM (linear)	35y	EU++ - Cyprus -Malta -Baltic Republics	Hourly	Country	Solar, Wind, Gas
Fraunhofer ISI [77] [90]	2011 - 2014	ResInvest & PowerACE-Europe	ODS & IDS	OM (linear)	35-40y	EU (-Croatia) +Switzerland +UK	Hourly	Country	Solar, Wind, Hydro, Biomass, Nuclear, Gas, Coal, Lignite, other RES

Zappa et al. [99]	2020	PLEXOS	ODS, IDS & S	OM (mixed-integer linear)	1y	EU + Norway +Switzerland	Hourly	Country	Solar, Wind, Hydro, Biomass, Geothermal
Jaehnert et al. [59]	2013	EMPS & own profitability investment algorithm	ODS & IDS	SM & OM (linear)	20y	Norway +Sweden +Finland +Denmark +Germany + Netherlands +Belgium +Great Britain	Hourly	Clusters & Country	Solar, Wind, Hydro, Biomass, Nuclear, Gas, Coal, other fossil fuel
Brown et al. [12]	2016	ENAPLAN	ODS & IDS	OM (linear)	1y	EU++	Hourly	Regional	Solar, Wind, other
Rodríguez et al. [85]	2014	CVXGEN	S	OM (linear & quadratic)	1y	EU++ - Cyprus -Malta	Hourly	Country	Solar, Wind
Gils et al. [52]	2017	REMix	ODS& S	OM (linear)	1y	EU++ - Cyprus +Ukraine +Belarus	Hourly	Countries grouped in Regions	Solar, Wind, Hydro, Coal, Gas
Knopf et al. [62]	2015	LIMES-EU	ODS, IDS & S	OM (linear) & EM	15y	EU++ - Cyprus -Malta	5y	Country	Solar, Wind, Hydro, Biomass, Coal, Gas, Lignite

Table 2.1: Used simulations. Additional methodology labels: S - Scenario, SM - Simulation Models , OM - Optimization Models, EM - Equilibrium Models [84]

Chapter 3

RES and Infrastructure expansion

The magnitude of our challenges has to be met by the measure of our actions

This chapter is dedicated to the exploration of future energy scenarios, by confrontation of the previously selected energy outlook. A bolder future to aim towards is proposed and discussed.
Secondly, a review is carried out of completed European grid simulations in the condition of high RES penetration. Similitudes are highlighted and, through the evaluation of their assumptions, a design of the grid, that can satisfy the bold energy envisioned above, is determined. The decision of the appropriate interconnection capacities are going to be calculated through weighted average of the optimization results of the different papers.

3.1 European Energy Outlook

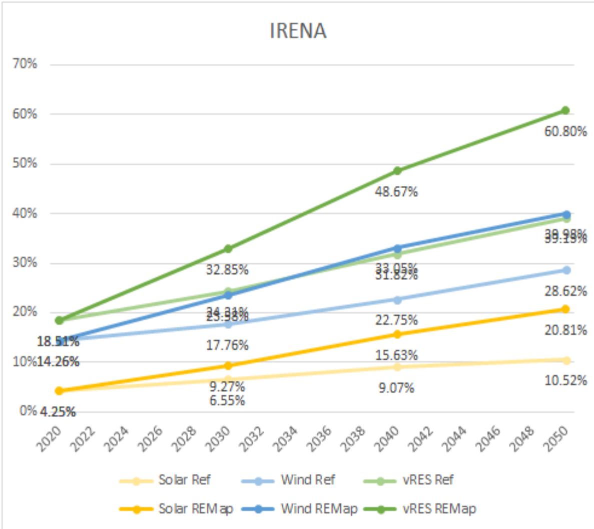
Of the energy mix, the most taxiing share is the one referred to vRES [84] [4]. At the moment of writing, this labeling compromise mainly photovoltaics technology and wind turbines. These sources are characterized by the instantaneous transformation of flux energy sources into electrical energy. These technologies pose stress on the power balance management of the grid, due to their "uncontrollable" source . These are the technologies who require more flexibility in the energy systems [68] [98][63].

Sources like dams with hydro potential energy, biomass burning facilities, molten salt solar and geothermal plants are characterized by more controllable power output [98]. There are new technologies on the horizon, like the marine energy harvesting tidal and wave plants. These European lead innovations directly transform a flow of kinetic energy in electrical power (much like wind turbines). Firstly, due to their nature, these technologies are envisioned to have a much more uniform or predictable output [64] [97]. Secondly, their development is in the testing phase right now, so we are going to omit their contribution to the variable energy mix for now. This assumption would probably age poorly the closer we get to 2040.

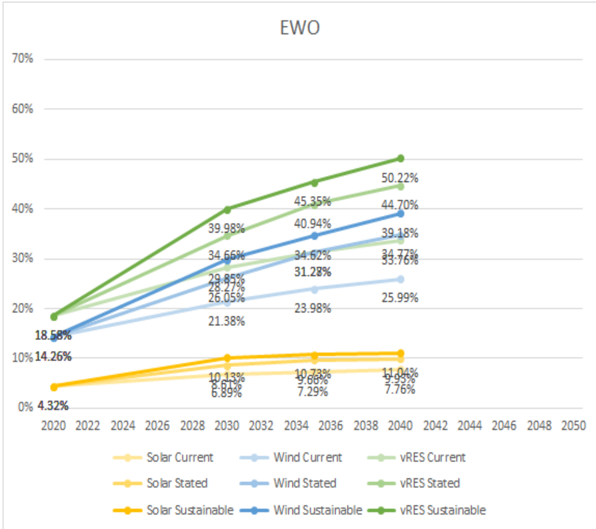
For these aforementioned reasons, the rest of this energy confrontation will be carried out through the examination of the level of wind and solar power production over the years. In the entire chapter, when confronting data of vRES, the color yellow identifies PV technology while the blue refers to wind power plants. The green is simply the sum of them, as it is for color theory. The scenarios from the next 4 studies are summarized in Fig. 3.1.

IRENA 2019 report [58]

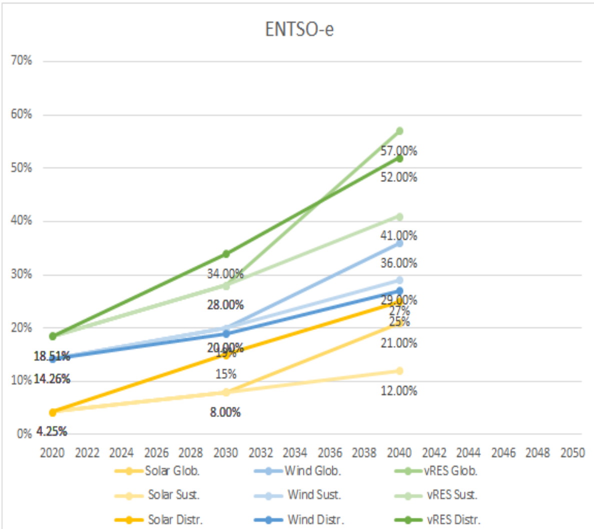
The International Renewable Energy Agency (IRENA) highlights 2 main scenarios: one in which the stated policies, and plans, are carried without any addition or efforts (reference scenario), the other in which a "transformation of the global energy system that limits the rise in global temperature to well below 2 degrees Celsius above pre-industrial levels" is proposed, the REMap. With this brief introduction, we can already see how the stated policies, until the creation of this thesis, could not deliver the



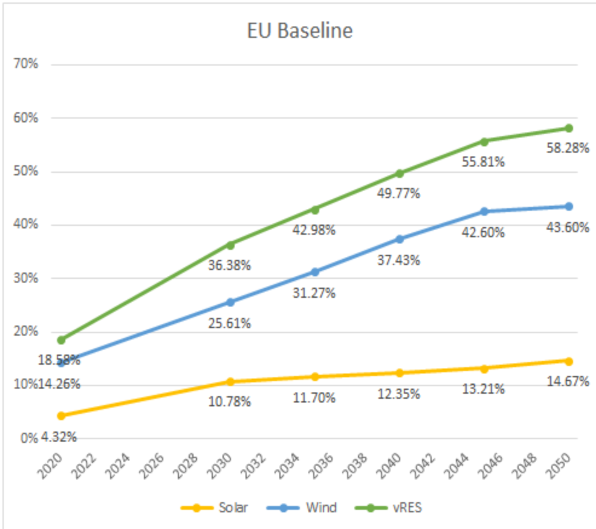
(a) REMap and Reference



(b) Sustainable, Stated, and Current



(c) Sustainable Transition, Global Climate Action, and Distributed



(d) EUCO 3232.5

Figure 3.1: The scenarios from the four energy outlooks examined.

Paris accord goal. On the other hand, the REMap scenario would allow for a 70% reduction of CO2 energy related emissions. Let us see how these visions stack up upon each other (Fig. 3.1a).

As for every following energy outlook, wind exceeds solar as a source of energy and becomes the main power engine of the European continent. The two vision see a fairly linear growth for both technologies. The difference between the sum of vRES arrives at 20%, which is equally spread in solar and wind development. In this sense, by considering its starting point, there is greater difficulty to assess the right rate of growth for PV technology. The boldest future has vRES reaching nearly 50% of electricity production by 2040 and 60% by 2050.

EWO 2019 [57]

The Energy World Outlook (EWO) by the IEA is its annual main report. In Fig. 3.1b, we can examine three different calculated trends. The lower one represents the modeled future if the only policies active in 2019 were maintained forward without any improvements. The seconds incorporate today's plans and policy intentions, similarly to the reference scenario of IRENA. At last, the third one shows the trend necessary to comply with the Paris agreement accord. The Sustainable Development Scenario is consistent with the goal of net zero emission by 2070 and a 66% chance of staying below 1.8 °C above pre-industrial level.

This outlooks express less variability in the solar forecast, while, on the contrary, wind has the largest (3% and 14% respectively). We can observe how the envisioned share of vRES necessary to deliver the reduction of CO2 following the Paris agreement in the WEO is practically the same as the IRENA report (around 49% in 2040). It can be noted, also, how solar technology is seriously understated, especially if confronted with the industry trends. Unfortunately, the outlook spans only two decades, but from the varying rate of growth, it can suggest a generally slowing increase in the following ten years.

TYNDP 2018 [45]

From the ENTSO-e, we are examining the three scenarios used in their last biannual report for the development assessment of the European grid. For the first time, they also used a scenario provided by the EC for 2030 (EUCO30). Then, up to 2040, the three scenarios are elaborated internally with the suggestions from stakeholders of the sector. These scenarios are used in the economic assessments that decide if expansion projects are approved and how much capacity is needed. As we can see in the Fig. 3.1c, these outlooks vary quite significantly, and this brings a considerable test of universality for a new expansion of the grid.

Specifically, the more extreme scenario would be the “Distributed” one. In it, the users who have the capacity to produce energy on their own (prosumers), or even storing it, are at the center. The small-scale energy solutions are ramping. For this reason, the solar share results to be the largest considered in this chapter. It nearly reaches the wind production by 2040, at around 26%. Together the vRES share of energy production would be 52%.

The second scenario, Sustainable Transition, sees national actions as the core drivers, through regulations, subsidies, and trading scheme. In this scenario, the existing infrastructure would be used at its maximum potential. Solar has a similar marginal role as it is in all WEO scenarios, wind has also quite a small quota. The combined effect is total vRES reaching “just” 41% by 2040. These levels should anyway comply with the stated goal of the EU to diminish by 80-95% the emission of GHG by 2050.

The third one, Global Climate Action, the speed of change is supported by large-scale development of renewable projects, also in the gas sector. Both solar and wind see a relevant increase between 2030 and 2040, reaching, with their sum, 57%. The highest level in all considered scenarios.

EUCO 3232.5 [20]

This is the most recent Energy outlook carried out by the EC and provide the baseline for the new policies coming up related to the energy sector. In it, the impacts of achieving an energy efficiency target of 32.5% and a renewable energy target of 32% by 2030 (as agreed in the “Clean Energy for all Europeans” package) are already accounted for. The result of this modelling is a reduction of greenhouse gas emissions in the EU that would be more than 40% compared to 1990.

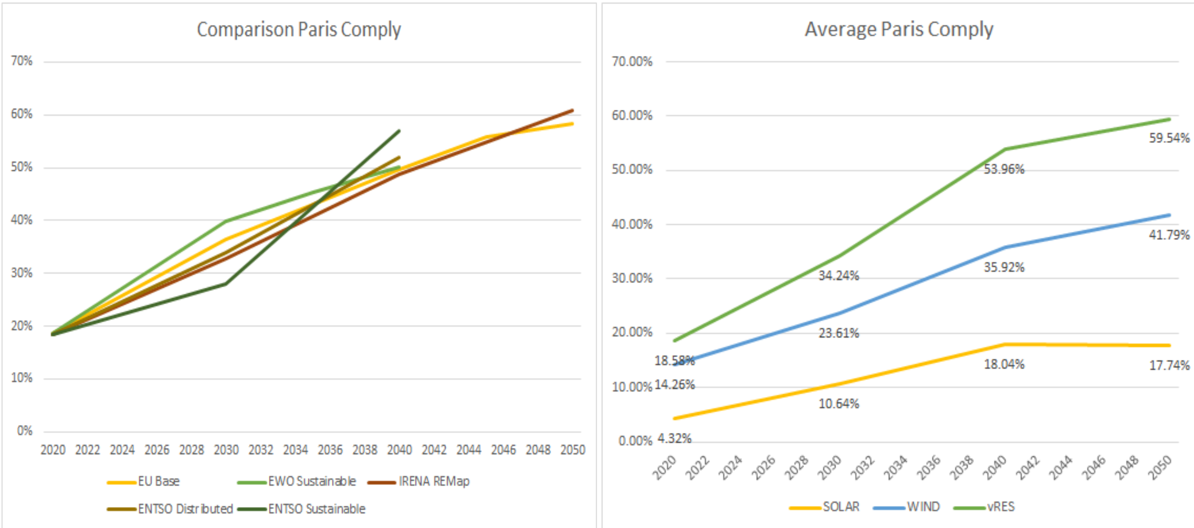
We can notice the clear majority role of wind energy. The pathways shown strike a balance between the different narratives of the previous agencies while keeping the boldness to reach the level of vRES integration necessary to comply with the Paris Accord. The trend also shows relevant growth in the first two decades, while between 2040 and 2050 it slows down. This is the opposite behavior if confronted with the ENTSO vision, but a remarkably similar one if confronted with the WEO.

The value reported until now in Fig. 3.1d refers solely to photovoltaics and Wind Turbine technology. For tables on the in-depth breakdown of energy sources for every scenario please refer to Appendix A.

Choice for the future

The subject of this study is an envisioned future in which the production of renewable energy can promptly deliver the reduction of CO2 required to comply with the goal of the Paris agreement. It is a work of futuring. Of the different kind of futuring, this work operates on the level of Foresight. Envisioning an alternative future from the status quo [78]. We have explored 4 different sets of scenarios. Of the previous, only 5 scenarios manage this result. The comparison of the final levels of vRES is carried out in Fig 3.2a:

- IRENA REMap
- EWO Sustainable
- ENTSO-e Distributed
- ENTSO-e Global Climate Action
- EU Baseline



(a) All scenarios complying with the Paris accord (b) The resulting average

Figure 3.2: The selected scenarios.

To proceed with a clearer picture, it is better to narrow our field of view to a unicum scenario. If a simple average is taken into consideration, the resulting outlook would look a little paradoxical. The fact is that the scenarios that end their modeling by 2040 push this final year's value generally higher than those who proceed up to 2050. The result is a bent knee which, according to industrial history and development assumption seems likely unprobeable. Especially in the case of solar showing a strong increase in one decade and then a decrease in the following period. For reference, the "Average" scenario is reported in Fig. 3.2b.

In order to strike a balance between reported values in the different scenarios and the rate of growth of the different technologies (the convexity in the graphs), the EU baseline is going to be used as the main reference from now onward.

The remaining share of electrical power is delivered mainly by fossil fuels at the moment, with a smaller percentage comprising hydropower and nuclear (10% each). Moving towards 2040, fossil fuel-based thermal plants are going to be decommissioned. The exact entity of this process and the possible remaining share depends on other variables: ETS prices for carbon permits, the introduction of CCU and CCS, biomass usage tradeoff with the agriculture sector, the political will of the governments, the development of Hydrogen infrastructure, fast storage reserve and the decommissioning of the European Nuclear fleet. The hydropower capacity of Europe is generally assumed to be fully used. The improvements that can come out from these plants are the upgrade of the turbine technology and the introduction of pumped storage, when possible.

Our goal is to examine what should be done, electrical infrastructure speaking, to get to this kind of future in a faster way. For this study, 10 years in advance. The reasons for achieving it are multiple: reaching an economic leading role with the irrefutable technologies powering our future, caring deeply for the future of humanity and environment, and taking responsibility for the amount of GHG emission that provided the wellness of the European societies just to cite a few.

The chosen Baseline scenario has to be shifted to be used in the rest of the thesis. The method adopted keeps growth ratios in 2020 the same, while the endpoint is anticipated by a decade. The consequence is an incremental acceleration towards the year 2040. This acceleration is modelled quadratically. For reference, the resulting graph is proposed in Fig 3.3. In the graph is also indicated the 2050 level of vRES envisioned in the "Clean Planet for All" proposal.

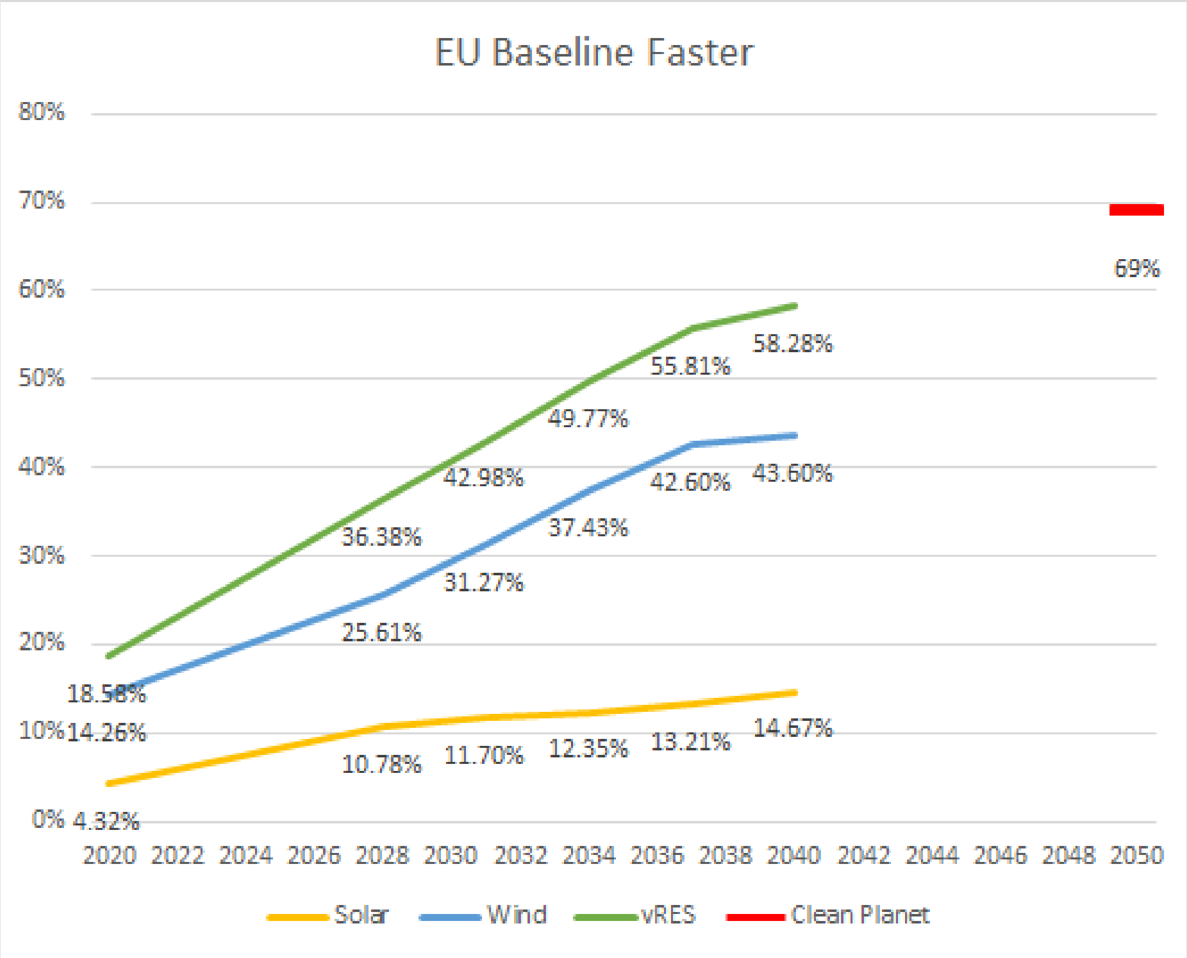


Figure 3.3: The accelerated version of EU Baseline

The amount of Energy demand for electricity is tricky. The electrification of the transport sector and the heating processes is a great unknown of the future. This aspect shouldn't be underestimated because the higher demand do not require only increased production and transmission capacity. It also provide measures of additional flexibility that are not widely used at the moment, thus increasing the uncertainties.

The two scenarios that reach 2050, the IRENA REmap and the EU Baseline, predict a total electricity demand of 4615TWh and 4820TWh respectively. While ENTSO-e and the IEA see in their three

scenarios for 2040: 4016TWh, 4150TWh, and 4450TWh.
Considering the goal of being 10 years ahead of time, the level of around 4200TWh is going to be considered as reference for 2040.

3.2 European Grid Infrastructure Outlook

To understand what the next right step is along the path of decarbonization of the power sector, the correct direction has to be clarified. One part is the energy mix, cleared in the previous section, the other is the consequent electrical infrastructure.

This thesis focusses on the high voltage transmission and, more specifically, the interconnection between countries. We will, therefore, examine the capacity level of interconnection needed in case of high share RES future.

According to the outlook mentioned above, an optimal compromised grid will then be defined. The process to extrapolate this compromise grid is based on a weighted average of the discussed layouts. If the assumption of a study comes closer to the scenario expressed in the previous section, then the results of this study will be weighted more prominently than one which differentiates to much.

ENTSO-e TYNDP [43] [41] [42] [39]

The Ten Years Network Development Plan is the reasonable starting point for this examination. It is the reference document for the entire electrical Europe, in which all the national and international high-voltage projects are reported and promoted. This document has also the role of presenting candidate projects to the EC for the beneficial title of PCI.
The development of this decennial plan needs 2-3 years. Of course, many listed projects will show up time and time again in subsequently TYNDP, until they are completed or dismissed. Right now, 166 transmission projects are listed.
In this report, the three scenarios already discussed in the previous section are used to assess which are the main boundaries present in the continent. These are highlighted in yellow in the Fig. 3.4, while the gray are other important ones.

This Decennial plan has the characteristic of presenting possible 2040 Net Transfer Capacity (NTC) to cope with the demanding situation in the envisioned scenarios. These values are reported in the Annex A and are going to be used as a benchmark for the next documents.
The main takeaways from scenario “ENTSO-e Distributed” & “ENTSO-e Global Climate Action” (the two selected in the previous section) for the ten boundaries are listed in the table 3.1.

#	Name	Increase	Capacity
1	Ireland – Great Britain and Continental Europe	230%	2.2GW
2	Great-Britain and Continental Europe – Nordics	375%	15GW
3	Nordics – Continental West Europe	170%	11.5GW
4	Nordic-Baltic to Continental East Europe	280%	3.1GW
5	Baltic integration	180%	3.2GW
6	Central East integration	800%	4.5GW
7	Iberian Peninsula integration	400%	10GW
8	Italian Peninsula integration	150%	15GW
9	South-East integration	180%	6.5GW
10	Eastern Balkan	260%	11.3GW

Table 3.1: The different envisioned levels of grid increase.

To put information into perspective, following the main research objective, this level of NTC should be reached in 2035. In this way, they would support the renewable energy mix in the envisioned future

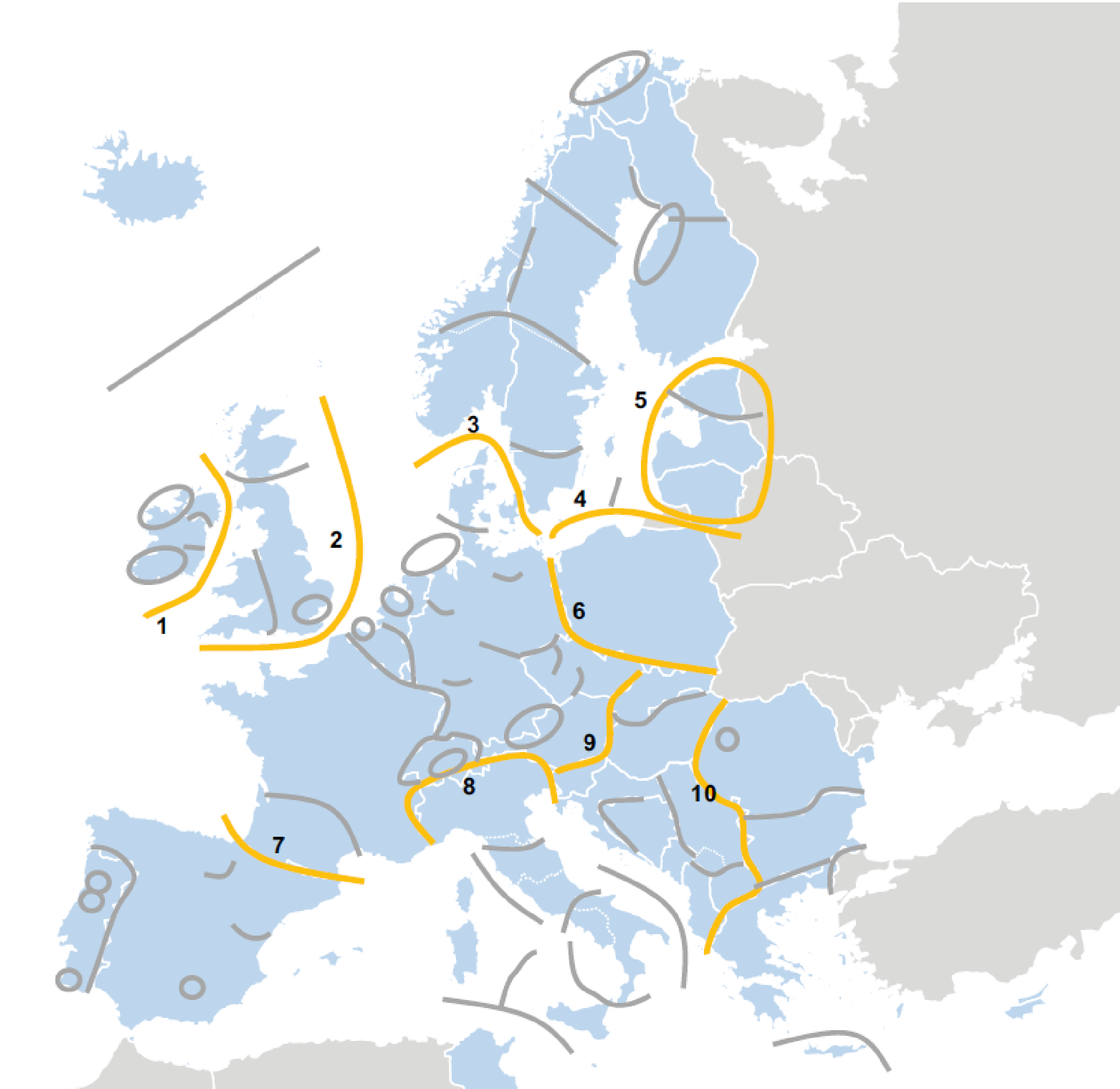


Figure 3.4: The active boundaries in the EU++ [40].

of the previous section.

e-HighWay2050 (2015) [37]

In this combined TSO work, 5 widely different future scenarios were used to guide the grid development up to 2050. It follows a similar mindset as the TYNDP: if a new infrastructure buildup can respond to many different situations effectively then it has higher priority and relevance.
Specifically, the 5 scenarios were characterized by:

1. Fossil & Nuclear. Fossil fuel plants are equipped with CCS and nuclear comprise 25% of the energy mix. A small role for Renewable and centralized processes are preferred. vRES equals 22%.

2. Big & Market. Market-driven; it prefers centralized solutions. vRES equals 42%.

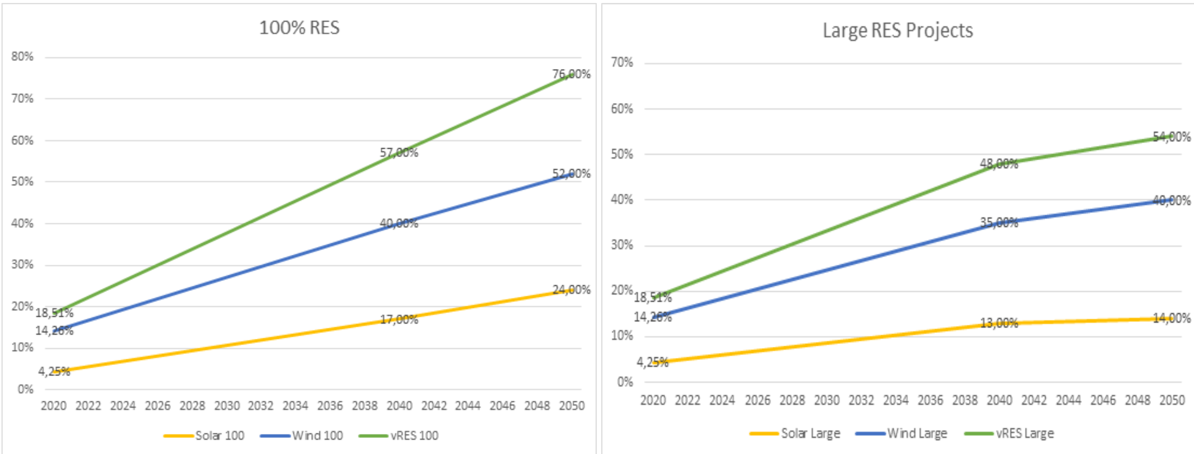
3. Large scale RES. Passive public attitude discourages energy efficiency and DSM. Big centralized renewable projects are envisioned (North Sea Grid and North Africa interconnection). vRES 54%.

4. Small & Local. Decentralized production is the key, energy efficiency is significant. vRES is 51%, with solar providing nearly half of it.

5. 100% RES. By 2050 only renewable sources considered. High electrification and efficiency measures. DSM and storage are used widely. vRES share from wind and solar is 76%.

The report promotes a “compromise” grid which is the average of the grid upgrade necessary between the different zones of Europe in all scenarios. The positive aspect of this result is the highlight of 5 critical corridors in Europe. These areas that need more attention in every scenario are: the connection of Spain-France-British Islands (Boundaries 1-2-7), North Sea Area, the Scandinavian Peninsula to central Europe (Boundary 3-4), Connection Finland-Baltic States-Poland (Boundaries 4-5) and connection Greece-Italy-Austria (Boundaries 8-10).

Of this work, the reconcilable scenarios with the scope of the thesis are the third and the fifth, Large scale RES and 100% RES. The first one comes close to the envisioned future of the previous section, but the dissociation of the public from climate and energy actions seems unlikely for the future of the continent. Nevertheless, it will still be considered in our analysis for the non-marginal role that nuclear could still offer for the European landscape (in the scenario it has a share of 20%).
Fig. 3.5 show the energy outlooks for vRES in the selected scenarios.



(a) The boldest scenario up until now

(b) More centralized solutions

Figure 3.5: The selected scenarios.

The grid layout of Europe with the necessary transmission upgrades are shown in Fig. 3.6 and 3.7. The similitudes between them are striking, with main north-south corridors increased to similar capacity, actively enabling the transportation away of bulk power from solar rich south and from wind-rich north.

Brown’s Synergies of Sector Coupling and Transmission Reinforcements[11]

In this work, the effects of grid expansion and sector coupling are considered together to integrate a high share of vRES. This model simulates many different scenarios, with different levels of storage possibility and integration of heating demand. The energy production investments and interconnection rollout are jointly optimized.
The main finding is the unique role of grid interconnection to bring down the overall costs for the electrical system. In fact, the cost development has a non-linear relationship with the volume of transmission capacity, as it is shown in the Fig. 3.8. The dashed green line highlights a compromise level of expansion that already achieves 66% of the possible cost savings with a greater grid. Thus, the capacity reaches 125 TWkm, which is four times 2016’s Net Transfer Capacities (NTC). To be noted, this illustrated scenario refers to a future in which the electricity demand is doubled with the integration of the heating and transportation sectors.

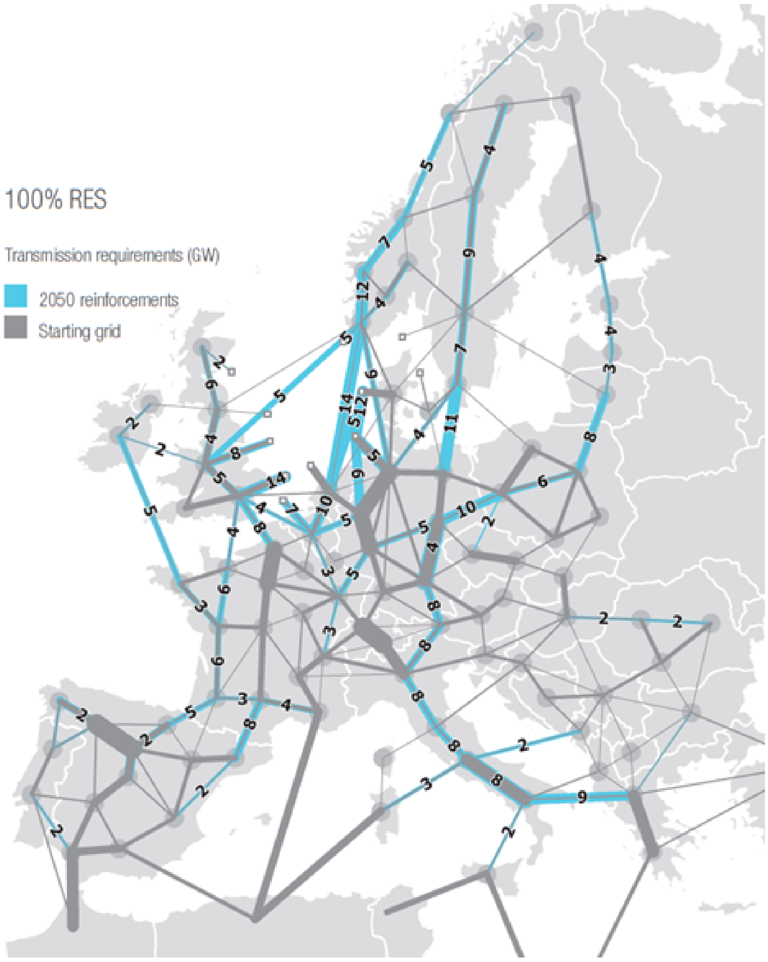


Figure 3.6: The boldest scenario up until now [37].

In the case of electrical demand and electrification of the private transport sector (no heating demand), the smaller systems costs can be found when the leverage of DSM, Grid to Vehicle (G2V), and Vehicle to Grid (V2G) are fully used. To understand the potential of using the transport sector as a mean of storage, it has to be noted that with just 50% of the cars participating the storage available is around 6,15TWh, equals to three-quarters of the daily regular electricity consumption.
If the heating demand is integrated, with the process of methanation and long thermal energy storage the season variation is smoothened out, while hydrogen and short thermal energy storage take care of the weekly variations.

The following European layout represents the optimized interconnection grid, and the energy sources per country, in the case of full demand (Electrical baseline, transport, and heating) and full measures of flexibility. Fig. 3.9.
We can see how in the south-east nations the higher share of PV is reflected in reduced demand for interconnections, while the Atlantic side (more prone to wind power) has higher grid requirements.

Schlachtberger and the benefit of Cooperation[89]

Similarly to Brown's work, in this modeling research, the topology of the European grid is fixed, while its overall capacity varies and is optimally allocated together with the energy sources. The objective is to reach 95% of CO2 reduction. The trade-off examined is between transmission (balancing at continental level) and local storage (balancing in the time domain).
It is found that at the optimal point of grid expansion the overall costs are comparable with today. Restricting this value, the costs would inevitably increase, with the more predominant role played by

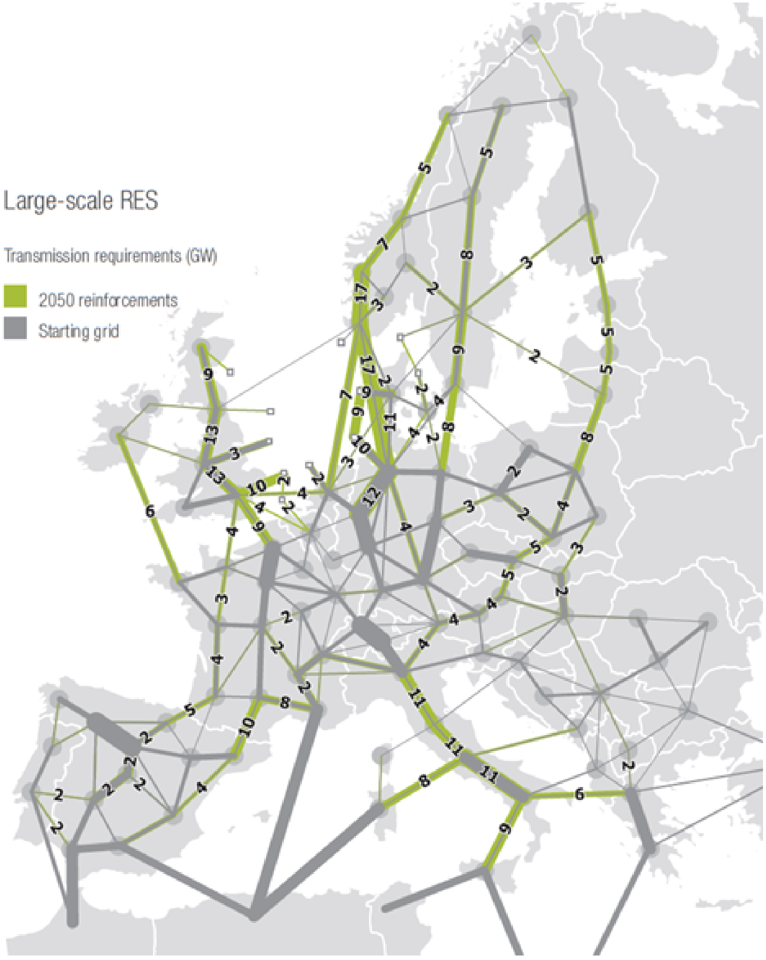


Figure 3.7: More centralized solutions [37].

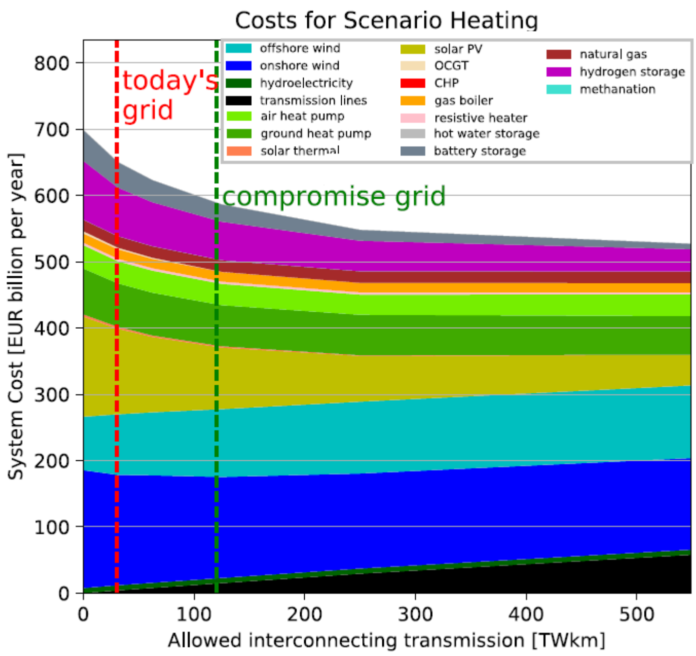


Figure 3.8: With increased interconnection, the overall costs diminish [11]

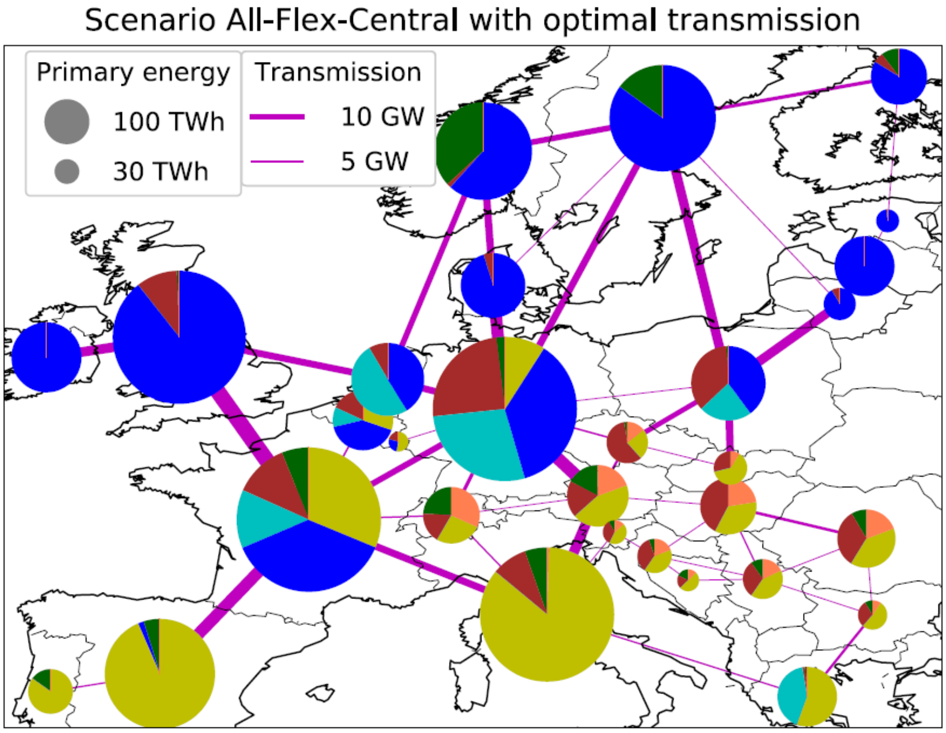


Figure 3.9: The optimized grid for full demand[11]

storage and solar. The optimal grid capacity would consist of a total NTC of 285,7 TWkm, an increase of 900% respect to the 2015 capacity of 31,25 TWkm. This level is already considered unfeasible by the authors.

In this sense, a compromise grid is defined. It would require “only” an increase of 400%, reaching an NTC of 125 TWkm. At the compromise level, the benefit achieved is still 85% of the possible total. This layout is characterized again by a higher level of wind generation, reaching 46,6% and 13,9%, for onshore and offshore respectively. Solar dominates in the second position with 24,6%. The remaining is covered with hydro dams and in a smaller percentage with gas and Run-of-River plants. The Compromise grid is presented in figure 3.10.

Becker’s build up of transmission grid extension[8]

This simulation study proposes boldly a 2050 scenario in which the average demand for power is covered with only wind and solar plants, it maximizes the production from vRES while minimizing the necessity of new transfer capacity. Becker et al. find that an additional balancing power is still necessary. This derives from a small level of correlation on the production side.
By doubling 2010’s grid NTC the balancing power can be reduced by 26% while a quadrupling of the grid reaches a 33% reduction. 90% of the benefit of unconstrained grid capacity is reached already with the quadrupling of the NTC.

The particular nature of this study is the focus on the build-up of the system. It simulates the 4 decades between 2010 to 2050. The finding is that between 2020 and 2030 there must be the most intense period of line build up in order to keep up with the need for flexibility and balancing power, and it then has to follow 15 years of slightly lower incremental capacity. With a higher level of interconnection, the wind share grows, from 70% without any grid, to 80% at the optimal grid level (which is twelve times the 2010 NTC).

The 2050 grid is reported in fig. 3.11 It can be noticed how, due to the year of publication, the Baltic republics are not even considered. Connection implemented or in development are equally not

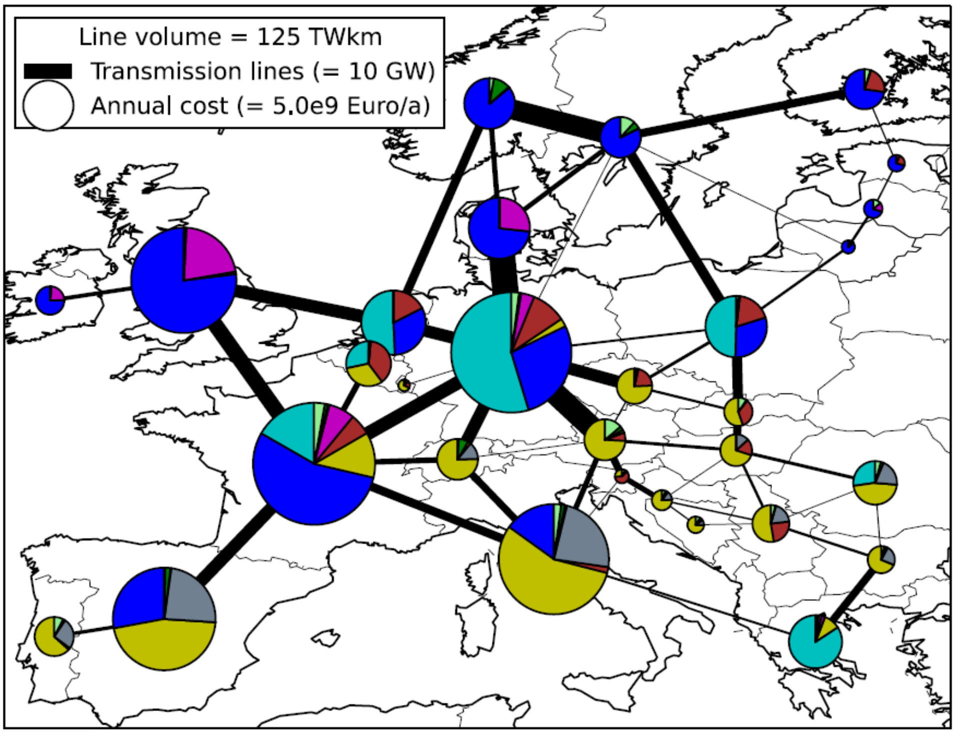


Figure 3.10: The compromise grid for this future[89]

considered (e.g. Great Britain connections with Belgium, Netherlands, and Norway). The level of vRES considered is legitimately exceptional due to the dismiss of any power source external to biomass and hydro, which are severely constrained by their assumption. Nevertheless, it is interesting to consider this study as an upper limit if only usual electrical load is considered. 3.11.

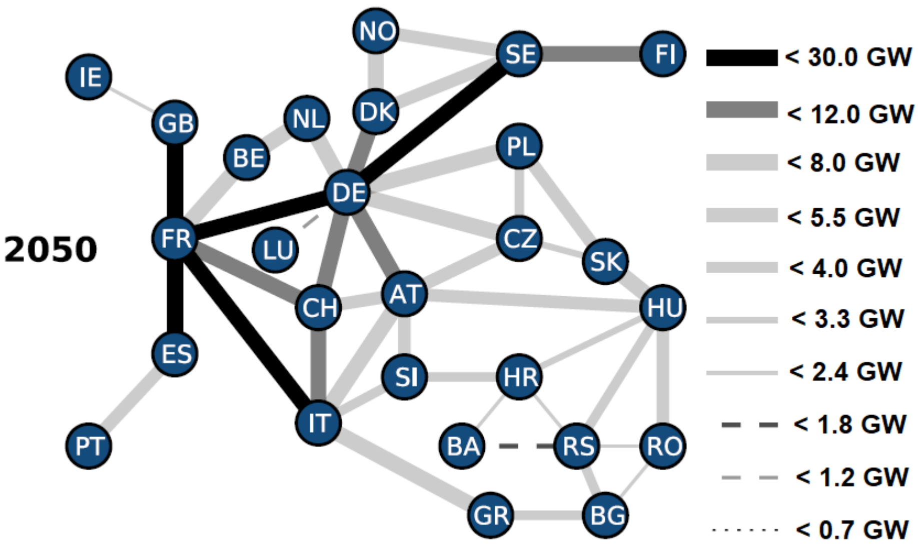


Figure 3.11: The fully built-up grid for 100% vRES[8]

Fraunhofer 2011 and 2014[77] [90]

This two studies examines in depth five Scenarios in total: A and B from 2011, C, D, and E from 2014. They are all optimized to reach a 95% reduction of CO2 emission by 2050.
The differences are: the level of energy efficiency pursued in the years between 2010 and 2050 (more relevant in A), the availability of CCS and nuclear in C, D, and E, higher demand in scenario D, scenario E reflects higher acceptance of wind onshore. From this, the final level of production capacity, energy generated and curtailed diverge.

RES reaches above 80% of the energy share in all cases, what is left are just gas plants. Unfortunately, the exact breakdown of the energy produced is not available in scenario A and B. If confronted with the work of Becker et al. [8], the grid layout is more refined with what concerns the north of Europe, while the non-EU Balkans states are omitted completely (due to the year of formulation, Croatia is also excluded).
The researchers point out an “under average” level of connection with the Scandinavian region. The area hosts the highest level of hydropotential in Europe, for this reason, it would be normally considered as one of the natural batteries for the European grid. The reason for an underplay of this resource is the optimization algorithm that prioritized the battery creation near production facilities. In this case, in the wind-rich Britain and solar rich Spain.
It should also be noted that between the two studies the role of PV has been downplayed, the results of this choice can be seen in the reduced role of interconnections in the South and the East of Europe.
The Fig. 3.12 is the 2050 envisioned grid layout for scenario C.

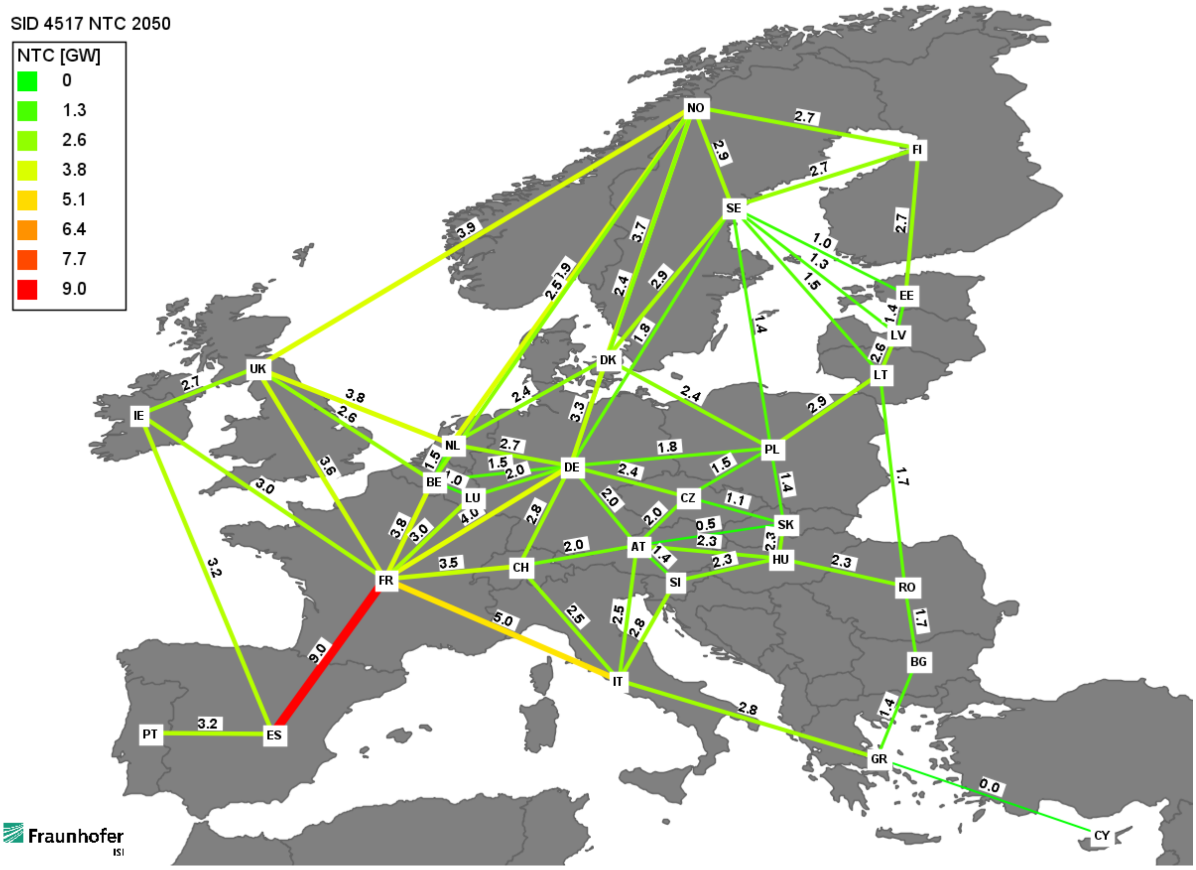


Figure 3.12: In all scenarios the Iberian peninsula border is the one in need of greater expansion[90]

Zappa and 100% Renewable Feasibility[99]

After the discussion on the shortcomings identified by Zappa in his work about energy system simulations, his model investigates the EU power system with a level of 100% RES in 2050. Power production investment, placement, and grid interconnection are optimized simultaneously.

Seven scenarios are elaborated but already in the Base one, the 2015 electricity demand is increased with expected HP and EV energy demand. Three scenarios constrain the allocation of RES differently while two others vary the energy request of the system. The last one allows non-RES in the optimization algorithm.
Yet again, the overall capacity is given, not the energy production, by sources. Overall, the vision resembling the pattern of our scenario is the "Free RES" one. In it, no Concentrated Solar Power (CSP) or geothermal is exogenously defined. In this way, 150 GW of CSP is not allocated in Spain, lightening, in turn, the burden on France's borders. The share of vRES reaches 50%, a lower value than in our reference scenario. The reason is the higher emphasis on other sources, first and foremost biomass, geothermal and CSP.

Unfortunately, a detailed breakdown of the grid expansion, border-by-border, is not retrievable. We can infer the layout from only Fig.3.13 . The starting grid has a cross-border capacity of 60GW, the extension in the Free-RES vision is of 142 GW. This increased value, smaller in comparison with the other studies, is explained by the larger presence of other dispatchable sources besides PV and wind turbines.

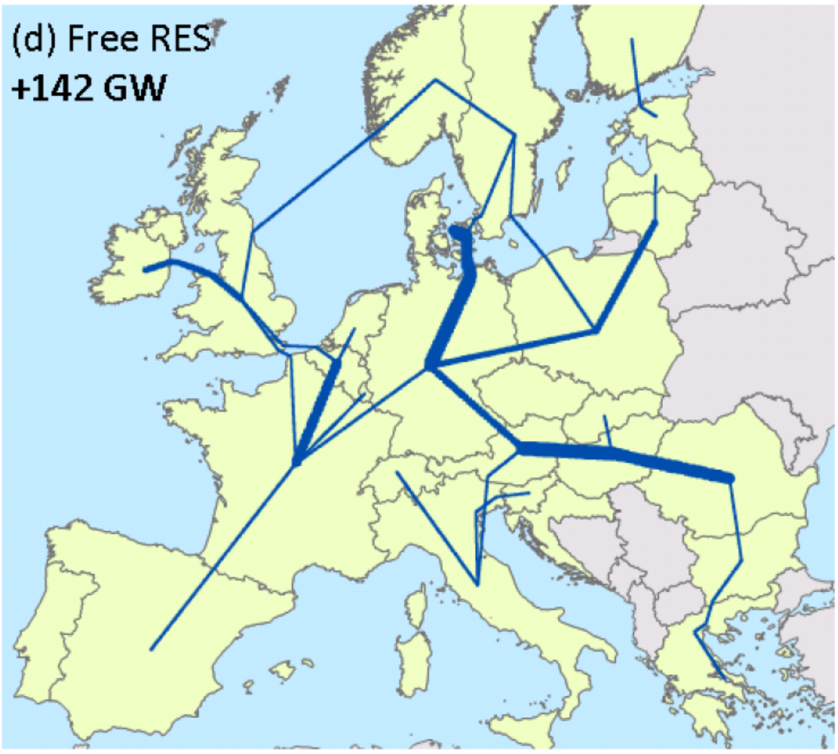


Figure 3.13: Due to the reduced role of CSP in Spain the border with France needs less investments[99]

Jaehnert and the Northern Hydro potential[59]

The work by Jaehnert et al. focuses on the North Sea region. More specifically, on the interaction of the Scandinavian hydropotential with the more renewable power system of the North Sea area. The scope is limited to a 2030 scenario, but it is helpful to guide the path forward in the region.

As expressed, time and time again in the literature, this study highlights the renewable source of flexibility of the Norwegian and Sweden hydropower plants. More wind production is integrated into the energy mix and the value of interconnectors is captured by the transfer of renewable power between countries. The paper focusses its attention on two other issues. Firstly, it points out an average increase in the price of electricity in Norway. This rise is imputed to the higher marginal cost of thermopower plants. The second point is the smoothening effect of reservoir level and electricity price in the Scandinavian peninsula. A real tangible effect of higher interconnection is the general convergence of the cost of electricity in the entire region.

The main upgrades resulting from the optimization are between Scotland and England, between Sweden and Germany and from the Netherlands to Great Britain. The reason for doing this is the connection of load centers to areas characterized by a higher surplus of energy. Here, the clustered north grid is reported with highlighted the new interconnection route, Fig. 3.14.

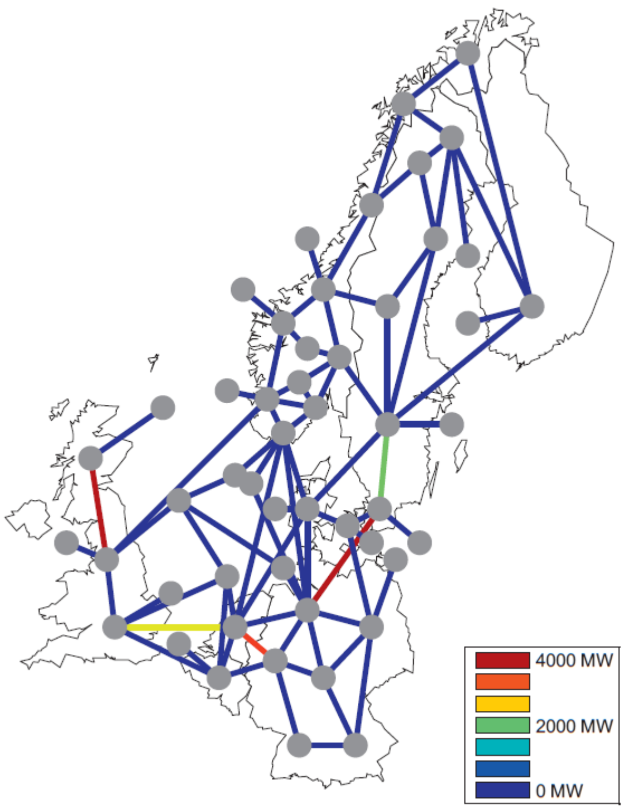


Figure 3.14: The increase needed by 2030 around the North Sea[59]

Schaber's parametric study[88]

In this techno-economic model the optimization of vRES, Grid and backup are carried out at the same time. Thus, the system shows the efficiency of the joint planning: the renewable sources are concentrated in the highest potential area, while the backup is built near the most connected zone of the grid so that they can serve the wider continental area. A parametric analysis is carried out at various share of wind and solar in the mix, with the attention posed on the consequent backup capacity, the mismatch between production and demand, and costs of the system.

Again, a point of optimization with the wind share equal to 80% of the vRES is found when these kinds of sources compromise 60% of the total energy production. The demand not served by RES is in turn covered by coal & nuclear, gas & other in equal measures. The emissions are reduced by roughly

85% compared to the reference year of 1990.
Yet again, for a 60% vRES (wind at 80% of vRES), the grid capacity grows with a factor of 3. Confronting the costs of building the grid with the total investment of the energy system, it leads to an increase of just 5% of the Cost of Electricity (CoE).

Gils's integrated energy mix and grid espansion modelling [52]

This integrated assessment of the short-term and long-term balance between production and demand, in Europe, brings to the surface the levels for which there is an optimum in investment for vRES, storage and grid expansion.

Of the three main pathways explored, majority of wind in vRES, majority of Solar or balance between them, the first one prevails as wind power covers 80% of vRES. At this level, the vRES share of 60% of the total leads to a minimum of investment. This study also supports two previous findings. The wind power share is divided around 70-65% onshore and 30-35% offshore. Secondly, coal but also CSP are pushed out from the energy mix while more vRES are present. This phenomenon is due to the fact that with less annual full-load hours the fixed costs for these plants are unbearable. Hydrogen, as a source of long-term storage flexibility, is still not used in this optimum scenario, intraday electric batteries are utilized. Comparing this work with the findings of Schaber et al. [88] the role of storage cannot be underestimated. For scenarios with 60% vRES, it reduces curtailment from 10% to 3%.

The integration costs of grid infrastructure remain in the order of 4-5% of the LCOE. There is no detailed Infrastructure layout and the only level of capacity added is for the extreme cases of 100% vRES or lower level of 40-50%. In Fig. 3.15, the break-down of the LCOE costs for the vRES composed of 80% wind and 20% solar.

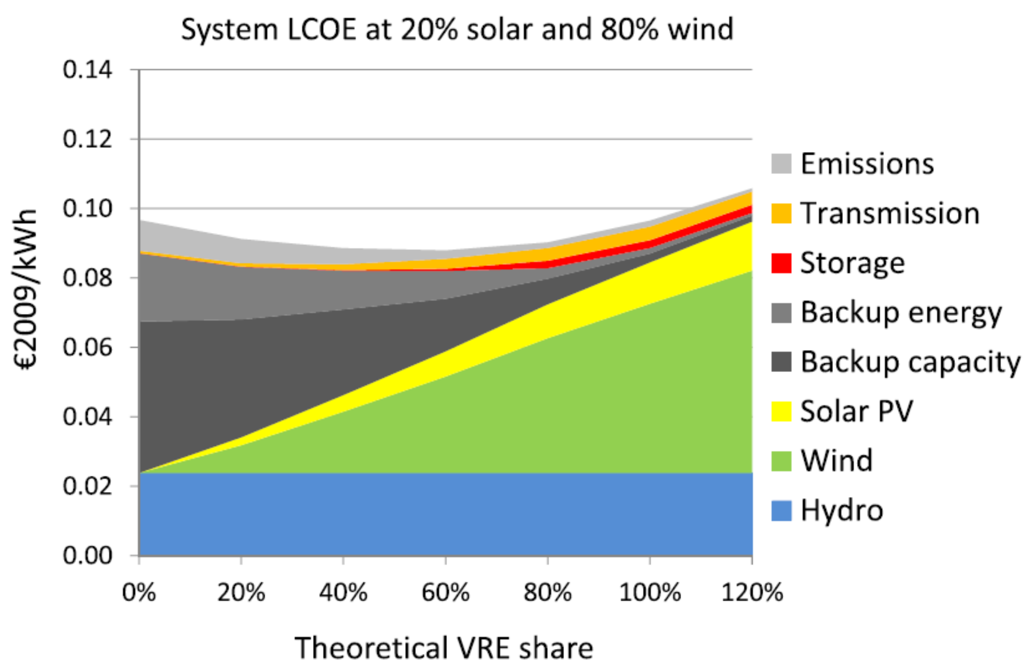


Figure 3.15: The LCOE at various levels of vRES, the minimum settles at 60% vRES[52]

3.3 Envisioning the Bold Grid for the Future

The following section is going to deal with the formulation of levels of transmission capacity across the critical borders to sustain the increased level of vRES. The findings of the studies presented above will

thus be confronted.
This section requires more than a simple average of numbers at the European levels. A weighted average could lead us closer to the kind of future scenario we are aiming at. On top of that, every border's value has to be discussed based on the assumption taken by the researchers.

Let us first clarify two points. Expansions of the transmission infrastructure inside the single countries are needed, but to quantify them is outside the scope of this thesis. Nevertheless, some countries will be examined more closely, due to their unique nature of hub or corridor between different regions (e.g. France, Italy).
The result is that by taking the ultimate levels of capacity envisioned in the following sections and combining them, we are not going to reach 3-4 times the amount of interconnection capacity in Europe highlighted in many papers. That level, necessary to harness the highest share of vRES efficiently considers the entirety of Europe, while we are now going to focus on the more troubling borders (e.g. Norway – Denmark instead of Norway – Sweden).

The table depicted in Fig.3.16 summarises the available concrete data from the major models used in the previous studies. The Highlighted rows are the scenarios that more closely resemble the 2040 vision elaborated in section 1 of this chapter. The first three columns summarise the load considered, the amount of CO2 reduced, and the share of vRES. The following columns are the main border bottleneck of Europe.
In the last column, the weighted value of each complete scenario is proposed. Brown and Becker do not have a value because in their respective results the load or the vRES share is not enunciated. Nevertheless, they will be considered in the discussion for each border.
The weighted average, as presented in the table, lead to a load factor of 4200 TWh and a vRES share of 60%. The calculated average capacity for every bottleneck is reported in the final bottom row.

Between the two ENTSO-e model results [40], the Global Climate Action, with its higher share of vRES and centralized power plant, requires a higher transmission capacity than the other. The situation is more balanced than expected by the fact that Distributed Generation one has a demand of 300 TWh superior.

Similarly, in the e-highway project[37], the capacity results are similar in both scenarios because the higher vRES share of the “100% RES” scenario is compensated with 1000 TWh of difference with the “Large Scale RES” scenario.

The Schlachtberger results [89] for the compromise grid are smaller than one would expect, considering the incredible share of 85% vRES, because the load modeled is just electricity, without heat and transportation.

Becker [8] tries to reach the full coverage of the average load with PV and wind alone, with balancing power from dispatchable renewable plants.

The 2011's results [77] from Fraunhofer do not disclose the level of vRES reached in 2050. Luckily, the 2014's do [90]. The bias toward the Scandinavian peninsula is also solved, with the transmission capacity closer to the other reports.

The final two rows are reserved for Brown's results [11]. The first one represents the optimal grid. The highlighted takes the original values and scale them down to the compromise layout suggested by the author.

Border 1: Ireland's Role in the Energy Transition

This island presents a peculiar challenge. Composed of two quite small nations the energy demand is low, condition reinforced by the low-level heavy industries. The stability is thus highly susceptible to low inertia, uncontrollable vRES. The effects on frequency stability have been already documented.

Author	Scenario	Load [TWh]	CO2 Reduction	vRES Share	1) Ireland to Great Britain & Continental Europe (GW)	2) Great Britain to Continental Europe and Nordics (GW)	3) Nordics-Continental Europe West North =>/<= South (GW)	4) Nordic/ Baltic - Continental Europe East North South (GW)	5) Baltic integration Export/ Import (GW)	6) Central East integration Export/ Import (GW)	7) Iberian Peninsula => North / <= South (GW)	8) Northern Italy => North / <= South (GW)	9) South East integration East/ West (GW)	10) Eastern Balkan East/ West (GW)	Weight
TYNDP	2016				0.95	3	4.94/5.4	1.1	2.22/2.2	1,3/0,45	2.4/2.8	8.5/3.6	2,95/3,75	2,55/2,41	
	2020				0.95/0.58	4	6.34/6.8	1.1	2.22/2.2	2,5/0,5	2.6/2.8	9.7/3.5	2,85/3,55	4,35/3,2	
	2027				0.95/0.78	14.4	7.02/7.56	1.6	2.72	03-feb	5	13.3/8.4	3,1/4,2	5/4,75	
	2035 ST, DG, EUCO				2.15/1.98	19.8	7.72/8.26	2.2	2.72	03-feb	8	13.9/8.9	4,25/5,44	6,76/7,15	
	2040 ST				2.7	16.1	9.04/9.5	1.6	2.22/2.2	3/4,5	9	13.9/8.9	4,1/5,5	6,8/5,5	
	2040 DG	4450	79%	52%	2.2	14.6	10/10.5	3.1	2.72/2.7	3/3,5	10	13.9/8.9	4,1/5,5	8,8/7,5	**0.1**
	2040 GCA	4150	88%	57%	2.2	15.1	11/11.5	2.6	3.22/3.2	3/4,5	9	14.9/9.9	5,1/6,5	11,3/10	**0.2**
	Large RES (2050)	5270		54%	9.6	26	45.4	9.6	9	15.4	18.8	14.1	6.2	12.9	**0.2**
	100% RES (2050)	4200		76%	8.7	26	45.4	9.6	9	16.4	16.8	16.1	2.2	14.9	**0.1**
Schlachtberger Compromise		3152	95%	85%	3.45	19.6	13.1	8.81	3.57	10.8	8.81	15.1	9.64	6.19	**0.05**
Becker	**(90%)2030**			57%	1.32	12.9	15.6	-	-	9.11	10.4	21.4	8.08	10.2	
	(90%)2040			90%	1.83	15.1	22.3	-	-	13.2	15.9	30.5	11.9	15.9	
	(90%)2050			100%	1.93	16.1	23.8	-	-	14.1	17.3	32.5	12.8	17.2	
Fraunhofer	Scenario A 2050	2805	95%		3.1	40.2	17.7	6.6	4	9.4	12.2	16.1	6.2	5.8	
	Scenario B 2050	3376	95%		10.7	52.6	19.3	7.9	6.2	11.3	20.8	27.2	9.1	7.7	
	Scenario C 2050	3370.3	95%	55%	8.9	13	17.2	6.7	11.1	4.7	9	12.8	5.3	6.8	**0.1**
	Scenario D 2050	4196.5	95%	58%	9	13.7	22.5	7.4	11.8	6.3	9.1	14.9	6.1	8.5	**0.2**
	Scenario E 2050	3370.3	95%	53%	8.9	12.4	18.9	6.6	11.2	4.7	9.5	14.2	5.3	7.3	
Browi	All-Central-Flex optimal (20	7630	95%		26.7	62.8	54.7	51.1	28.9	37.5	32.8	52.8	3.6	14.4	
	All-Central-Flex Compromis	7630	95%		8.4	19.9	17.3	16.2	9.1	11.9	10.4	16.7	1.1	4.6	
	Proposed Grid	4.2 GWh		60%	6.64	18.2	25.1	6.63	7.64	8.68	12.00	14.5	5.83	10.3	0.95

Figure 3.16: The Sumamry of all previous Studies

At the moment, there are two interconnections towards Great Britain, two undersea cables whose total capacity reaches 1 GW. For this reason, Brown's, Becker's and Schlachtberger's layout only provide the option of connection with the major Island. On top of that, Schlachtberger is "only" interpolating the past RES development up to 100% of the load demand of the island.
The reality could lead to a future with higher capacity installed. Due to their isolated electrical grid, the TSO of the Republic of Ireland has been pushing in the past years different research and implementation projects on FACTS, Flexible AC Transmission System. Their role for the stabilization of the AC grid is necessary for a continuous push of wind in the region.

Together with the North Sea area, the British Isles have the highest wind potential in Europe. For this reason, their role as a provider of renewable energy to the European system cannot be understated. The average yearly generation is set to become much more than the average demand of the island. To cope with this high export potential ENTSO-e and other researchers do not only see the interconnection with Wales, England and Scotland increased, but also recommend and visualize to connect Ireland directly to Brittany, the closest region of France, and even to Spain.
The possibility of connecting Ireland to the main continent would alleviate stress onto the English grid and open the direct market coupling with the UCTE. From the baseline scenario of the EC in just the next 10 years the RES share in the electricity production will double, reaching 10GW and more than half of the year energy production would come from wind alone.
It is clear how the 2,5GW envisioned by 2040 in the TYNDP is not enough. By considering more the exporter advantage given by the natural potential of the island, an interconnection of 7GW would be more adequate for 2040 to look for.

Border 2: Great Britain Connection, never ending increase

The main British island, the union of England, Scotland and Wales suffer a similar condition as Ireland's island. The high renewable wind potential can overtake the stability of the electrical system, but also allowing a fruitful season of large power exchange.

Currently, 5GW connects the island to the continent, half of that through France, the rest via Belgium and Netherlands. Various projects are planned to bring the capacity to 10,3GW by 2022. It is curious to note how from the TYNDP by 2035 there are 19 GW of interconnection planned while around 15GW are envisioned for 2040 between Great Britain, the main continent and Scandinavia. This final level would hardly comply with the requirements of a highly volatile British market, especially if increased electrification takes place. For reference, in Schlachtberger et al. study, the interconnection required is 20GW when heating and the transport sector are not coupled.

Considering the assumptions of export towards the continent and balancing with Norway valid, 20 GW seems a more appropriate value, and it comes directly from the e-highway scenarios. 4GW of this total capacity would make the connection with Norway alone, while from Jaehnert et al. present an economic case for already 2,3GW additional capacity towards the Benelux region by 2030.

Border 3: Scandinavia bridge to Central Europe

The Scandinavian peninsula has the widely recognized potential of being the natural hydro battery of Europe. It is composed of two nations that have the energy demand of the Netherlands and Poland combined. Norway uses hydropower for around 98% of its energy demand, while Sweden has the potential for 40%. The focus of this barrier is the connection with Denmark, Germany, and central Europe at large. Here the larger possibility to employ the flexibility potential of the hydro reserves meets with the largest gap with the reality.

Right now, 6,8GW are operative across this barrier, while the studies demand for at least 3 times this value. If Schlachtberger sets the minimum at 13GW, the e-highway project takes full advantage of the region with an astonishing 45GW capacity by undersea cables. This final value would cover the entire power output of the hydro plants of the region. Considering the exceptional work of reinforcement that should take place across the countries to support this power bridge, the required interconnection capacity would be in the middle, around 25 GW. The connection should be spread out across the largest area possible, to keep a strong mashed grid, with a lower level of line and cable usage.

Border 4, 5 & 6: Focus on Poland Borders and Baltic Integration

This is the region on the farther East of central Europe. Here the connections are towards Poland and the Baltics Republic, with the clear goal to bring these three Republics in synchronous operation with the rest of the continent. These states inherited, in fact, the electrical operation and frequency from the Russian UPS grid.

These 4 nations are considered together due to their role as being one of the five main corridors of the e-Highway study. Generally speaking, the Baltic and Poland needs higher interconnection to have relevant access to the electrical market of Europe and most importantly, due to their land connection, their electrical union should be tighter than 500MW as it is right now.
The challenge is complicated by the time needed for the synchronization and the diffidence between the German and Polish authority regarding the joint project of interconnection.

The connection of Poland is limited to 4,8GW, while the Baltic states have only 2,2GW. Different studies have different routes suggested: strong German-Polish reinforcement, Polish-Baltic backbones, preference for subsea cables from Sweden, etc. The best approach would result to be the one that can assure the wider security of supply and stability for the grid, with backup route and a more meshed layout.

An increase on the continental border of Poland is necessary in equal volume with Germany, Check Republic, and Slovakia. In this way, the nasty loop flow from Germany can be taken care of complying at the same time with the 70% rule which is in adoption from this year.
The available results for the weighted average skew away from the results present in all the other studies. For this reason, instead of the average 8,7GW, this thesis suggests 10GW. It would be better divided in 4GW with Germany, 3 GW with the Check Republic and Slovakia.
Secondly, the northward interconnection of 7GW should be divided similarly between Sweden and the Baltics, assuring at least 3,5GW for the latter.
Finally, undersea cables linking Sweden and Finland with the three Republics should double in capacity, reaching a total of 8GW for the Baltic integration.

This grid arrangement, that is going to be highlighted in the conclusive map of Electrical Europe, is preferring a high meshed layout, ensuring more feasibility during the build-up due to smaller capacity increase, but also higher resiliency to faults and disruption in the energy supply.

Border 7: The Iberian Peninsula Bottleneck

This Border is probably the most troublesome of all. It connects two of the largest countries with an actual physical barrier between them, the Pyrenees. From just an initial technical difficulty, in the decades a strong public opposition has grown towards grid expansion in the border regions.

Spain remains the country with the lowest ratio between the level of interconnection and production capacity, falling short of the EU guideline of 10% in 2020. This year the interconnection between France and Spain is lower than 3GW, while the total production capacity of Spain is 104GW, and half of it is RES. The incentives are huge towards a stronger interconnection: the unmatched solar surplus could be pushed out from Spain during the day, and the more balanced wind production from the northern regions could be brought in to stabilize and alleviate the Iberian electricity system and market.

The e-Highway considers this border, together with the already discussed number two, as part of one of the main corridors, that need to be upgraded even in scenarios less RES dependent. The different studies are in this case more homogenous, suggesting an interconnection level of around 12GW. The increase, compared to nowadays, is a considerable challenge and has to be tackled with all the measures and techniques discussed in the following chapters. The timing is also an issue. Due to the public entrenched opposition, this border has experienced the longer-lasting project of entire Europe, 30 years, to build just 1,5 GW. In the next 20 years, the capacity should increase by 5 times.

It is now the moment of spending a few words on the central role of France.
This large country is in the dead center between 4 large energy demanding country (United Kingdom, Germany, Spain and Italy). All the studies highlights how it will function as a hub between these nations, balancing the solar potential of the South with the wind production from the North.
The readiness of the internal meshed grid of France is critical for the well functioning of the entire Electrical Europe. As the country with the higher capacity (and investment) on nuclear, it has also the role of potential exporter in time of poor renewable production.

Border 8: Hiccups and resources across the Alps, the Italian case

Similar to the previous case, this border is characterized by the technical difficulty of crossing a mountain ridge and the consequent isolation of one of the major countries of the EU. As 2020, France and Switzerland provide the bulk of connection with over 4GW each, reaching a total of 9,8GW across the Alps.

Luckily, the required capacity by 2040 is mostly in line with the TYNDP: 14GW. This is mostly due to the more prevalent solar share in the national energy mix that would benefit less from a strong grid connection. The timely completion of these upgrades is the essence.

Additionally, northern Italy, Switzerland, and Austria have the potential to provide the second hydro battery for the European grid. Thus, the connection to the zone can be kept mostly radial from the mountain ridge outward, without the necessity of crossing it. All country specific studies stress the fact that a stronger internal transmission capacity is needed in Italy, of around 10 GW. This would help the country to fully utilize the hydropower flexibility and also help with the undersea interconnections to the Balkans.

But, if the great solar potential of northern Africa is harnessed through the joint venture of MEDTSO, then Italy could take advantage of if natural bridge towards the area [24]. If this is the case, the crossing of the Alps, together with higher investment along the full length of the peninsula is necessary to bring this power to the continent.

Border 9 & 10: Crossing to East of Europe with new thinking

The East border of Austria and the Check Republic provides the first barrier, while the west border of Romania, Bulgaria, and Greece comprise the other. Here the amount of yearly energy demand at stake is lower than the previous cases. The development of RES has started slower than in the larger western countries and, in a linked way, the phaseout of coal is not defined in some countries (e.g. Romania and Bulgaria).

The envisioned capacity increase along these borders is around 6GW and 10 GW. The increase from the planned TYNDP is small due to the higher potential for solar, which can take a predominant role in this region.

A new solution that is starting to take hold, is the connection across the Adriatic and Ionian sea. Greece and Montenegro are already been connected with Italy. The development between Greece and the south of Italy has the potential of becoming the beginning of a Mediterranean floating wind grid. The potential for offshore wind in Greece and Romania is, in fact, nontrivial and could balance more effectively the solar dominated south-east of Europe. If this project starts to take hold, then the estimation for grid capacity levels in the critical border number 10 should be assessed again upward.

#	Name	2027 - TYNDP - 2035		Proposed 2040
1	Ireland – Great Britain and Continental Europe	0.95GW	2,15GW	7GW
2	Great-Britain and Continental Europe – Nordics	14.4GW	20GW	20GW
3	Nordics – Continental West Europe	7.54GW	8,26GW	25GW
4	Nordic-Baltic to Continental East Europe	1.6GW	2,2GW	7GW
5	Baltic integration	2.72GW	2,72GW	8GW
6	Central East integration	4.6GW	4.6GW	10GW
7	Iberian Peninsula integration	5GW	8GW	12GW
8	Italian Peninsula integration	13.5GW	14GW	14GW
9	South-East integration	4.2GW	5,44GW	6GW
10	Eastern Balkan	5GW	7,15GW	10GW

Table 3.2: The envisioned levels of necessary grid increase by 2040

Summary

After a comparison between the different studies, their results have been used to come up with a proposed level of interconnection by 2040.
This level have been assessed to comply with a share of vRES of 60%. The critical borders detected in the 2018 TYNDP have been used as reference for the discussion.
In the table 3.2 the proposed level of capacity are summarised and placed next to the planned capacities by 2027 and the envisioned one for 2035.

Chapter 4

Challenges and Speed of Development

If you want something you have never had, you must do something you have never done.
- Thomas Jefferson

This chapter deals with the insight provided by the experts between March and June 2020. Every section is based on the information that came out from the interviews. This information is then expanded through the literature suggested by the expert themselves or from appropriate research.
In the first section 4.1 the method adopted to carry out the interviews is explained. in the second section 4.2, the current approach and time frame behind the infrastructure development are explained. In the following section 4.3, the critical bottlenecks are individuated. The main finding here is the important presence of non-technical problems that have to be resolved in not-strictly technical manners. In section 4.4, to have a more informed discussion some improvements occurred during the past 10 years are reported. In section 4.5, solutions to the individuated problems are suggested.

4.1 Interview Process

As a newcomer to the field of the academic interview, some papers have been reviewed to acquire a baseline level of skills required to complete the process more efficiently and professionally. Of these, two, in particular, have provided much-needed assistance.
The main takeaways have been on the level of technicality, the order of questions (summarised in the structure of the interview), and the right balance on the kind of relationship to have with the interviewed [65].

Firstly, the level of technicality is fundamental. A question too broad or vague is likely to lead to superficial, non-consequent answers. The risk is the inability to reach the level of personal insight capable of adding to this work. On the other hand of the spectrum, to specific and closed questions not only can lead to brief answers, but they can also alienate the interlocutor, which may feel pin down or restraint. The middle road is, of course, the right one [65].
Anyhow, the interview's goal is not to gather many quantitative data, but more qualitative ones. The focus is on approaches, developments, and ideas. This style easily lends the interviews to be semi-structured: developed "around a set of predetermined open-ended questions, with other questions emerging from the dialogue" [33].

The structuring of the question has been developed to be from the objective and less intimidating ones to the most personal [65]. Some questions have been repeated among all one-on-one interviews. In this way, the competence and the initial perspective of the expert can be confronted with the others [26].

The selection of the experts has been dictated from one principle: equally consideration of different perspectives and backgrounds. This meant choosing people working not only inside TSOs, but also at lower voltage levels (DSOs), at continent managing level (ENTSO-e), civil servants in Non-Governmental Organization (NGO)s, and public interest groups.
From the initial list of names coming from my knowledge, additional people to contact have come out from the interviews themselves, as a final question to the interviewed.
For the Complete list of experts, see Appendix B.

For every specific expert, there is a preliminary question asking something directly related to their expertise or their job, this would pave the ground for the following ones:

1. *Timeframe for Interconnection: what are the present time requirements for Planning (studying and decision), Permitting (authorization and crossing location), and Realization?*
2. *What is the role of (for example) GermanWatch in the landscape of European grid development?*

There are two recurring questions asked for every interview. These concerns the present-day difficult situation in expanding the interconnections:

3. *Where are the most critical places in Europe and why? (The Pyrenees are more challenging than the Alps for instance? Did we manage to streamline enough the interconnection by sea?)*
4. *What are the bottlenecks active right now in the path towards the necessary grid infrastructure for zero-carbon electricity? Social acceptance, capital investment, authority interference, no clear scenario to aim to?*

The final or two finals questions that concerns with possible future development are drawn from these:

5. *What are the recent positive developments to streamline the projects, value public involvement, and honor nature protection?*
6. *What possible next steps would you suggest in this direction? What academia, lawmaking, and NGO can provide to the table to reach faster a more sustainable future through grid management?*
7. *Your opinion regarding the necessary, or promising policies, techniques, methods, or technology capable of delivering a more connected grid in a shorter time. (Time frame of 2040 grid by 2035/2030? 2050 grid by 2040?)*

4.2 Time frame for Interconnection

The most up to date time frame for these kinds of projects is retrieved from four agreeing sources: the five interviews with TSOs personnel (Staschus, Keandler, Grisey, van der Meijden and Kees), and the Agency for the Cooperation of Energy Regulars (ACER). Founded in 2009, this European agency guarantees the correct functioning of the single European market for gas and electricity. It assists and coordinate the national level adoption of common regulations.

On average, 10 to 12 years are needed for an electrical transmission project (note: all kind of transmission, not only interconnection between countries). The ACER 2019 report [3] asses that the electrical PCI takes on average 9.9 years. The **Planning** takes around 2-3 years, proceeding in synchronous with the TYNDP. **Permitting** has a larger amount of uncertainties, with an average of 5-6 years required (the vegetation assessment by itself requires 1 year), and **Implementation** time is technology dependent. With standard 440 kW Over Head Line (OHL) the construction itself can take as little as 1 to 2 years, while for underground and sea cable, due to the non-parallel nature and weather dependence operations, the time reference increase to 3 or 4 years.

As a reference for the permitting phase, we can draw some insights from the 2019 ACER report on the progress of PCI projects [3]. There are 106 electrical projects and of them 46 are interconnectors. The status development of all these projects is thus reported: 10% under consideration, 19% planned, but not yet in permitting, 45% **permitting**, 21% under construction, 4% commissioned, and 1% canceled.
Another important figure to consider is the progress: while 59% of the projects are on time, the 25% is delayed, and another 12% is rescheduled. The amount of delays or rescheduling is on average between 6 months, to 3 years and a half.
The reasons for these time jumps are also reported. The first most recurring reason is the Permitting granting process, which is complicated by **Public Opposition, Environmental Problems**, and difficulty when different national laws are at play. All the interviewd agree on the single most pressing problem being the Public Acceptance of these kind of projects.

Technology-wise, the interconnections do not differ so much from a usual transmission infrastructure. There is more interest in combining these grid expansions with Phase Shifters Transformers, to control the power flow at the boundary between two nations where the physical electrical world and the economic one obeys different laws. There can be special substations at both ends of the interconnector to control the frequency modulation. In the case of the Baltic Republics there are right now back-to-back converters over land borders, (similarly to USA's wide-area synchronous grids), while for DC submarine cables the substation switches the nature of the current from AC to DC and vice versa. Substations are also present when switching from OHL to underground cable solutions [38].

If an OHL spans over non-urban areas, the land surface underneath it has to be strictly managed. Natural formations can be avoided, but the growth of natural vegetation has to be blocked. In the crossing of forests, open fields, and other natural vegetative rich environment, a Vegetation Management protocol is adopted from TSOs. With it, yearly or bi-yearly treatments prevent the growth of plants that could cause contacts, faults, and wildfires. Slashing and herbicides are common practices [81].
With underground cables, the type of constructions carried out over them is regulated and depends on the nature of the cable itself. When this transmission is used in cultivated areas even the type of vegetation and crops need to comply with specifications. Specifically, plants with deep root structure have to be avoided.
When dealing with undersea cables the area directly above is restricted for phishing and anchoring. This area can be wide as much as 15 km due to the difficulty of repairs for this technology when damage occur. Moreover, the cables, if not anchored to the bedrock, are dig under the sediment layer of the sea floor to prevent movement and corrosion [5]. Sea cable needs permission from relatively fewer landowners, especially if the substations are close to the shore. In this sense, having to deal whit just the maritime authorities for most of the route, the permitting phase could intrinsically take less time, from 10-12 years down to 7-8 (Personal Interview - Kees).
In all these kinds of transmissions, after the construction phase, there are regular controls to be carried out on the line. As expectable, OHLs, underground, and sea cables have progressively more difficult maintenance activities.

4.3 Critical bottlenecks

With no doubt, crossing a mountainous region is a **technical challenge**. Locations can be difficult to access and the transportation of materials and workforce is logistically complex. Moreover, the rerouting due to public opposition is inherently more difficult due to the limited route available [3]. The Pyrenees and the Alps are thus recognized as difficult terrain to work in (Personal Interview - Keandler, Staschus).
Crossing a large body of water with sea cables is an inherent **challenge**. Specialize vessels are needed, together with robots operating at the bottom of the sea to excavate trenches and set the cable. The cable themselves have to endure enormous pressure over decades of operation, corrosion from saltwater, and the mechanical stress of the laying procedure. On top of that, if joints are necessary to connect two consecutive spools of kilometers long cables, these weak points need also to endure

these kinds of problems [5].
A reassuring finding is that ”for a purely technical problem, usually a technical solution is not difficult to find” (Personal Interview - Keandler). For example: if a river crosses the designed path for a power line (Personal Interview - Keandler) or a bird sanctuary is nearby (Personal Interview - Bax) then an underground tunnel is adopted. If the sea bed brings the cable to deep waters, like in the case of the Italian-Sardinia connection, and the mere weight of the line would make the operation impossible a solution was found. The normally used copper core cables were swapped with an aluminum one. In this way, tensile strength was preserved and the lightweight characteristics needed has been achieved (Cigre - 2012).

Public acceptance and **Insufficient regulation** are both consistently identified as important barriers (Personal Interview - Staschus, Keandler, Sander, Bax, Frank,van der Meijden, Kees) [7]. In the survey designed by the Battaglini et al., a breakdown of the second macro problem is provided. Lack of comprehensive and stable regulations, regulations that do not reflect the current situation in Europe, grid planning driven by national interests and primitive coordination at the European level are all regarded as hindering the completion of high-voltage power transmission infrastructure. Other complicating issues are the lengthy and complex permitting process, choice and deployment of technologies, insufficient knowledge about future capacity needs, costs of cables and cost allocation, insufficient knowledge about future capacity needs [7].

The public opposition can arise because of the power line’s potentially high visibility from houses, roads, tourist attractions, and other populated locations. Other impacts include potential damage to archaeological remains or sites of nature conservation or special scientific interest, noise pollution from humming and crackling noises, interference with electrical equipment. Also, potential health risks from exposure to electric and magnetic fields [27].
Legal procedures are comparable in all member states, but the planning and implementation processes differ. Moreover, the analysis pointed to the fact that administrative procedures for building interconnectors tend to be very complicated [7].

A lack of coordination between authorities of local and national levels together with problems in public acceptance (based on issues of participation, transparency, and technology) are also highlighted [94]. When these problems exacerbate, we can find the situations respectively at the border between Germany and Poland [79], and the 3 decades-long issues on the Spanish French border [16].

Another issue coming up in recent debates [71] is the process of scenario development for the future energy systems of Europe. There are two main problems here. Firstly, the need for longer time frame planning, right now it is of 10 years. Secondly, the usage of scenarios which are not compatible with the Paris agreement (e.g. the dominant role envisioned for natural gas going forward) (Personal Interview - Frank, Sander).
Closely related is the Trans-European Energy Networks (TEN-E) Revision under the updated EU goals. This piece of regulation sets the criteria for which projects can be eligible for the PCI status.
Right now, the building of further infrastructure for fossil fuels, such as gas and oil, is enabled by the TEN-E regulation, contradicts the EU‘s pathway to 1.5 ° C and the Paris Agreement.
This framework was adopted for energy security (after the Ukrainian energy supply crisis of 2009). Assessment of costs and impacts in the complete lifetime of the project should be used when evaluating new projects (Personal interview - Bax). A redefinition of scope and priorities in line with the Paris Agreement need climate-resilient infrastructure planning for the future as a goal, with electrical interconnection as main benefited.

4.4 Recent Developments

From the previous section, a few improvements have occurred in the last 10 years.
The ENTSO-e have brought more stakeholders to the same tables, providing a place where national decisions are shared, and common projects are eased. The TYNDP helped the creation of an overarching vision of European infrastructure (Personal interview - Staschus, Kees). Planning together and

forecasting are strictly intertwined here since future envisioning corresponds to making assumptions and consequently establishing a general frame for the different national stakeholders involved, so that they can coordinate their contribution to the vision [14]. The ACER has provided more uniformed regulation for every country in the EU. Another improvement was the creation of the PCI label.

Projects of Common Interest (PCI) benefit from accelerated planning and permit granting, a single national authority for obtaining permits, improved regulatory conditions, lower administrative costs due to streamlined environmental assessment processes, increased public participation via consultations, increased visibility to investors, also have the right to apply for funding from the Connecting EuropeFacility (CEF) [21].

The funding of interconnections is reported to not be a huge problem right now, the investment costs are usually passed on to consumers, and the access to capital is not considered problematic (Personal interview - Keandler). The CEF fund is a resource that exists to support these kinds of projects (Grisey – Personal interview).

If procedures and regulations have improved, facing public opposition has not improved at the same pace (Keandler – Personal interview).
More often than not, in case of public opposition to OHL and entrenchment of positions, like in the case of France-Spain interconnections [16], the developers fall back on the proposal of changing the infrastructure technology to underground cables. This change delivers a shockwave of effects: an increase of 5 to 10 in terms of costs (Interview – Stashus), new surveys, nature assessments, possible downrating of the transmission capacity, and the emboldening of similar request from other communities facing a similar issue.

The results are increased time delay for the completion or even possible discard of the project altogether.

4.5 Proposals and Solutions

In this section solutions to the problem of public acceptance are proposed. Next, three technical innovations and proposals are presented for the increase in power transfer capacity. In the end, the experience of the German reform in the transmission field is discussed.

4.5.1 Public Acceptance

The most recurring solution in the interviews to the problem of Public Acceptance is the concept of early stakeholder engagement (Personal Interview - Sander, Keandler, Frank). Other solutions to the same issue are community compensation schemes and Integration Vegetation Management.

The subject of **Early Stakeholders Engagement** has been already mentioned as of capital importance in the literature (Personal Interview - Sander) [35] [94] [80] [86]. Simply put, it can significantly increase the amount of knowledge available in the decision phase and create a more trustworthy environment. In the case of Public acceptance (or public opposition) a concrete work of stakeholder management would be preferable as it *allows for the anticipation of hiccups* and positive junctures possibly affecting the project throughout its life cycle. Local residents, even if lack contractual connection to the transmission projects, has to be considered stakeholders due to the impact a piece of infrastructure has in their life. In practice they have a level of legitimacy to be at the decision table [14]. Early engagement of the public results to be a powerful move because the main decisions are made in the beginning, and when these are settled there is less room for changes. This in turn provides less room for public outcry or a generalized feeling of exclusion, both sources of rigid opposition. The recent German experience with early-on local participation is considerably positive: "Since the introduction in May 2019, only one project of 50Hertz (out of 15 line sections currently) experienced a noticeable delay" [35]. As remarked during the interviews, the TSO has the possibility to understand the request of benefits from the community, what can the TSO provide to them to compensate for the negative externality of an exogenous infrastructure (Kaendler – personal interview).

The involvement of non-knowledgeable general public can be looked with suspicion from grid planners because of the high demanding task of bringing every time a new local community up to speed with the inner working of the infrastructure functioning and requirements [14]. With early engagement there could be a knowledgeable party representing the public interests, like NGOs. This can legitimize to the wider audience the credibility of choices made for grid expansions [94].
In summary, by including different stakeholders with diverse views and interests in the project planning process, disruptions to plans during the execution phase are reduced (Personal Interview - van der Meijden) [14].

TSO and industry perspective over the reason for public opposition can be limited and counterproductive. Generally, it is assumed to stem from a Not-in-my-back-yard approach, ignoring the real motives for an opposition (Personal Interview - Kaendler)[23]. Seeing the Transmission lines as an unstructured project, instead of a set in stone one, opens up to the necessary early-stage involvement. An example of a solution to open the perspective of the grid developers and involve the public is **Q Methodology** for Stakeholders' involvement [28] [27]. Q methodology reveals the subject's viewpoints on a given issue among a group of people. An analysis of these answers produces different clustered viewpoints.
Q methodology combines the open nature of qualitative methods with the structuring nature of quantitative methods. It relies on purposed sampling and smaller sample sizes of people. The number of respondents is smaller than in conventional survey research.
This system of interviewing was used for example for a transmission Network upgrades in the Somerset, England. It revealed more viewpoints than the assumed "Not In My Back Yard" (NIMBY) attitude [27]. Thanks to this approach, with interests and concerns of the public taken care of, the line was readily completed. Another example comes from the personal experience of Mr. Keandler, in which the installation of a new power line next to a highway was vigorously opposed by the nearby residents. The reason for that was discover to be a general sense of bitterness because the last public infrastructure, the highway, produced annoying noises for most of the day. The solution has been the installation of the power line along the highway, installing along the route acoustic barriers to damper the sound of vehicles passing by (Personal Interview - Keandler).

On the subject of **Community Payments**, the United States of America have more experience (Sander – Personal Interview). The objective of this practice is to raise the perceived value for the local community of a piece of infrastructure by providing funds directly to affected comunities or to their local projects.
Europe has some projects supported mainly by TSO and also by electrical energy provider (e.g. Wind Plants owners). There is no uniform system of local compensation, nor the nature of the electrical infrastructure is widely relevant for the implementation of the scheme (upgrading and new lines entail different schemes in different countries). From the actual utilisation of this system, we can distinguish 4 main systems of community payments adopted in Europe:

- **To affected authorities**. Explored in Germany, France, and Italy. Here the methodology varies considerably: from a fixed amount per km inside the local municipality to a fixed percentage of the infrastructure total cost to be divided into the affected communities. This system of compensation also allows for a complete disconnection for the TSO related to the use of the money (e.g. in Germany) but also tighter cooperation in the definition of the eligible projects (e.g. Italy).
  The positive aspects of this system are the legitimacy of relating directly with elected officials, that can have a better assessment of the need of the community, and lower administration effort and legal risk for the TSO. On the negative side there is lower visibility to the community, thus diminishing the desired effect, less flexibility, and possible lower efficacy if the money is simply directed into the authority fund.

- **To selected projects proposed by the community.** Adopted in France and Ireland. This more participatory system allows for higher engagement and visibility. The effort on the TSO side is increased and the transparency issue of providing money becomes greater.

- **To individuals.** Used only in Ireland, this method directly targets those individuals directly affected by the new power line, with contributions proportional to the vicinity. We can expect higher support from the locals, but the flip side is the not "public good" nature of these payments, thus more susceptible to be viewed as bribery.

- **Investment based mechanisms.** This method, applied only in Germany, was a non-successful system that allows a preferential path individuals affected by a new power line to invest, with bonds, in this infrastructure. It was doomed by its complex design and the necessary hard promotion. This system is more widespread in the United States of America.

The common challenges affecting these innovative systems of public compensation are the issue of Transparency (i.e. where the money go and how it was decided), Equity (are the most affected people benefiting from the compensation?) and the precedence set from these experience (e.g. communities demanding compensation for the perceived damaged of an old infrastructure) [83] [82].

The literature regarding the effectiveness of community payment schemes, for electrical infrastructure, is not substantial yet. Nonetheless, we can find some claims from studies carried out for other community impacting projects (e.g. nuclear sites, landfills, incinerators, etc.).
More specifically, community compensations are overwhelmingly more accepted and effective when they are in non-monetary forms [96]. Form of *in-kind and public good compensation is better received* and considered more appropriate [18]. Direct compensation is more likely to be viewed as a bribe and thus capable of wrecking the delicate relationship-building effort with the community [48]. The reasons why this is the public response to community compensations the more common theories are the "bribe-effect" and the "crowding out of public spirit" [50].

The size of the compensation offer has a limited impact on the response of the community. Some studies find no direct correlation between them (e.g. [50]), while others suggest that the number of compensation matters to some extends [55].
For the difference between compensation dealt directly to the individual or to the community, there is no conclusive empirical evidence of a more effective solution [96].

The usual Vegetation Management adopted by TSO offers room for improvement. Integration Vegetation Management (**IVM**) provides added value to the abundant square kilometers of land underneath OHL by creating and managing a healthy ecosystem. Experiments and interviews with stakeholders highlight how IVM is an appreciated practice from the local community, providing at the same time missing ecological function to the barren corridors created by electrical infrastructures [87] [81].

The first piece of this shift in management is the creation of a functional edge between the natural environment (e.g. the crossed forest) and the electrical corridor. Switching from a simple hard slashed edge to a selected choice of plants at the boundary region. The selection prevents the growth of taller trees the closer we get to the power line. The created ecotones are valuable for small animals and plants normally not incentivized [81] [17].
In the proper corridor the height limit is kept by restoring natural or semi-natural grassland, heathland, peat bogs, or small ponds. In this way, invasive weeds are naturally avoided. Natural pollinator, such as bees, are reported in larger numbers and in more diversified communities [87].

All these measures *increase public acceptance*. This is the number one reason for TSO to adopt this system. On top of this, the selective creation of this "Green Corridor" reduces the necessary operation and management costs, compensating the higher initial investment [81].

4.5.2 Technical Improvements

On a more technical level, three area of improvements are highlighted, as expectable, by the interviewed who have experience inside the TSO environment.

Firstly, the usage of **Ultra High Voltage Alternate Current** powerlines (UHVAC). At the moment the High Voltage Alternate Current (HVAC) reaches 420kV in the EU++ [38]. ”The biggest regret” of Mr. Staschus is the non-usage of this technology on European soil (Personal Interview - Staschus).
The People’s Republic of China, after the impact on the operation of many companies from power shortages in 2005, has invested heavily in this solution for bulk transmission over long distance [53]. Nations of the former Soviet Union and Japan host other older examples of UHVAC [34].
UHVAC operates on the order of magnitude of >800kV. The benefit of this higher voltage is the reduced current level. In turn, lower currents lead to fewer thermal power loss and, as a consequence, a higher power rating for the lines. Higher voltage in alternated current means also greater electromagnetic fields around the infrastructure. This is the main reason for which TSOs have been contrary to this development because the public opposition for them could be even larger.
The interviewed suggest its use in open corridors where past power lines already exist. The refurbishment of old lines or the reuse of power corridors is known to be more welcomed the new corridors creation (Personal interview - Keandler). In this way, the amount of built circuits can be lower, together with the footprint of the area needed [15]. Hence reducing the possible cumulative backlash to these power lines.

Secondly, use **Uprating** as a method to make up for the temporary lack of higher structural capacity by maximizing the power transfer through existing power lines. Uprating can be done in two different ways:

- Current Increase. Cheaper and with lower impact. The amount of power is increased in a control way. The optimizing constraint is to keep the sagging and load loss, due to over heating, into safe and economical limits. With excess temperature the aluminium can anneal, losing it elasticity [29]. The measurements of temperature and sagging can be direct with Dynamic Line Thermal Rating (DLTR) installed on the cables or through remote sensing and calculation of the area’s conditions [73]. With different weather condition, the thermal line rating changes. In the Netherlands, we can see this technique capable of delivering a 10% to 50% increase of current (from the standard 2.5kA) for line operating at 380kV (Personal Interview - Kees).
  Other options to increase the current are the re-tension of the cables, raising the suspension points, or changing the mechanical properties of the cables [73]. The central ring of transmission of the Netherlands, operating at 380kV, is seeing the current limit persistently increased to 4kA through the change of all cables. The limit of 4kA is now dependent on the substations system, whose safety devices can handle that amount of current.

- Voltage Increase.By leaving unaltered the current flow or even reducing it the thermal loss does not increase. For this reason, this uprating can result in a much higher rating increase than thermal uprating. For example, the Norwegian TSO, Statnett, is undertaking a vast task of uprating nearly 30% of their 300kV OHLs to 420kV. For lines with a twin-conductor bundle, this is reflected in a 40% increase of power capacity [9].
  It is carried out with improvement of insulation and/or the aforementioned mechanical method to improve the clearance distance to the ground [29]. The costs of this operation are generally higher due to the necessity of uprating the voltage class of substation equipments.

Another solution is the addition of circuits in the cleared corridor. If this is feasible, it is cheaper and easier than replacing the old altogether (Personal interview - Keandler)

When dealing with underground cable the uprating can be done in similar fashion: increase of the current by considering the heat loos of the cable to the surrounding soil or increasing the voltage operation point. Forced circulation of insulating gas or fluid is an option for localized hotspot [6].
The excavation of old cables to replace them with newer ones is generally discarded as too costly. The choice of cables inside pipes or duct bank allows uprating through additional cables. There are cases of transmission projects with cables in which additional pipes are already laid down for hypothetical future reconductoring (Personal Interview - Sander).

If the subject is sea cable, the technology process to achieve uprating by means of Dynamic Power Management is being tested at the moment in TenneT. Dynamic Line Rating for overhead lines seems a prominent solution (Personal Interview - van der Meijden).

The third aspect is closely linked with the regulation realm. It has to do with the **Trade-off calculation** carried out in Cost Benefit Analysis (CBA) for new projects (Personal Interview - Staschus).
These trade-off are implicit components in the decision making process of grid developers. To improve the transparency in this process, the regulators at National and European level have been requiring more explicit accountability for the trade-off.

Mr. Stashus welcomes the strive for accountability to the citizens and sees the difficult position in which the TSO are put when the regulators are imposing their trade-off figures. He recommends the TSO to step up and bring to the regulator tables their experience and systematic view (e.g. knowing the value of lost energy provision) and leading the suggestions, leaving to the elected officials to set the figures that are non competence of grid developers (e.g. the value of human life).

4.5.3 An example of good practice

Germany is an interesting study case because of the 4 TSOs dividing the nation. This is a similar situation of Europe, divided into member states. In past years, a set of reforms changed the landscape of regulation and practices in the nation [94].
There is room for learning from this experience, by expanding the approach to our considered EU++ region, the changes were based on three pillars:

1. *More involvement of the government to provide legitimacy*. On one side, by actively participating at the decision table when assessing the need for the electrical infrastructure, the expected load, and the future development of national energy needs. On the other, by enshrining into law, through the parliament, the necessity for the agreed upgrades.

2. *The early engagement of the local population*. This aspect is already discussed in depth above. The key concept is to move the exchange with the public from the validation stage to the decision one.

3. *Transparency and new transmission technologies*. Data on load flows were made available to the public to make the assessment of the grid's expansion requirements. From the TSO side, there has been more flexibility and aperture towards transmission technology different from OHL such as underground cables and DC lines.

A single authority approach was created, giving to a single national regulator the power of planning, authorization, and regulation.
To balance this centralization of power the authorization approval procedure was changed. Before the submission of all the documents from the grid developer, a conference is called. In it, all the interested stakeholders can log into, offer suggestions, and raise questions for the developer.
From the results of this confrontation the regulator will decide the assessments needed for the project.
The EC adopted the German approach in its policy guidelines for other MS [94].

Chapter 5

Discussion and Conclusions

In this final chapter, a critical overview of this thesis takes place. The methodology and the sources are judged in a detached way.
After that, the conclusion of this work is going to take place. A summary proposes the main findings of the previous chapters, a brief overview of the critical borders and the possible developments to confront their situations.
The answer to the main research question is then reported.
In the ending section, the Framework Analysis for the stakeholders involved in the interconnection system is explained. It proposes an overarching method to deal with the general problems facing the electrical grid of Europe.

5.1 Discussion

The literature studies over grid development are based on own optimization simulations. This thesis examined this issue through the confrontation of other peer-reviewed works and was necessary due to the complexity of creating, and running, an European wide thorough model. The application of this method, for the grid envisioning, was based on the idea of removing the unique defects coming from every study's bias or shortcomings.

Of the possible European grid studies present in the literature only a dozen were considered in this work. This is the result of the framework adopted to choose them. Arbitrary decisions were adopted when concerning the oldness of the study and the percentage of the EU++ needed to qualify as adequate for the analysis.
Then, only 4 studies, for a total of 7 simulations, were actually used to calculate the proposed grid. 2 other studies, with their 3 simulations, provided additional qualitative indications. This reduction of sources is due to the tight parameters necessary to operate the mathematical calculations, namely: vRES share and load demand.
All the choices in the selection process lead to a relatively small sampling of studies with which to operate. The tradeoff between the relaxing of the selecting parameters standards and the validity of the result was not examined. As a consequence the method adopted for the formulation of the grid outlook could be improved in it efficiency.

The advantages of the method adopted in this thesis are the feaster time of completion of the project (between data gathering, model development and simulation execution and analysis a year can easily pass by) and the immediate confrontation with other sources, so that glaring errors can be easily spotted. Even if some of the results are confronted in the literature, here the confrontation is the starting principle of the method.
The disadvantage is the impossibility of providing a perspective outside of the realm of the already tested ones. A way to improve the thesis method would be to evaluate the mathematical average for every critical border independently. The specific conditions of the countries in every location can push the calculation toward a different direction than the general trend.

This works faces the entirety of the European continent and more. Works at this scale usually involve experts in their field for every different nation. It is clear that the lacking of personal experience in every area is detrimental to the level of nuance that I can provide.

Deep flexibility from coupling is not dealt with in the specific. An appropriate modeling simulation study is necessary to show the consequent changing transmission requirements. The work of Brown et al. is relevant in this case. Unfortunately, it was not readily modifiable.
The results found in this work can still be considered valid because of the intrinsic increase of electricity transported in the grid when sector coupling increases. More specifically: with higher sector coupling the flexibility provided by the "demand-side" increases, thus reducing in principle the need for transmission flexibility. On the other hand, the increase of electrification in the continent will require more transmission capacity anyway. In summary, the sector coupling will change the reasons for infrastructure expansion, but it will not change the required value so much [11].

An important aspect of this thesis is the direct interaction with the experts in the field. The envisioned number of interviews at the beginning of this work was 10. The final possible conversations were just 8. The critical aspect was the low rate of response from the potential interview. Of the 36 personal or group contacts, only 9 initially accepted to take questions.
I have attested a lower response rate from the legislative institution and civil servants. While there was a higher disponibility from experts of the NGO world.
The result is a minor than envisioned confidence level regarding the present situation. Even if the solutions proposed overlap quite extensively, the missing of real insights from the legislative branch of the EU is a handicap when assessing the globality of the problems and their solutions.

As a consequence, the level of knowledge and insight approachable for the regulative and legislative of this complex problem was not safeguarded by external voices. The information was obtained only from research papers, reports, and laws of the European Institutions. On the bright side, these entities are relatively transparent.

The market aspects of the energy transition are not fully accounted for. The increase of net-zero marginal cost power plants, like wind turbines and photovoltaic arrays, will require a reformulation of the market incentives and mechanisms. In turn, this reshaping could reduce the economic incentives for interconnections in the long term. In the shorter term, there could be benefits instead for RES exporting countries [85].

Finally, the infrastructure bottlenecks inside countries are considered more feasible to resolve than cross-country interconnections. If in general this view can be considered correct, because of the stacking of additional authorities, language & cultural barriers, and the number of entities involved, the reality can be more multifaced. In particular, the barriers and thus the difficulty of infrastructure planning and realization lay on a continuous spectrum. This is true for both nations and supranational level.
The result is that some country-specific situations can be more problematic than between two different nations.
When assessing the implementable recommendations, we should consider the national development process in line with the Framework Analysis proposed (i.e. the solutions proposed for the European level should be applied also for the country level).

5.2 Analysis of Solutions for the Main Interconnections

An outlook for the European Grid Development is proposed. In chapter 3, it has been constructed to support a share of vRES in the electricity production of 60% by 2040. The flexibility required to integrate these variable sources is envisioned to be mainly provided by the interconnections between countries, which can gather economically load and production across the continent.

The capacity needed, across the main border identified by ENTSO-e, is reported in table 5.1. It

#	Name	2027 - TYNDP - 2035		Proposed 2040
1	Ireland – Great Britain and Continental Europe	0.95GW	2,15GW	7GW
2	Great-Britain and Continental Europe – Nordics	14.4GW	20GW	20GW
3	Nordics – Continental West Europe	7.54GW	8,26GW	25GW
4	Nordic-Baltic to Continental East Europe	1.6GW	2,2GW	7GW
5	Baltic integration	2.72GW	2,72GW	8GW
6	Central East integration	4.6GW	4.6GW	10GW
7	Iberian Peninsula integration	5GW	8GW	12GW
8	Italian Peninsula integration	13.5GW	14GW	14GW
9	South-East integration	4.2GW	5,44GW	6GW
10	Eastern Balkan	5GW	7,15GW	10GW

Table 5.1: The envisioned levels of necessary grid increase by 2040

is important to consider how the column of the TYNDP 2035 is a collection of the maximum capacity envisioned for two different scenarios by the association.
On top of that, there are *currently no specific plans for the interconnection projects needed to reach those levels by 2035*, only up to 2027 levels.

Looking at the results, there isn't a clear relationship between the technical challenges to overcome and the good positioning of the borders when related to the planning in the TYNDP. The second, eighth, and ninth borders seem to be the best positioned, with a relative difference between planned and simulated capacity below 10%. These three borders are characterized by, respectively, sea crossing, mountain crossing, and relatively normal terrains. On the other hand, borders one, seven, and six, even if affected by comparable technical hurdles, have larger discrepancies.

In chapter 4, the timeframe for interconnection projects has been examined, be it OHL, underground cable, or sea cable. Ten years seems to be the average time for facilitated PCI cases. Successful stories can be found, like the ALEGrO interconnection between Germany and Belgium (Personal Interview - Keandler).
Normally, twelve years should be considered as quite appropriate number. Natural opposition during the permitting process is poised to happen, and thus unplanned delays move the operational period ahead in the future.
Uprating, as discussed in chapter 4, is a method to increase the transfer capacity of present lines. It is easier and quicker to implement, but its effect cannot provide the level resulting from this comparative research. Its effect can range from some percentage point to even 60%. This amount is still not enough to cover the required increase of roughtly 3 to 4 times the present grid capacity. Especially for sea cable where the research for uprating is still ongoing and the disparity between planned capacity and the modelled one is higher. If history is a good indicator, the levels presented in the table will not be reached in time.

We can conclude that the European Electricity grid is ill-prepared for the tectonic shift required from the transition to renewable, and especially variable, sources. The probability of reaching these calculated level by 2040 is slim.

Sea Crossing in the Northern Europe

Borders 1, 2, 3, 4, and 5 are all characterized by the need for an extensive offshore cable infrastructure (see table 5.1). Connections already in place between the involved countries show the technical feasibility of these water crossing.

As expressed by the respondents, the main issue is the need for early regional planing. This is particularly true in the North Sea region, a crowded area when considering communication cables,

pipelines and electrical transmission cables running on the seabed (e.g. the new North Sea Link alone between England and Norway will cross 14 different gas pipelines [5]). On one side there are natural and commercial limitations to the crossable areas on the nation's economic zone in the open sea, on the other side there is the urgency to roll-out these interconnections.
A viable technical solution to the overcrowding of the seabed is the connection of wind park to two different countries. This system, if allowed by new regulations, can provide a flexible interconnection between areas and at the same time integrate RES expansion [2].

Only by anticipating the hiccups that could arise along the way with centralized discussion and planning ahead of time the level of required interconnection can be achieved.
Clustering of cables on a single route, albeit with safety distancing to avoid disruption from the same accident [5], can be a practical solution for reducing the seabed examination and permitting. Additionally, the building of additional vessels for the laying of cables will need to take place if the reusing of those used for communication infrastructure will not be feasible.

Central-East Europe

Concerning Poland, **borders 4 and 6**, the challenge of mainly land interconnection shouldn't be underestimated. Together with Spain, the Uk and Cyprus, it is not going to reach the target of 10% capacity through interconnection with its neighbours in 2020 and the required increase is considerable, see 5.1.

Here, the issues are different and thus need variegated approaches. The operation of synchronisation with Estonia and the Baltic Republics will provide the opportunity of establishing large land interconnection and, due to the importance of this undertaking, the funding and attention aren't going to be difficult to found. Towards Czech Republic and Slovakia, fellow member of the Visegràd group, the issue is mainly due to the mountainous region on the border. As long as the RES growth in the region pushes for means of flexibility, this technical challenge can be overcome, especially if knowledge transfer is seek from TSO specialized in these kind of terrain (e.g. APG and Swissgrid). Trust between the Polish and German authorities is the biggest problem. The issue of power loop-flow has to be addressed as a starting point, before tackling the capacity requirements induced by future RES growth. A starting technical solutions will be the uprating along the border, until reliance upon each others is built.

Mountains towards peninsulas

The required final capacity across the Alps and Pyrenees are similar, see table 5.1, but have very different prospects, with Spain facing a dire outlook.

The issues of public opposition on **border 7** are long in the making. Decades of entrenchment on one hand and mismanage on the other have resulted in little progress apart from an underground connection through a tunnel under the Pyrenees. At the moment, to solve this border problem, a lesson has been taken from the Italian situation: using sea cables (in the Adriatic Sea) instead of building over land. Through the Bay of Biscay, two progressively difficult projects aim to double the transfer capacity between Spain and France.
From the experience of the SACOI cable (Italy-Corsica-Sardinia) with multi-terminal High Voltage Direct Current (HVDC) connection and the SAPEI cable which dives deep to 1650m below sea level, the connection between Spain, France and England could actually result in success [5]. But this is not enough to cover the envisioned 2040 capacity.
On the other side of the border, the trafficked Gulf of Lion could provide relatively shallow seabed for cables. The problems here stem from the naturalistic protected area on the Golf under the Natura 2000 directive [74]. In this case, a solution is to closely follow the route of the newly funded 2Africa communication cable from Barcelona to Marseilles with a large capacity HVDC cable [1]. Increased interconnection can be thus achieved.

On top of these measures, active public engagement together with retroactively community compensation schemes could be considered to cure citizens' distrust in the mountain region. This is a necessary step if additional land connection would be deemed necessary.

Balkans connections

For the final two **borders, number 9 and 10**, the difficult situation comes from the relatively low level of energy demand in the region. RES are expected to grow, with the prominence of solar technology. In this sense, the flexibility from interconnection is less relevant inside the region, and the results can be seen in the low capacity envisioned, regardless of the long span of these borders.

As previously mentioned in chapter 3, electrical connection across the Adriatic Sea could provide an innovative solution against land based bottlenecks. On top of that, allowing the transfer of power along the East-West direction, daily solar production can be used more effectively due to time zones difference: morning ramp-up in Italy can be facilitated by Balkan's solar generation already some hours ahead, while on the other way peak production in Italy can help the evening ramp-up in the eastern region.
Another way to skip the mountains region in the center of Balkans is through a dedicated energy corridor from Poland to Romania. Ukraine is already connected through 8 interconnectors to the EU++ group, and a closer relationship is envisioned for the region. In fact, the Burshtynska TPP Island on the western side of Ukrain already operates in synchronous with the EU++ group. As a mean to overcome borders 9 and 10 the full operation of these interconnectors would provide immediate benefit (at the moment the three towards Romania and Moldova are not in operation) [24].

5.3 Conclusions

The starting question for this work is: *"How to enhance the contribution of flexibility in the European power system to reach rapidly a decarbonized electricity production through cross border interconnection by 2040?"*
It was tackled through 2 separate questions. The first, approaching what is the required level of flexibility using interconnections. The second, looking at if and how this grid expansion is possible.

Firstly, the level to aim towards by 2035-2040 needs to be revised upward. The TYNDP does not comply with the scenario of a 60% vRES power sector by 2040.
Secondly, if the goal is to increase flexibility through cross border interconnection, additional work is required, directed to the problem of insufficient planning and delays. The latter is mostly caused by public opposition issues and permitting in sensitive areas.
When combining the main solutions to these problems, we can extrapolate the practice of early planning with broad stakeholder engagement.

To reach the grid infrastructure necessary to sustain the decarbonized power sector by 2040, planning of 15-20 years should be carried out by 2024 (the next TYNDP) with this decarbonization goal in mind. 2024 is the first first available TYNDP because the 2022's scenarios are already in development. It is also the last opportunity for a longer term planning that can bring the necessary changes by 2040. The individuated projects need to start as soon as possible with the integration of early participation from communities and NGOs. In this way, delays will not prevent the timely completion by 2040.
Underground cables, even if costlier than OHLs, need to be considered the go-to choice when dealing with urban centers proximities. The peerless European experience with sea cables should be leveraged as an innovative way to surmount land constriction and provide meshed connection.
As two works have expressed in this research, the kind of investment needed for these interconnections levels entail on its own a net economical benefit. it produces in fact savings in the system's costs or a reduction of LCOE [11][52] (see Fig.3.8).

5.4 Recommendations

The thesis aims to provide recommendations for the stakeholders at play. Ideas and experiences are gathered in chapter 4. The liberalization and unbundling of the energy market have been necessary to eliminate the monopolistic power in the sector of the past century, and right now the scattered nature of these actors hinders the reactivity of the electricity sector to meet its challenges.
The central concept coming out from the interviews is the need for a "Transparent, Coordinated, and Participative planning" for the future of the European Energy System. Long term planning in concordance with high-end environmental goals should be the norm.

The following table 5.1 summarizes the action and rate of involvement (represented in the intensity of color green) for stakeholders during the implementation of interconnection infrastructure.

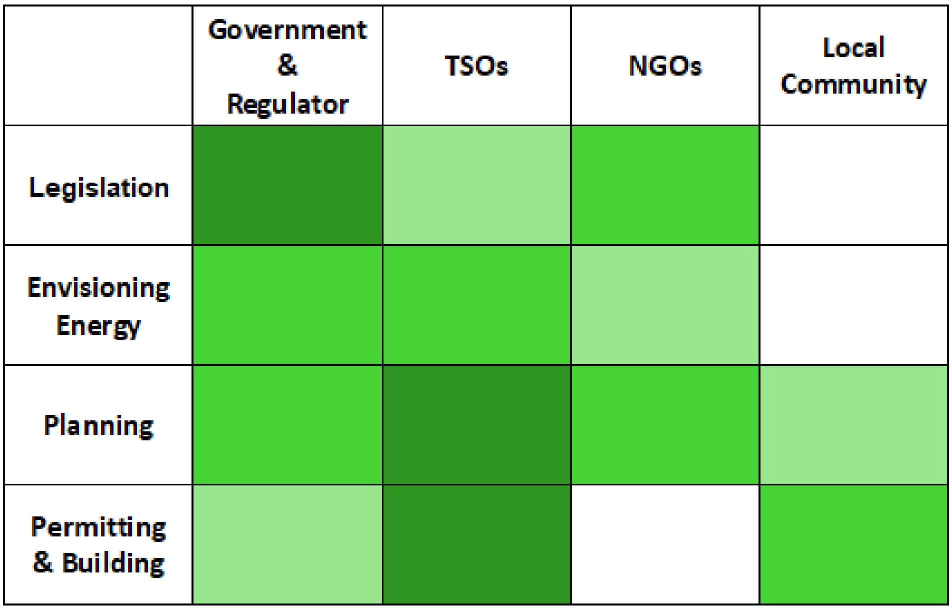


Figure 5.1: The envisioned levels of new participation to prepare the grid for the energy transition

Legislation

The change has to start from here. Climate change, as a Global Phenomenon, needs to be tackled from a high government level.

This is traduced in the necessity to set into law the goals of the European block regarding the energy transition. Will it be net-zero emission by 2040 or 2050? Once this is set indefinitely, the envisioning scenarios, the funding, and the economic apparatus will follow as a consequence. The institutions of the EU (Commission, Parliament, and Council) are the prime actors that have the power and possibilities to create the market distortion needed in Europe and elsewhere. By setting the framework with clear emission constraints and assigning the externalities costs, the market can operate as a means for providing appropriate solutions without the necessity for state intervention into founding specific technologies.

Secondly, and closely related, the revision of the TEN-E Regulation. As mentioned in chapter 4, the decision process of the PCI should follow the abovementioned goals of climate protection. Thus, the financing of projects which will promote the emission of GHG in their lifetime should be avoided. On the contrary, electrical interconnections, as a means of market unity and emission avoidance, should be

kept as the prime beneficiary of this label, together with other climate-resilient projects (e.g. Hydrogen infrastructure).
All these decisions need to be informed and supported by NGOs that represent the interests of the citizens and the environment. Support from these advocacy groups, for every action, will generate a cascade effect of legitimacy for the resulting actions decided down the line.

Closely related, the TSO should bring up to the table their experience with the energy system related trade-offs. Their knowledge on the matter is needed for the definition of feasible sets of regulation and sound CBA assessments.

Envisioning Energy

In the planning process of the TYNDP, as well documented in chapters 2 and 3, the scenario definition is of crucial importance. At the moment it is solely based on workshops between energy utilities, grid operators, and consultants. For 2018 the EUCO scenario was considered and for 2020 a collaboration with the European Network of Transmission System Operators for Gas (ENTSO-g) is underway.

As Antonella Battaglini puts it: “In the long run, grid development issues have a ‘‘chicken and egg’’ character, in which the grid needs to be in place for increased renewables generation capacity, but the generation capacity has to be in place to provide the incentive for the grid development projects”[7].
The change needed for this step is the real integration of the planning process for RES installation: coordination between government’s auctions sites, high potential locations selling, grid developers, and nationals and regional goals. Of course, it is unlikely that there will be information to pinpoint every new RES installation in the next two or three decades. The coordination is necessary to assess a minimum and broad outlook of RES development envisioned.

From the regulatory side, there is the need to have consistent support, the literature has already highlighted how an intermittent approach produces harm when dealing with new technologies uptake [91]. The scenario formulation will be necessary to assess the different pathways to reach the goals defined in the previous step.

In summary, the base for this envisioning exercise is provided by the coordination and share of information regarding new RES development from the legislative branch. The energy aim in the long term is set instead by the climate goals and energy indicators.

Planning

We have seen the time horizon increase in the past decade of TSOs collaboration. To prepare the grid for the Energy Transition, long term planning is a necessity.
Right now, the TYNDP develops the next 10 years projects. The e-highway project exemplified the ability of the joint venture between TSOs to develop 35 years-long planning. A time horizon of at least 20 years can open up space for much necessary early-stakeholders engagement. By starting the project processes right now the recurring delays can be prevented and avoided altogether. This approach surely requires more investments in terms of time, people’s expertise, and money. It is indeed the price to be prepared for the RES uptake in the energy sector.

The planning should use the precaution approach: if there is a doubt regarding the most appropriate capacity level to plan, the more flexible the electrical corridors the better. This could mean the predisposition for quick and easy uprating, or the implementation of higher capacity altogether.
The role of the NGOs in this phase is to mediate between the economic and physical necessity of the grid developers, the local communities, and the protected natural areas. Their participation can prevent future rerouting of the planned power corridors.

Permitting and Building

Once the planning is completed, the TSOs role is to follow thoroughly the agreed blueprint. This phase rolls-out similarly to how these kinds of projects are carried out at the moment.

The new supporting role of the government is to enshrine the need for those agreed plans into law. The permits still need to be fulfilled on a quantitative scale, but lower-level authorities are limited in their power to overrule a sovra regional need. In this way, the streamline of the permitting phase can reduce the building time and anticipate the benefits of the electrical interconnections.
On the TSO side, the early engagement with the locals is the key card, together with practices such as communities' payments as an in-kind or public good as discussed in chapter 4, to promote an efficient realization of the projects.

All these measures need to be enacted together. A push measure, as it can be the enacting as a law of the need for transmission update, will work much better with a pull measure, as it is the community payments.
By bringing together people, more perspective, at a single table, with a unified goal of a clean, just and transparent electrical infrastructure, the Energy Transition can happen in the European Continent.

Acronyms

AC Alternate Current. 33, 39

ACER Agency for the Cooperation of Energy Regulars. 38, 39, 41

CBA Cost Benefit Analysis. 45, 53

CCS Carbon Capture & Storage. 18, 21, 27

CCU Carbon Capture & Utilisation. 18

CEF Connecting EuropeFacility. 41

CGT Cycle Gas Turbine. 5

CSP Concentrated Solar Power. 28, 30

DC Direct Current. 39, 45

DSM Demand Side Management. 9, 21–23

DSO Distribution System Operator. 4, 38

EC European Commission. 9, 11, 17, 20, 33, 45, 57, 58

ENTSO-e European Network of Transmission System Operators for Electricity. 4, 9, 11–13, 17–20, 31, 33, 38, 40, 48, 60, 67

EU European Union. 1–3, 7, 9, 11, 13, 14, 17–19, 28, 34, 35, 40, 41, 48, 52, 57, 67

GHG Greenhouse Gasses. 1, 2, 10, 11, 17, 19, 52

HVDC High Voltage Direct Current. 50

IEA International Energy Agency. 11, 16, 19

IRENA International Renewable Energy Agency. 11, 15–19, 57, 64

IVM Integration Vegetation Management. 43

MS Member State. 10, 12, 45

NGO Non-Governmental Organization. 38, 42, 48, 51, 53, 67

OHL Over Head Line. 38, 39, 41, 43–45, 49, 51

PCI Projects of Common Interest. 20, 38–41, 49, 52

PV Photovoltaics. 4–7, 9, 15, 16, 23, 27, 28, 31

RES Renewable Energy Source. 1, 5–7, 9, 11–13, 15, 20–22, 27–29, 31, 33–35, 48, 50, 51, 53, 57, 62

TEN-E Trans-European Energy Networks. 40, 52

TSO Transmission System Operator. 4, 5, 21, 33, 38, 39, 41–45, 50, 53, 54, 67

TYNDP Ten Years Network Development Plan. 4, 11–13, 20, 21, 33, 35, 36, 38, 40, 49, 51, 53, 57, 60

vRES variable Renewable Energy Source. 5–7, 10, 13, 15–19, 21, 22, 25, 26, 28–31, 36, 47, 48, 51

WEO World Energy Outlook. 11, 17, 57, 65

Appendix A

Scenarios examined

IRENA 2019 Table 5.2 presents the total generation of the EU + United Kingdom for years 2030, 2040, 2050 and 2016, the last year available when the report was created. The RES are subdivided in 5 categories, while all the others non renewable are grouped together.

WEO 2019 Table 5.3 shows Scenario referring to the Stated Policies, Table 5.4 shows Scenario referring to the Current Policies while Table 5.5 presents the envision able future in the Sustainable Development scenario.

TYNDP 2018 From Figures 5.2 and 5.3 the principal data for the various scenarios of the TYNDP are retrieved.

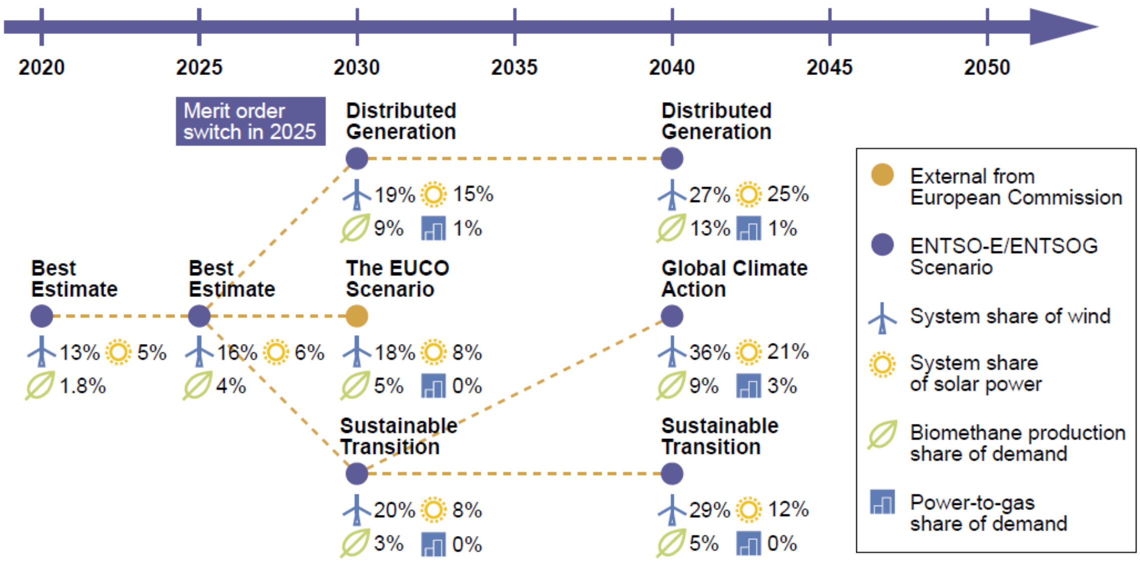


Figure 5.2: A single picture showing the different paths for the energy scenarios[45].

EUCO 3232.5 This scenario is composed with the data from two EC reports, Figure 5.4 and 5.5.

e-Highway A summary of the five scenarios elaborated for this project can be retrieved from the following 3 figures. Figues 5.6 presents clearly the generation for Europe, Figure 5.7 highlights what is produced in the mainland and Figure 5.8 expose the solar share from Africa, and Middle-East, and the off-shore wind share from the North-Sea.

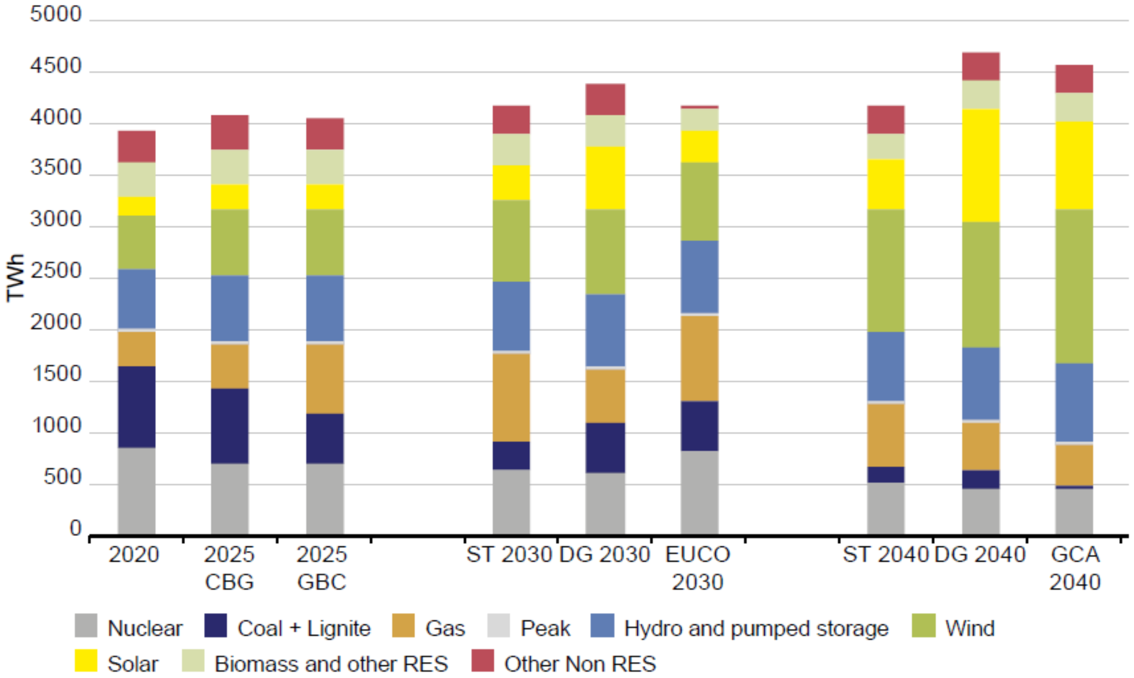


Figure 5.3: A single picture showing the different generation levels in the scenarios[45].

SUMMARY ENERGY BALANCE AND INDICATORS (A)										EU28: EUCO3232.5
	2000	2005	2010	2015	2020	2025	2030	'00-'10	'10-'20	'20-'30
Gross Electricity generation by source (1) (GWh$_e$)	**3005548**	**3289991**	**3332773**	**3251330**	**3378948**	**3525758**	**3498306**	1,0	0,1	0,3
Nuclear energy	944993	997699	916610	867402	772986	717746	750269	-0,3	-1,7	-0,3
Solids	933855	965565	830393	848120	760337	629724	413894	-1,2	-0,9	-5,9
Oil (including refinery gas)	181296	142772	86899	34579	22122	17403	9900	-7,1	-12,8	-7,7
Gas (including derived gases)	514267	705961	798645	564505	595217	565092	373450	4,5	-2,9	-4,6
Biomass-waste	46401	87831	145814	189157	215166	262976	287649	12,1	4,0	2,9
Hydro (pumping excluded)	357072	312372	375785	362405	376816	376273	380572	0,5	0,0	0,1
Wind	22254	70455	149278	274278	481817	667946	895790	21,0	12,4	6,4
Solar	117	1458	22502	103798	146026	279683	377049	69,1	20,6	10,0
Geothermal and other renewables	5293	5878	6847	7086	8461	8916	9732	2,6	2,1	1,4
Other fuels (hydrogen, methanol)	0	0	0	0	0	0	0	0,0	0,0	0,0

Figure 5.4: The most recent iteration of Europe Energy Outlook from the EC [20].

Transmission layout capacity

All capacities in the tables are expressed in MW.

Today's The most recent figures on the European grid regarding the Net Transfer Capacity between countries are presented in Table 5.4. The table also summarised the planned capacities for 2035. There are two columns for every year. The reason is that the first of the pairs refers to the transfer capacity from country A to country B, the second is the inverse.

Country A	Country B	Border	2020	2020	2035	2035
Albania	Greece	AL-GR	250	250	250	250
Albania	Montenegro	AL-ME	350	350	400	400
Albania	North Macedonia	AL-MK	500	500	500	500
Albania	Serbia	AL-RS	650	500	500	500
Austria	Czech Republic	AT-CZ	900	800	1,000	1,200

Austria	Germany	AT-DE	5,000	5,000	7,500	7,500
Austria	Hungary	AT-HU	800	800	1,200	800
Austria	Italy	AT-ITn	405	235	1,650	1,350
Austria	Slovenia	AT-SI	950	950	1,950	1,800
Austria	Switzerland	AT-CH	1,200	1,200	1,700	1,700
Belgium	France	BE-FR	1,800	3,300	3,800	5,300
Belgium	Germany	BE-DE	1,000	1,000	2,000	2,000
Belgium	Great Brittain	BE-GB	1,000	1,000	2,400	2,400
Belgium	Luxembourg	BE-LUB	380	0	380	500
Belgium	Luxembourg	BE-LUG	300	180	800	180
Belgium	Netherlands	BE-NL	2,400	1,400	4,400	4,400
Bosnia and Herzegovina	Croatia	BA-HR	750	700	1,894	1,548
Bosnia and Herzegovina	Montenegro	BA-ME	500	400	800	750
Bosnia and Herzegovina	Serbia	BA-RS	600	600	1,100	1,200
Bulgaria	Greece	BG-GR	600	400	1,350	800
Bulgaria	North Macedonia	BG-MK	400	100	500	500
Bulgaria	Romania	BG-RO	300	300	1,100	1,500
Bulgaria	Serbia	BG-RS	500	200	1,080	386
Bulgaria	Turkey	BG-TR	700	300	1,200	500
Croatia	Hungary	HR-HU	2,000	2,000	2,000	2,000
Croatia	Italy	HR-ITn	0	0	0	0
Croatia	Serbia	HR-RS	600	600	600	600
Croatia	Slovenia	HR-SI	1,500	1,500	2,000	2,000
Cyprus	Greece	CY-GR	0	0	0	0
Czech Republic	Germany	CZ-DE	2,100	1,500	2,600	2,000
Czech Republic	Poland	CZ-PLE	0	800	0	600
Czech Republic	Poland	CZ-PLI	600	0	600	0
Czech Republic	Slovakia	CZ-SK	1,800	1,100	2,290	1,650
Denmark	Great Brittain	DKw-GB	0	0	1,400	1,400
Denmark	Netherlands	DKw-NL	700	700	700	700
Denmark	Norway	DKw-NOs	1,640	1,640	1,700	1,640
Denmark	Poland	DKe-PL	0	0	600	600
Denmark	Sweden	DKe-SE4	1,700	1,300	1,700	1,300
Denmark	Sweden	DKw-SE3	740	680	740	680
Estonia	Finland	EE-FI	1,016	1,000	1,016	1,016
Estonia	Latvia	EE-LV	900	900	1,379	1,379
Finland	Norway	FI-NOn	0	0	0	0
Finland	Sweden	FI-SE1	1,100	1,200	2,000	2,000
Finland	Sweden	FI-SE2	0	0	800	800
Finland	Sweden	FI-SE3	1,200	1,200	1,200	1,200
France	Great Brittain	FR-GB	2,000	2,000	8,800	8,800
France	Ireland	FR-IE	0	0	700	700
France	Italy	FR-ITn	4,350	2,160	4,350	2,160
France	Italy	FRc-ITCO	50	150	150	200
France	Luxembourg	FR-LUF	380	0	380	0
Germany	Denmark	DE-DKe	600	585	1,200	1,185
Germany	Denmark	DE-DKw	1,500	1,780	3,000	3,000
Germany	Denmark	DEkf-DKkf	400	400	400	400
Germany	France	DE-FR	2,300	1,800	4,800	4,800
Germany	Great Brittain	DE-GB	0	0	1,400	1,400
Germany	Luxembourg	DE-LUG	1,000	1,000	2,000	2,000
Germany	Luxembourg	DE-LUv	1,300	1,300	1,300	1,300
Germany	Netherlands	DE-NL	4,250	4,250	5,000	5,000

Germany	Norway	DE-NOs	1,400	1,400	1,400	1,400
Germany	Poland	DE-PLE	0	2,500	0	3,000
Germany	Poland	DE-PLI	500	0	2,000	0
Germany	Sweden	DE-SE4	615	615	2,015	2,000
Great Brittain	Iceland	GB-IS	0	0	0	0
Great Brittain	Ireland	GB-IE	500	500	1,000	1,000
Great Brittain	Netherlands	GB-NL	1,000	1,000	3,000	3,000
Great Brittain	North Ireland	GB-NI	450	80	450	280
Great Brittain	Norway	GB-NOs	0	0	2,800	2,800
Greece	Italy	GR-ITs	500	500	500	500
Greece	North Macedonia	GR-MK	1,100	850	1,200	1,679
Greece	Turkey	GR-TR	660	580	660	580
Hungary	Romania	HU-RO	1,000	1,100	2,417	2,085
Hungary	Serbia	HU-RS	600	600	600	600
Hungary	Slovakia	HU-SK	2,000	2,000	2,000	2,000
Hungary	Slovenia	HU-SI	1,200	1,200	1,200	1,200
Ireland	North Ireland	IE-NI	300	300	1,820	1,770
Italy	Malta	ITsic-MT	200	200	200	200
Italy	Montenegro	ITcs-ME	600	600	1,200	1,200
Italy	Slovenia	ITn-SI	680	730	1,660	1,895
Italy	Tunisia	ITsic-TN	0	0	600	600
Lithuania	Latvia	LT-LV	1,200	1,500	1,200	1,500
Lithuania	Poland	LT-PL	500	500	1,000	1,000
Lithuania	Sweden	LT-SE4	700	700	700	700
Montenegro	Serbia	ME-RS	500	600	700	700
Netherlands	Norway	NL-NOs	700	700	700	700
North Macedonia	Serbia	MK-RS	650	800	750	750
Norway	Sweden	NOm-SE2	600	1,000	600	1,000
Norway	Sweden	NOn-SE1	700	600	700	600
Norway	Sweden	NOn-SE2	250	300	250	300
Norway	Sweden	NOs-SE3	2,145	2,095	2,145	2,095
Poland	Slovakia	PLE-SK	990	0	990	0
Poland	Slovakia	PLI-SK	0	990	0	990
Poland	Sweden	PL-SE4	600	600	600	600
Romania	Serbia	RO-RS	1,000	800	1,647	1,922
Spain	France	ES-FR	2,600	2,800	8,000	8,000
Spain	Portugal	ES-PT	4,200	3,500	4,200	3,500
Spain France	Great Brittain	ES-FR-GB	0	0	0	8,000
Switzerland	France	CH-FR	1,300	3,150	1,900	5,200
Switzerland	Germany	CH-DE	4,600	2,700	6,600	4,300
Switzerland	Italy	CH-ITn	4,240	1,910	6,000	3,700

Table 5.6: ENTSO-e Net Present Transfer Capacity in MW by 2020 and the stated plan up to before 2035

TYNDP the various capacities elaborated for the two scenarios considered of the e-Highway project are reported in table 5.4.

				Large Scale		100% RES	
Country A	Country B	Cluster	Cluster	Addition	Final	Addition	Final
Austria	Hungary	51_at	58_hu	1000	2600	0	1600

Austria	Italy	49_at	52_it	4000	6300	8000	10300
Belgium	Germany	28_be	33_de	0	1000	5000	6000
Belgium	Great Brittain	28_be	90_uk	4000	5000	4000	5000
Belgium	Netherlands	28_be	30_nl	0	3500	10000	13500
Bulgaria	Greece	66_bg	68_gr	0	500	1000	1500
Czech Republic	Austria	40_cz	51_at	5000	7100	0	2100
Czech Republic	Czech Republic	39_cz	40_cz	1000	8600	0	7600
Czech Republic	Poland	39_cz	44_pl	0	0	2000	2000
Czech Republic	Poland	40_cz	43_pl	5000	7100	0	2100
Czech Republic	Slovakia	40_cz	46_sk	1000	3700	0	2700
Denmark	Norway	38_dk	79_no	2000	3700	0	1700
Denmark	Sweden	38_dk	88_se	0	740	0	740
Denmark	Sweden	72_dk	89_se	4000	5700	0	1700
Estonia	Finland	73_ee	75_fi	5000	6000	4000	5000
Estonia	Latvia	73_ee	78_lv	5000	5950	4000	4950
Finland	Norway	74_fi	85_no	1000	1050	0	50
Finland	Sweden	75_fi	88_se	3000	4350	0	1350
France	Belgium	25_fr	28_be	0	400	3000	3400
France	Germany	25_fr	35_de	0	2100	5000	7100
France	Germany	25_fr	36_de	1000	2800	0	1800
France	Great Brittain	22_fr	90_uk	4000	5000	4000	5000
France	Great Brittain	26_fr	90_uk	9000	11000	8000	10000
France	Ireland	21_fr	96_ie	6000	6700	5000	5700
France	Italy	19_fr	52_it	1000	2000	0	1000
France	Italy	20_fr	52_it	1000	5800	0	4800
Germany	Austria	37_de	49_at	1000	3500	8000	10500
Germany	Czech Reublic	37_de	39_cz	1000	3000	0	2000
Germany	Denmark	31_de	38_dk	11000	14000	0	3000
Germany	Denmark	31_de	72_dk	4000	4000	0	0
Germany	Denmark	32_de	38_dk	0	0	0	0
Germany	Denmark	32_de	72_dk	2000	2600	0	600
Germany	Norway	31_de	79_no	17000	18400	9000	10400
Germany	Poland	34_de	44_pl	3000	4700	10000	11700
Germany	Sweden	31_de	89_se	0	1200	4000	5200
Germany	Sweden	32_de	89_se	8000	8000	11000	11000
Great Brittain	Ireland	92_uk	96_ie	1000	1500	2000	2500
Great Brittain	North Ireland	93_uk	95_uk	1000	1500	0	500
Hungary	Romania	58_hu	59_ro	1000	2400	2000	3400
Hungary	Serbia	58_hu	65_rs	1000	1700	0	700
Italy	Corsica	53_it	99_fr	0	300	0	300
Italy	Greece	55_it	68_gr	6000	7000	9000	10000
Italy	Montenegro	54_it	64_me	1000	2000	2000	3000
Italy	Sardinia	54_it	98_it	8000	8700	3000	3700
Lithuania	Latvia	77_lt	78_lv	5000	6500	3000	4500
Lithuania	Sweden	77_lt	88_se	2000	2700	0	700
Netherlands	Denmark	30_nl	38_dk	3000	3700	0	700
Netherlands	Germany	30_nl	31_de	1000	2400	0	1400
Netherlands	Great Brittain	30_nl	90_uk	4000	5000	0	1000
Netherlands	Norway	30_nl	79_no	7000	7700	14000	14700
North Ireland	Ireland	95_uk	96_ie	1000	2100	2000	3100
North Macedonia	Greece	67_mk	68_gr	2000	2600	0	600
North Sea	Belgium	110_ns	28_be	2000	2000	7000	7000
North Sea	Denmark	113_ns	38_dk	9000	9000	0	0

North Sea	Denmark	114_ns	72_dk	2000	2000	0	0
North Sea	Germany	112_ns	31_de	10000	10000	5000	5000
North Sea	Germany	112_ns	33_de	0	0	6000	6000
North Sea	Great Brittain	106_ns	90_uk	10000	10000	14000	14000
North Sea	Great Brittain	107_ns	92_uk	3000	3000	8000	8000
North Sea	Great Brittain	108_ns	93_uk	1000	1000	0	0
North Sea	Great Brittain	109_ns	94_uk	1000	1000	2000	2000
North Sea	Netherlands	111_ns	30_nl	2000	2000	1000	1000
North Sea	Netherlands	112_ns	30_nl	0	0	0	0
North Sea	Netherlands	113_ns	30_nl	0	0	5000	5000
North Sea	Norway	115_ns	79_no	0	0	5000	5000
North Sea	Sweden	116_ns	88_se	1000	1000	0	0
Norway	Great Brittain	79_no	92_uk	0	0	5000	5000
Norway	Great Brittain	81_no	90_uk	0	0	0	0
Norway	Sweden	82_no	88_se	2000	4148	0	2148
Poland	Lithuaniua	41_pl	77_lt	8000	9000	8000	9000
Poland	Slovakia	42_pl	46_sk	3000	3600	0	600
Poland	Sweden	45_pl	89_se	0	600	0	600
Sardinia	Corsica	98_it	99_fr	800	1200	0	400
Serbia	Bulgaria	65_rs	66_bg	0	900	0	900
Serbia	North Macedonia	65_rs	67_mk	1000	2900	0	1900
Slovakia	Hungary	46_sk	58_hu	2000	7400	0	5400
Slovenia	Hungary	57_si	58_hu	1000	1900	0	900
Spain	France	04_es	14_fr	5000	7000	5000	7000
Spain	France	06_es	15_fr	10000	11800	8000	9800
Spain	Portugal	01_es	12_pt	1000	20100	1000	20100
Spain	Portugal	02_es	12_pt	1000	1950	1000	1950
Spain	Portugal	07_es	12_pt	0	0	0	0
Spain	Portugal	08_es	13_pt	2000	2900	0	900
Spain	Portugal	09_es	13_pt	2000	2500	2000	2500

Table 5.7: The calculated Net Transfer Capacities in MW calculated in the e-Highway project for scenarios Large RES and 100% RES

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Solids	829	792	751	607	395	298	180	92	37
Oil	87	61	24	24	20	13	8	10	8
Natural Gas	799	530	585	537	492	565	593	632	637
Nuclear	917	857	773	695	677	730	681	647	688
Hydro	408	371	375	362	380	366	370	372	376
Biomass & waste	143	201	208	269	325	289	274	254	268
Wind	149	302	487	664	955	1149	1440	1761	1905
Solar, tidal etc.	23	108	147	307	412	430	475	546	641
Geothermal	10	13	7	7	9	9	10	17	17

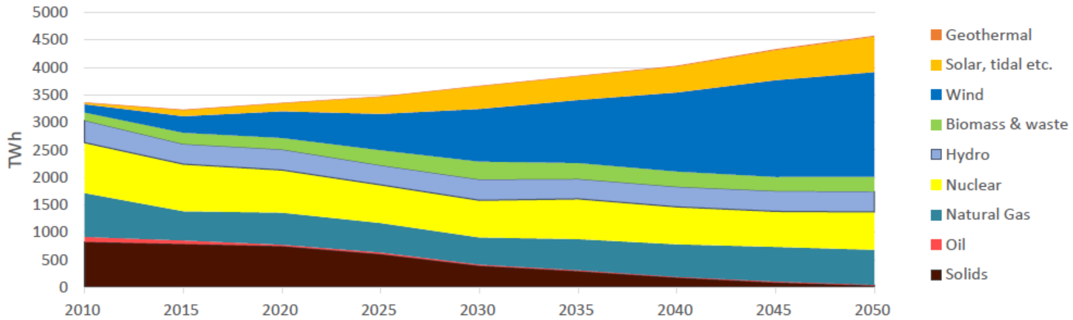


Figure 5.5: This scenario is retrieved from the long-term analysis of the A Clean Planet for all proposal [46].

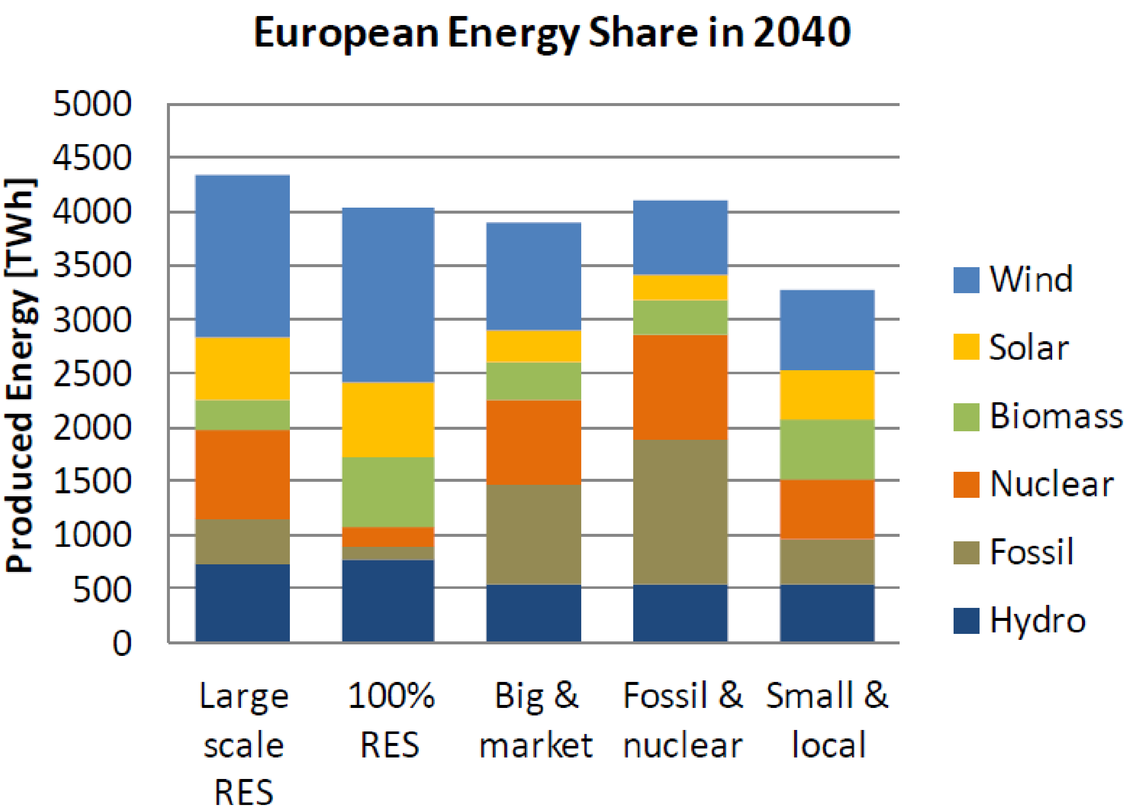


Figure 5.6: Overview of Europe generation in 2040 [54].

Generation (TWh)	Scenario	2016	2030	2040	2050	Shares_2016 (%)	Shares_2050 (%)
Total	Reference	3201.538	3479.035176	3623.406969	3795.670777	100	100
Non- Renewables	Reference	2236.147	1953.052394	1794.500178	1588.393388	69.846024	41.84750155
Other renewables	Reference	207.156	272.4273221	274.9778688	313.5855523	6.470515109	8.261663634
Hydro	Reference	350.121	407.8405508	400.8947494	408.3397731	10.93602512	10.75803981
Wind - total	Reference	302.894	617.9610396	824.4215162	1086.18763	9.46089036	28.61648689
Onshore	Reference	274.214	492.5489493	669.3642961	901.835537	8.565070913	23.75958269
Offshore	Reference	28.68	125.4120903	155.0572201	184.3520932	0.895819447	4.856904194
Solar PV	Reference	105.22	227.7538691	328.6126574	399.1644341	3.286545404	10.51630812
Total	REmap	3201.538	3598.86343	4156.661092	4819.915269		100
Non- Renewables	REmap	2236.147	1629.226617	1131.613916	688.159302		14.27741493
Other renewables	REmap	207.156	370.9005303	582.3098943	777.9410845		16.14014025
Hydro	REmap	350.121	416.5005473	419.4892821	423.4312821		8.785035805
Wind - total	REmap	302.894	848.568973	1373.7256	1927.2396		39.98492697
Onshore	REmap	274.214	590.853473	833.7256	1013.4896		21.02712483
Offshore	REmap	28.68	257.7155	540	913.75		18.95780214
Solar PV	REmap	105.22	333.666763	649.5224	1003.144		20.81248205

Table 5.2: IRENA Scenarios of the 2019 Report [58].

Generation (TWh)	2010	2017	2018	2025	2030	2035	2040	2018(%)	2040(%)
Total	3 336	3 269	3 279	3 351	3 396	3 468	3 565	100	100
Coal	864	710	666	351	238	126	65	20	2
Oil	87	61	58	28	20	17	12	2	0
Natural gas	765	663	629	698	627	591	523	19	15
Nuclear	917	830	829	693	636	575	595	25	17
Renewables	699	1 000	1 092	1 579	1 872	2 156	2 368	33	66
Hydro	377	301	339	383	403	414	422	10	12
Bioenergy	143	211	225	265	279	298	312	7	9
Wind	149	362	392	682	884	1 084	1 239	12	35
Geothermal	6	7	7	7	10	13	15	0	0
Solar PV	23	114	124	234	282	319	332	4	9
CSP	1	6	5	6	10	15	22	0	1
Marine	0	1	1	1	4	13	27	0	1

Table 5.3: WEO Stated Scenario of the 2019 Report[57].

Generation (TWh)	2025	2030	2035	2040	2040(%)
Total generation	3 437	3 515	3 597	3 702	100
Coal	545	479	359	293	8
Oil	28	21	18	14	0
Natural gas	614	663	763	761	21
Nuclear	729	673	620	644	17
Renewables	1 517	1 677	1 835	1 987	54
Hydro	383	394	403	411	11
Bioenergy	263	278	292	303	8
Wind	640	751	862	962	26
Geothermal	7	9	10	12	0
Solar PV	219	234	251	271	7
CSP	6	8	11	16	0
Marine	1	2	5	12	0

Table 5.4: WEO Current Scenario of the 2019 Report[57].

Generation (TWh)	2025	2030	2035	2040	2040(%)
Total generation	3 351	3 418	3 700	4 016	100
Coal	232	64	46	48	1
Oil	27	19	15	9	0
Natural gas	664	549	504	401	10
Nuclear	704	679	658	685	17
Renewables	1 721	2 103	2 474	2 871	71
Hydro	386	404	417	428	11
Bioenergy	279	317	347	372	9
Wind	768	1 019	1 280	1 573	39
Geothermal	7	12	16	20	1
Solar PV	274	333	372	408	10
CSP	6	13	24	35	1
Marine	1	5	17	36	1

Table 5.5: WEO Current Scenario of the 2019 Report[57].

Type Gen	Wind	Solar	Biomass	Hydro	Fossil	Nuclear	Σ Total
Scenario	GWh	GWh	GWh	GWh	GWh	GWh	GWh
Large Scale RES	1,207,104	317,525	303,653	744,067	522,488	791,712	3,886,550
100% RES	1,270,404	606,547	649,070	764,972	206,363	215,352	3,712,708
Big & Market	785,510	286,999	329,135	539,259	943,723	788,493	3,673,119
Fossil & Nuclear	566,866	215,119	324,275	552,276	1,327,998	985,209	3,971,743
Small & Local	671,954	455,062	539,949	549,435	426,012	549,034	3,191,445

Figure 5.7: The generation in mainland Europe by 2040 [54].

Scenario	Large Scale RES	100% RES	Big & Market	Fossil & Nuclear	Small & Local
Region	GWh	GWh	GWh	GWh	GWh
MA	56,904	20,023	6,793	0	4,730
DZ	110,076	38,506	12,886	0	9,292
TN	18,814	6,482	2,161	0	1,528
LY	52,881	18,585	6,315	0	4,466
MI	5,850	2,161	633	0	633
Sum	244,526	85,758	28,787	0	20,650
Off-shore	308,634	332,500	204,353	134,001	65,253

Figure 5.8: The generation outside of mainland Europe [54].

Appendix B

Hereafter, the experts who agreed for a 30-minute questioning are presented. Those who have been contacted but did not reply to the invitation are not going to be nominated due to consideration of their privacy.

- **Konstantin Staschus**. He is the former Secretary-General of the ENTSO-e, a position he has occupied since February 2009. He now operates as a consultant on global and European energy transition, still helping the ENTSO-e activities. Aside from this ten years' experience, he previously had positions as manager and supervisor in both a German association of electricity networks and a US company of gas and electricity.
- **Gerald Kendler**. Director Asset Management at Amprion, one of the German TSOs, and Vice Chairman of the System Development Committee at ENTSO-e. For the last 25 years, he has worked in electrical grid-related business.
- **Antina Sander**. She is Deputy Executive Director at Renewable Grid Initiative (RGI), a unique collaboration of NGOs and TSOs from across Europe. From 2007 she holds various positions as a consultant.
- **Nathalie Grisey**. Osmose H2020 project coordinator. Working for RTE, the French TSO, she was directly involved in the e-Highway project. Unfortunately, she was not available for a full-length interview, thus her answers were reported by mail.
- **David Frank**. He's the developer of the project "Shaping the grid debate". Working at the moment for Germanwatch.
- **Vera Bax**. The Policy Officer EU-Energy and Climate Politics at NABU. Collaborating for BirdLife.
- **Jansen Kees**. Net strategist for TenneT (TSO of the Netherlands and part of Germany). He has 40 years of experience in the Energy Sector, starting with twenty years in the fossil fuel industry.
- **Mart van der Meijden**. The Manager Innovation at TenneT. With 30 years of experience with gas, district heating and electricity, he chaired national and international energy groups. He is also full professor at TU Delft, EEMCS faculty.

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