Renewables and electrification in Europe

A critical analysis

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Master thesis

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“Prediction is very difficult, especially if it’s about the future”.

Niels Bohr

Abstract

Electrification of processes has become the cornerstone of the strategy to decarbonise energy supply, especially in recent years. This study aims to define the main issues underlying the electrification of the European energy mix, especially those caused by an increasing share of intermittent energies. To this end, through a mix of qualitative and quantitative analysis and personal contributions via modelling, I undertake a critical analysis of the opportunities and challenges of upscaling renewable technologies on the European territory. The examination of the different European scenarios for the energy transition sheds light on their dependence on the cost assumptions for renewables, which have proven to be highly overestimated. Incorrect cost assumptions and the lack of consideration of transmission, curtailment and sector coupling are the main reasons for the overestimation of storage needs, estimates that tend to decrease over time. Batteries are expected to play an increasing role for daily storage, while hydrogen is preferred for seasonal storage. The latter will become essential once variable renewable energies play a significant role, especially during Dunkelflaute, periods of low wind and solar potential, which are particularly challenging in Europe. Based on 40 years of historical data, I show how these phenomena can be significantly mitigated by increasing the pooling of VRE production on the continent. I also estimate that electrification of the steel, ammonia and methanol sectors can provide 166 TWh of flexible electricity demand by 2050. In general, the problems associated with inertia and frequency management, while significant, are not an obstacle to VRE expansion. Finally, the results of this work argue for the broadest possible cooperation on electrification strategy at the continental level.

Keywords: Electrification; Renewables; Storage; Flexibility; Transmission; Europe.

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First of all, I would like to thank Lars J. Nilsson and Greg De Temmerman for the kindness they showed me and for the invaluable advice they gave me during the whole period. I was able to have a great deal of freedom in my thesis work while being able to rely on them if I had any questions. More broadly, I would like to thank the entire IMES department team for their warm welcome. Finally, I would like to thank the University of Lund and more particularly LTH for having welcomed me this year, as well as my French school, Centrale Nantes, for giving me the opportunity to spend my final year in Sweden.

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Nomenclature

ASU: Air Separation Unit
AWE: Alkaline Water Electrolysis
CAPEX: Capital Expenditure
CF: Capacity Factor
ENTSOE-E: European Network of Transmission System Operators for Electricity
EROI: Energy Return On Investment
EUMENA: Europe, the Middle East and North Africa
FCR : Frequency Containment Reserves
GHG: Greenhouse gas
HB: Haber-Bosch
H-DR: Hydrogen-Direct Reduction
HVAC: High-Voltage Alternating Current
HVDC: High-Voltage Direct Current
IBR: Inverter-Based Sesource
IEA: International Energy Agency
LCOE: Levelized Cost of Energy
LCOS: Levelized Cost of Storage
NREL: National Renewable Energy Laboratory
OPEX: Operating expense
PEM: Proton Exchange Membrane Electrolysis
PHS: Pumped hydro storage
PtG: Power-to-Gas
PtH : Power-to-Heat
PtM: Power to Methanol
RES: Renewable Energy Supply
ROCOF: Rate Of Change Of Frequency
SC: Synchronous Condenser
SCL: Short Circuit Level
SG: Synchronous Generator
SOEC: Solid Oxide Electrolyzer Cell
TMR : Total Material Requirement
TRL: Technology Readiness Level
TSO: Transmission System Operator
VRE: Variable Renewable Energy
WPP: Wind Power Plant

1 Introduction

Awareness of the urgent need to combat global warming is growing as its impacts become increasingly apparent. European countries, which could consider themselves less vulnerable to the impacts of climate change compared to southern countries, have been experiencing particularly significant climatic phenomena for several years. What's more, vulnerability to exogenous shocks, as demonstrated by the war in Ukraine in 2022, reflects the great dependence of European states on hydrocarbon-producing countries. It is for these reasons that the European Union, to combat climate change and reduce its energy dependency, is developing a far-reaching decarbonisation strategy. The electrification of the energy mix is seen, in Europe as elsewhere, as the cornerstone of decarbonisation strategies in the energy sector.

1.1.Aim

The aim of this thesis is to understand the challenges underlying the electrification of the European energy mix. To electrify their industrial processes, transport, heating, etc., European countries need to build new power generation facilities. As in the rest of the world, in the short term (up to 2050), these facilities will be mainly solar and wind power. The objective is therefore to analyze the new issues intrinsic to the variable renewable energies (VRE) that are emerging as part of the energy transition. The purpose of this work is not to support the arguments in favor of a 100% renewable electricity mix, but to understand the main challenges underlying the ramp-up of these technologies, and thus to assess the relevance of such a technical choice in the context of the fight against climate change. Particular attention is paid to the role of Europe in this transition.

1.2.Research questions

The research questions I am addressing in this thesis are as follows:

- What are the main technological trends underpinning the decarbonisation of Europe's energy mix?
- What are the main challenges and benefits caused by the significant increase in the penetration rate of VRE in the coming years?
- What are the benefits and challenges of greater pooling of energy transition strategies at European level?

1.3.Scope and limitations

The aim of this study is to deal specifically with the electrification of the energy mix and therefore the study will focus mainly on electrical energy. In addition, I am concentrating on the European area, even if I offer comparisons with the situation worldwide or in other regions to back up my comments. Furthermore, I deliberately propose to look at the issue of energy exclusively through the prism of reducing greenhouse gas emissions. Other benefits (or threats) in terms of biodiversity, water, air pollution etc. are not (or only marginally) addressed in this thesis. The proposed approach is relatively exploratory and as such, I propose not to confine myself to technical subjects but also, where useful in answering research questions, to use a multidisciplinary approach.

1.4 Method

In this study I use a mixed method approach, with a combination of qualitative and quantitative analysis of the problems associated with the upscaling VREs in Europe. I also make several calculations on points in the literature that seem to me to be little studied.

To this end, I first give a brief overview of the energy and climate situation in the world and in Europe. Then, based on historical data up to the present day and the scientific literature, I summarise the technical characteristics of the key technologies for the electrification of the European energy mix.

This enables me to provide an analysis divided into five parts. Firstly, by basing my analysis on the literature and the evolution of institutional scenarios[1], I provide an overview of the changing perception of energy needs. Then, through a synthesis of the main energy transition scenarios published in the literature since the 2010s for the European territory, I elaborate, in a more exploratory way but based on quantitative and qualitative analyses, the main trends underlying these scenarios in order to understand their limitations and conclusions for the future of the European energy mix. Particular attention is paid to the issue of storage. Scenarios are selected on the basis of their scope and influence in the literature. Thus, the main European scenarios published in the literature are mentioned, and particular attention has been given to having a diversity in the years of publication. Some institutional scenarios are also studied. I then address four issues underlying the electrification of the energy mix through the expansion of renewables: Dunkelflaute periods, industrial flexibilities, peak demand response and grid stability issues related to inertia and frequency. Since I found very little literature on the first two topics, I would like to present some results in this thesis through calculation and modelling. For the Dunkelflaute study, I am using the RenewableNinja open-data database which gives hourly capacity factors for solar and wind power over 40 consecutive years, and I develop a model based on this to quantify the benefits of pooling VRE sources on the European continent. To do this, a comparison of the evolution of capacity factors between several entities, different European countries taken into autarky, as well as the aggregate situation on the European continent, is carried out. For industrial flexibilities, based on IEA (NZE) projections of hydrogen consumption in industry, I re-evaluate the degree of flexibility that can be expected from specific industries in light of the emerging scientific literature on the subject. Interviews were conducted to discuss the hypotheses. The other two topics are dealt with using a mixed approach, based on literature and historical data, enabling me to provide a critical analysis of the situation in Europe on these subjects.

I conclude this study with two shorter sections in a relatively exploratory way, based on the literature and data from institutional sources, on the difficulties of fueling the energy transition and the role that Europe must play in it.

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[1] National and regional scenarios produced by research institutes, NGOs and public institutions responsible for energy forecasting.

2 Background

2.1 Climate change

In 2015, most countries agreed, through the Paris agreements, to limit global warming to below 2°C, and preferably 1.5°C. While some estimates suggest that 1.5°C could be exceeded as early as the 2030s (IPCC, 2021), countries still do not have targets that match their international commitments(UNFCCC, 2022).

Moreover, Europe has a historical responsibility for cumulative greenhouse gas emissions, having been one of the pioneer regions of the industrial revolution. Responsible for only 15% of CO2 emissions in 2021(Ritchie & Roser, 2020), Europe remains responsible for 32% of cumulative emissions since 1750 (compared to 33% for Asia and 29% for North America).

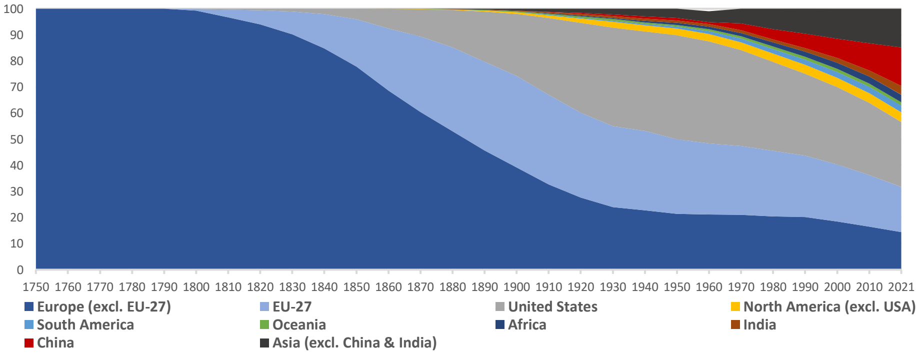


Figure 2-1 Global cumulative CO2 emissions share (%) by region (1750-2021) (Statista, 2023).

The main cause of greenhouse gas emissions worldwide is the use of energy, mainly through combustion and to a lesser extent through various industrial processes. This accounts for 73% of global GHG emissions(Ritchie & Roser, 2020). A rapid exit from fossil fuels is thus considered the cornerstone of all decarbonisation strategies worldwide. This is the background to the European Commission's Fit for 55 package (ECCEU, 2023), which aims to reduce the European Union's net emissions by 55% by 2030 compared to 1990.

2.2 Role of energy

Energy plays a particularly structuring role in the development of societies. As the anthropologist White (1943) explained in his time, the degree of cultural development of a society varies in proportion to the amount of energy per person per year that it is able to mobilise and put to work. Although this notion needs updating in view of the profound change in perceptions of energy demand (see 4.1.1), it bears witness to the central role played by energy and to the fact that a change in the structure and quantity of energy consumed must be considered as equally central.

Combating climate change requires a global energy transition within a constrained timeframe. The concept of energy transition can be defined as the process of substituting fossil fuels, i.e. oil, gas and coal, with low greenhouse gas emitting energy sources(Smil, 2010).

Historically, fossil fuels first took off with coal, the engine of the industrial revolution, and then with oil and gas in the early 20th century. On a global scale, the development of the various fossil fuels has not been achieved by substituting one fossil fuel for another, but by adding them together (Figure 2-2). Moreover, this interlocking has allowed them to develop mutually, making it possible to increase the quantity of consumable energy once again. For example, the massive extraction of coal was only possible by using large quantities of wood to line the tunnels, and the development of pipelines is only possible thanks to large quantities of coal for steel production(Fressoz, 2021).

On a global scale, no energy transition of the magnitude we are facing has ever taken place in history(Smil, 2022). Thus, the challenge is of a singular nature and deserves to be treated as such, i.e. a profound change from a fossil fuel based economy to one that is free of fossil fuels. This transition implies not only being able to develop low-carbon production sources, but also to make them independent of fossil fuels(Fressoz, 2021).

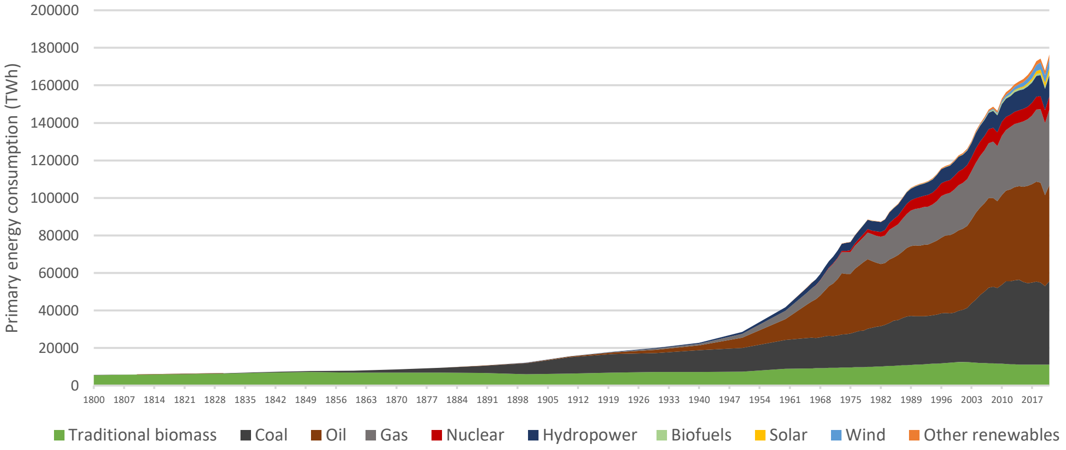


Figure 2-2 Global primary energy consumption by source from 1800 to 2021 in the World (OWD, 2021).

There is a broad consensus that electrification of the energy mix is one of the main strategies for decarbonisation(IEA, 2021c). Indeed, many sectors can be massively electrified, in industry, in heating, in transport, etc... Many sectors historically intrinsically linked to fossil fuels have interesting electrification paths, such as steel production or road transport for example, allowing them to potentially de-integrate with fossil fuels. Other sectors, such as cement production or aeronautics, seem to be much more difficult to decarbonise.

2.3 World and European Trends

Europe is experiencing a trend quite similar to other regions of the world in terms of the electrification of its energy mix, characterized by an increase of a few percent per decade. In 30 years, Europe's share of electricity in its final energy mix has risen from 16% to 21% (Figure 2-4). The increase in electricity production, which will make it possible to provide for the new electrical uses that will be created in the context of decarbonization, will greatly increase this rate. The latest ENTSOE report forecasts electrification of between 42 and 49% (EU 27) by 2050(ENTSOE, 2022b). Moreover, the amount of electricity needed has been systematically increased in Europe and more widely in the world for several years. We can therefore think that these electrification rates can be interpreted as lower limits.

Solar and wind power have one of the highest growth rates in Europe compared to other regions of the world (Figure 2-3). By 2022, in the EU, solar and wind have overtaken gas-fired electricity generation, with 22% of electricity coming from these two sources (Ember, 2023).

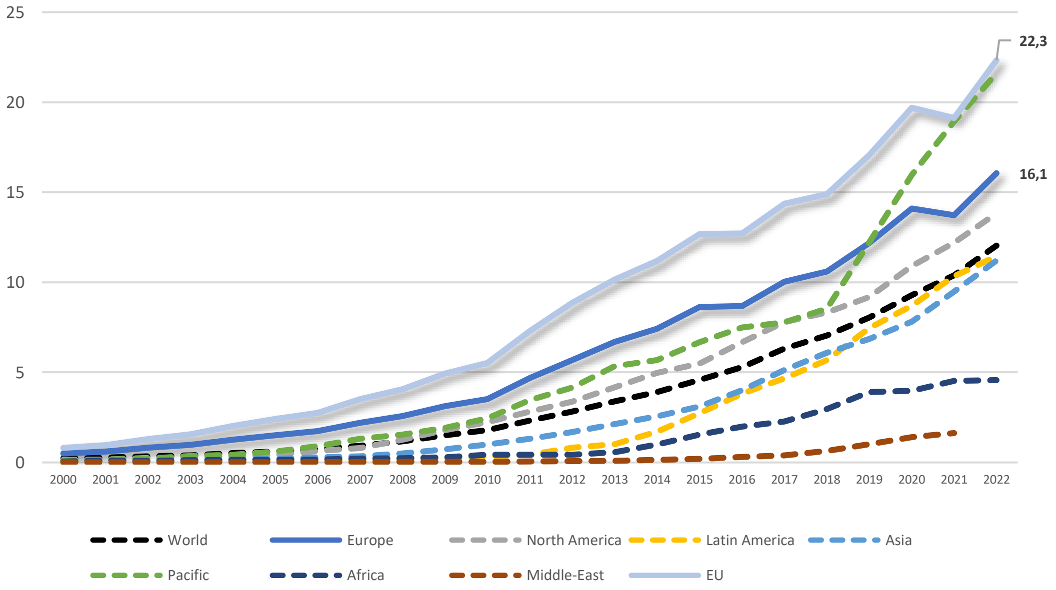


Figure 2-3 Share of wind and solar in electricity production (%)(Ember, 2023).

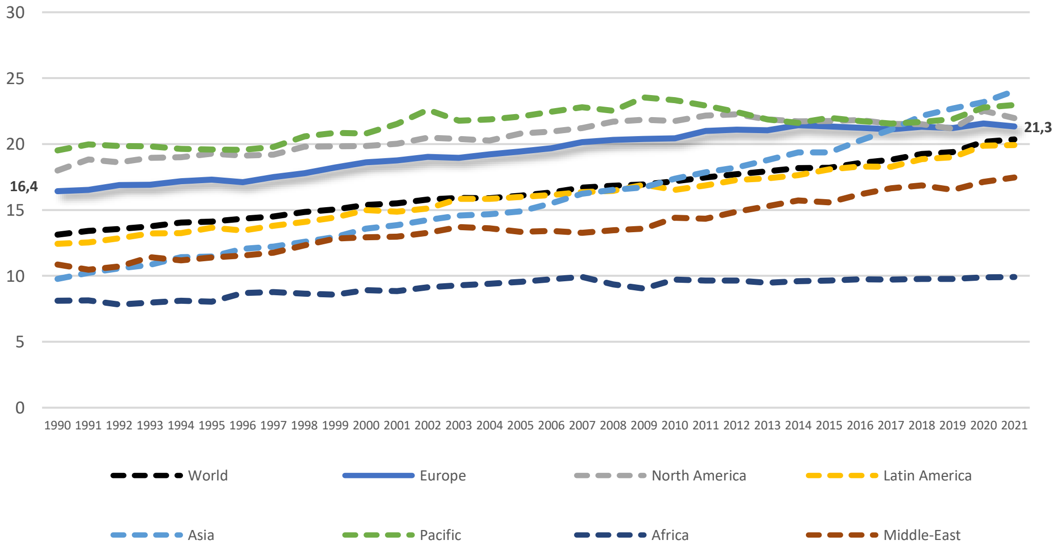


Figure 2-4 Share of electricity in total final consumption for different regions (%) (Enerdata, 2023).

3 Technical background

This section provides a synthesis of the technical elements around the technologies that will make up the bulk of growth in the coming decades. I therefore confine myself here to VREs, a selection of storage technologies and the transmission grid. Other technologies may be useful for the transition but will not be defined here.

3.1 Power generation

The capacity factor (CF) is an indicator of the amount of electricity produced in relation to the installed capacity. The average CF over a year of an electrical production facility is defined as follows(Bajpai & Tekumalla, 2021):

$$CF(\%) = \frac{E_{output}\ (GWh.yr^{-1})}{P_{installed}(GW) * 8760(h.yr^{-1})} \tag{4.1}$$

E_{oupout} being the actual energy output and $P_{installed}$ the power installed.

The cost of energy technologies is most often expressed as investment cost (€/kW) or Levelized Cost of Energy (LCOE) (€/kWh).

3.1.1 VRE

In Europe, as in the rest of the world, the development of VRE has been accompanied by a drastic decrease in its costs, particularly notable for solar (Figure 3-1). VRE technologies are mainly CAPEX-intensive, meaning that the total cost of the generating plant over its lifetime is mainly governed by its investment cost. OPEX costs are low, since no fuel is used, compared with a thermal power plant. Within the investment cost, the cost of capital plays an important role. In Europe, as the VRE market is mature, the cost of capital is relatively low (4.4%) compared to emerging markets (8.2%)(IRENA, 2023). However, within Europe, there are large disparities: Germany has a solar financing cost of 1.3%, while Croatia is at 5.3% and Ukraine 9.9%(IRENA, 2023).

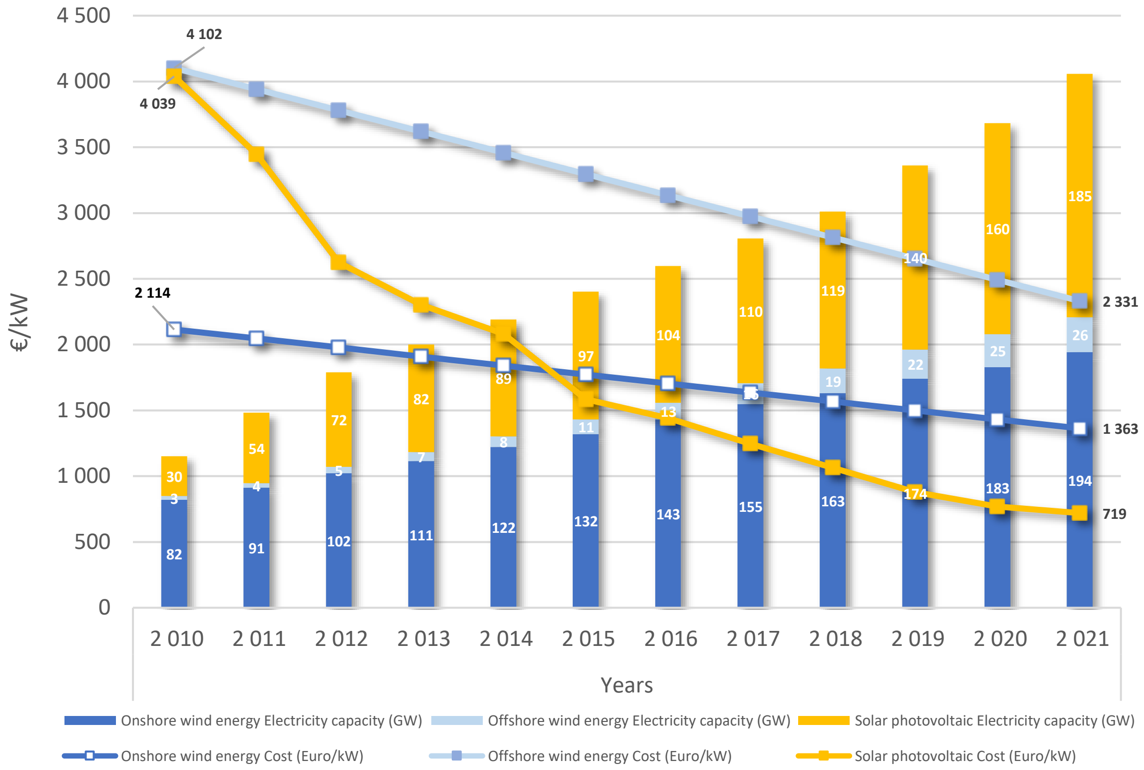


Figure 3-1 Power capacity and investment cost of VRE, Europe

Note: Investment cost for Wind correspond to the average value in Europe and investment cost for Solar corresponds to the average value worldwide(IRENA, 2022b). Wind investment costs have been interpolated from 2010 to 2021. All costs are in €2021/kW. Power capacity of PV, Offshore wind and Onshore wind correspond to Europe (IRENA, 2022a).

3.1.1.1 Wind

Today, onshore wind power has a higher variability than offshore wind power when considering production per unit of output, or even at the country level. On the other hand, by aggregating the data across Europe, it is possible to see that the variability of onshore wind power is decreasing (Figure 3-2), as onshore wind power plants are relatively spread across the whole of Europe (Figure 3-3), and can therefore benefit from different wind regimes.

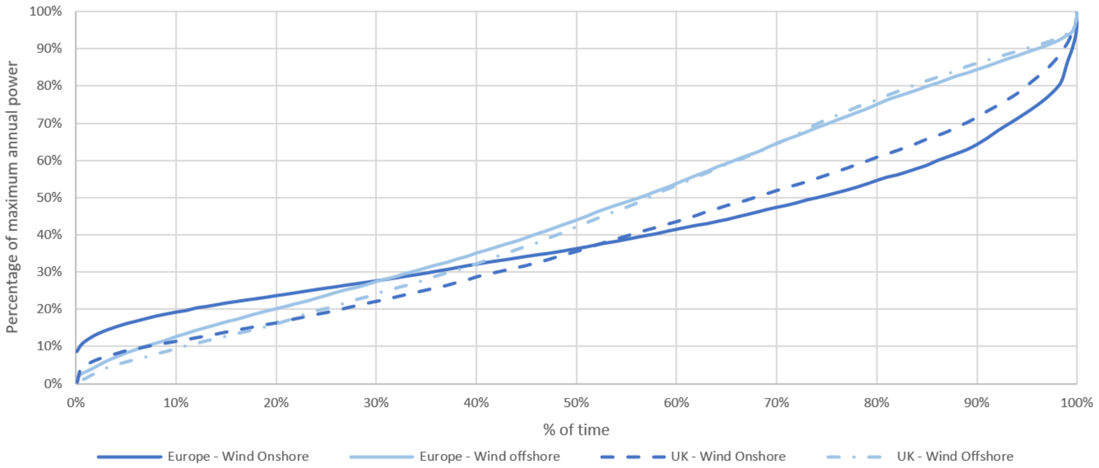


Figure 3-2 Availability curve for onshore and offshore wind power in Europe and the UK as example for the year 2020.

Note : This curve describes the percentage of times when production is above or below a certain level. This graph is plotted first by aggregating the hourly production of all European countries via ENTSOE (2023), then by sorting each hour of wind generation in ascending order. Finally, the 8760 hours are plotted according to this sorting, and the data are expressed relative to the time when production is at its peak.

On the contrary, offshore wind, although less variable at the scale of the production unit, benefits for the moment less from the aggregation at the European level (Figure 3-2) concerning its variability since the European production is localized in a very limited area (mainly in the North Sea)(Figure 3-4). This concentration is partly explained by the favourable wind regime and the shallow depth of the North Sea(CDE, 2018).

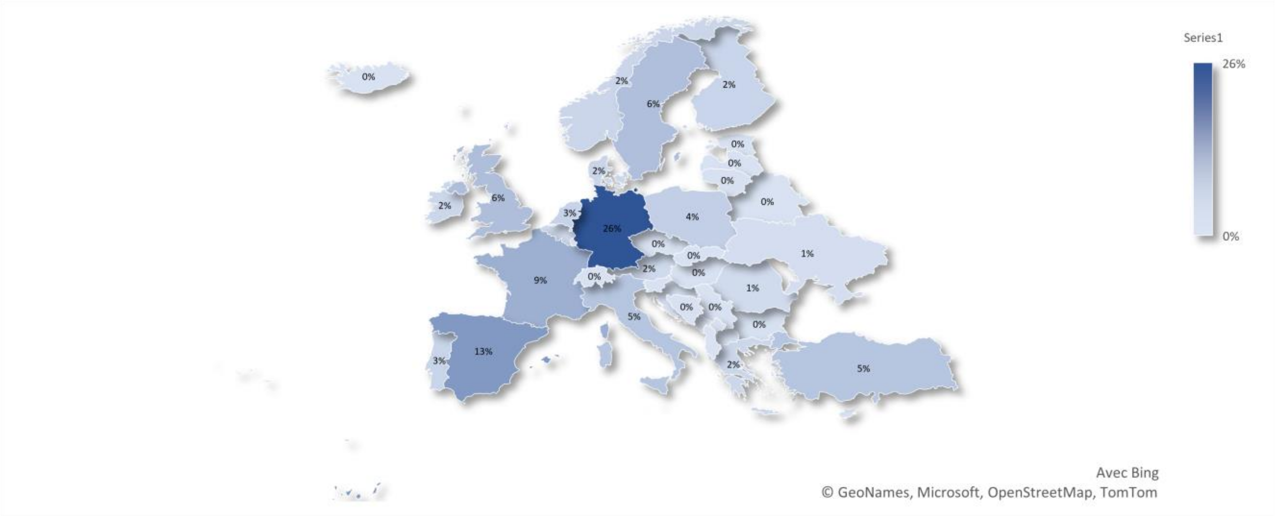


Figure 3-3 Distribution of Onshore Wind Capacity in 2022, Europe(WindEurope, 2023)

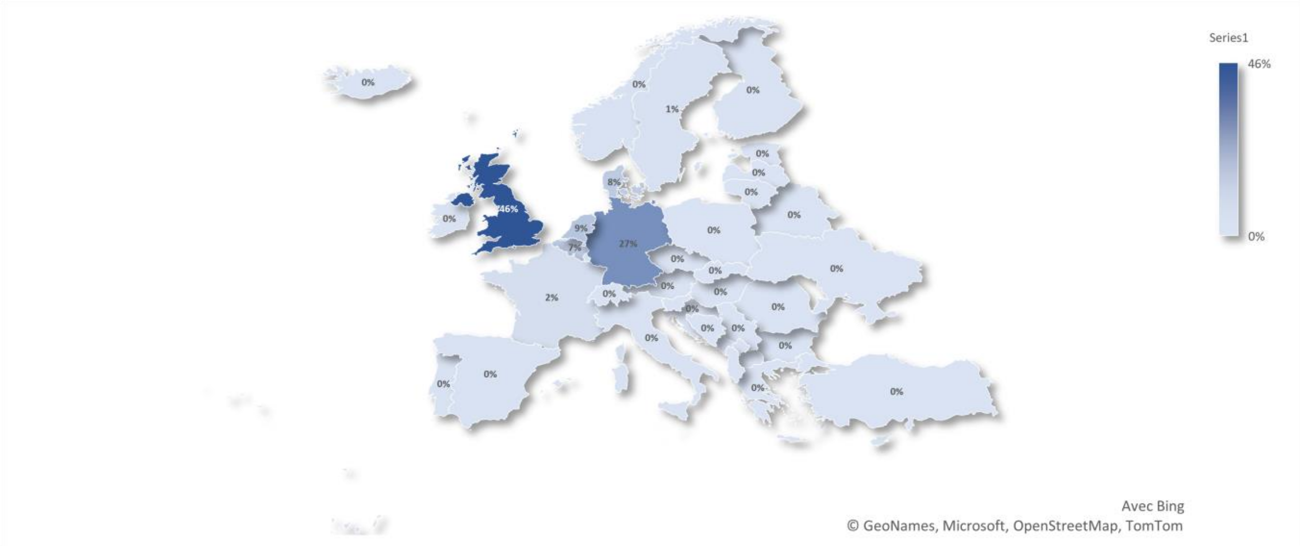


Figure 3-4 Distribution of Offshore Wind Capacity in 2022, Europe(WindEurope, 2023).

According to Grams et al. (2017), one way to reduce the variability of wind power in Europe is to diversify their production locations. Today, on a European scale, it is possible to experiment a variability of about 20% of the wind potential, depending on the wind regime present in Europe (8 different wind regimes can be identified). Thus, developing in the future a larger share of wind power in the Iberian Peninsula, Scandinavia and the Balkans would allow to strongly minimize the variability at the European scale(Grams et al., 2017; Prol, 2023). The capacity factor of wind energy during winter would be much more stable. It goes without saying that such a deployment is dependent on a large-scale power transmission system. To be effective and significantly reduce variability, it is important that the deployment must be done at a large scale, as the national level is not sufficient, even for countries facing several wind regimes and being large, like France(Cai & Bréon, 2021). Work studying the impact of climate change on wind regimes suggests that greater variability for wind power is likely in the long term(Russo et al., 2022).

Europe is a pioneer in the development of offshore wind energy, particularly with the United Kingdom, which has a majority of the European wind farm, and whose capacity factor is among the highest in the world: 45% in 2021 (Figure 3-6). Thanks to the development of new offshore wind technologies, the capacity factor of new offshore wind farms is expected to be 50% in Europe (Wind Europe, 2023).

Onshore wind power, which is more widespread in Europe, is also benefiting from technological improvements and better deposits. Its average CF in Europe has increased by 5% in 20 years (Figure 3-5), and new European onshore wind farms have an CF above 35%(Wind Europe, 2023).

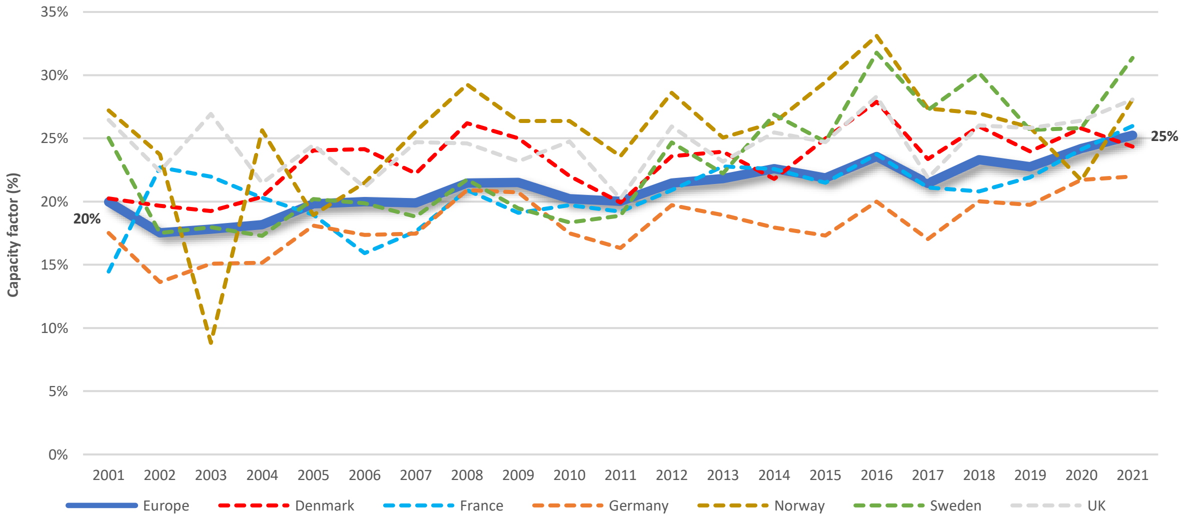


Figure 3-5 Capacity factor of onshore wind in different European countries (IRENA, 2022a).

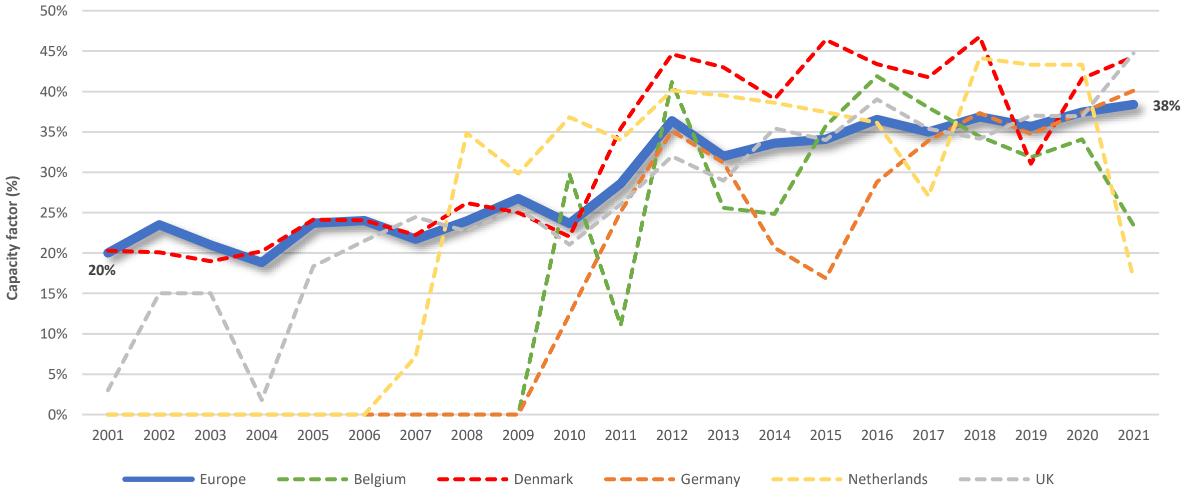


Figure 3-6 Capacity factor of offshore wind in different European countries (IRENA, 2022a).

3.1.1.2 Solar PV

Solar energy has seen its average CF increase from 7 to 12% over the period 2001-2021 in Europe. However, it is possible to note that strong disparities exist, with capacity factors significantly higher in the Iberian Peninsula in particular, and lower in the northern countries (Figure 3-8). This increase in the average CF is partly explained by the geographical diversification of PV installations in Europe, especially in areas with more sunshine. Indeed, in 2001, 57% of the European capacity was located in Germany, which has a lower CF than the European average. In 2021, this share will only be 32%, in favor of countries further south(IRENA, 2022a).

In contrast to wind power, solar power is relatively homogeneous between countries. Thus, its integration over a large part of the territory helps to reduce short-term intermittency, but not seasonal variability(Prol, 2023).

The technical and industrial capabilities of photovoltaics have been in turmoil for several decades. First of all, from a technical point of view, the efficiency of the different photovoltaic cell technologies has been growing steadily for 50 years(NREL, 2023a). Moreover, the learning rate of PV modules has been 23% since 1976, i.e. the cost is reduced by 23% every time the capacity doubles(Victoria et al., 2021).

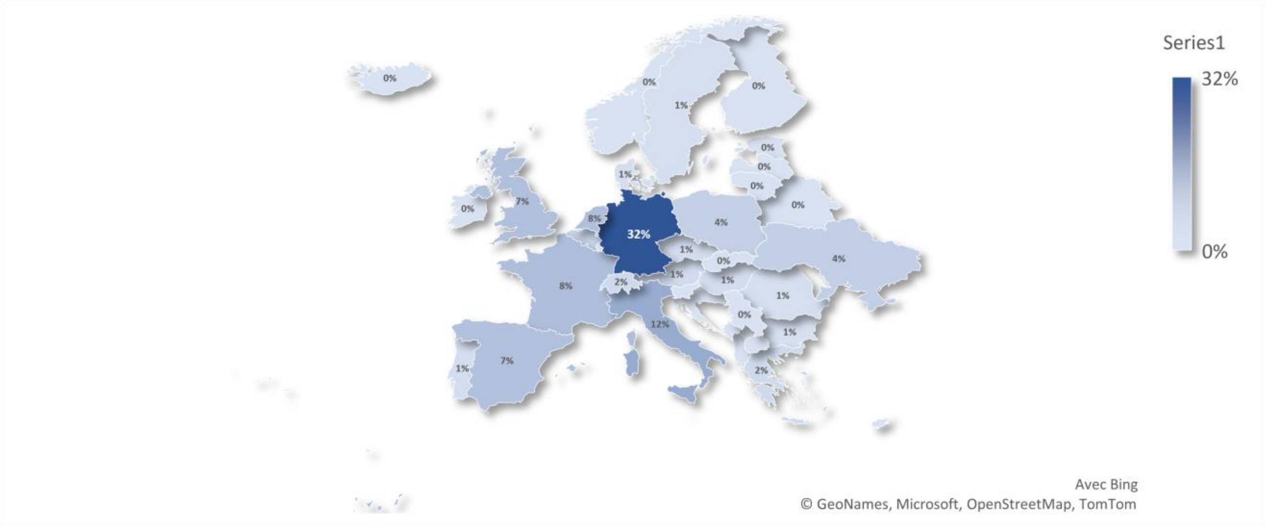


Figure 3-7 Distribution of Solar Capacity in 2021, Europe (IRENA, 2022a).

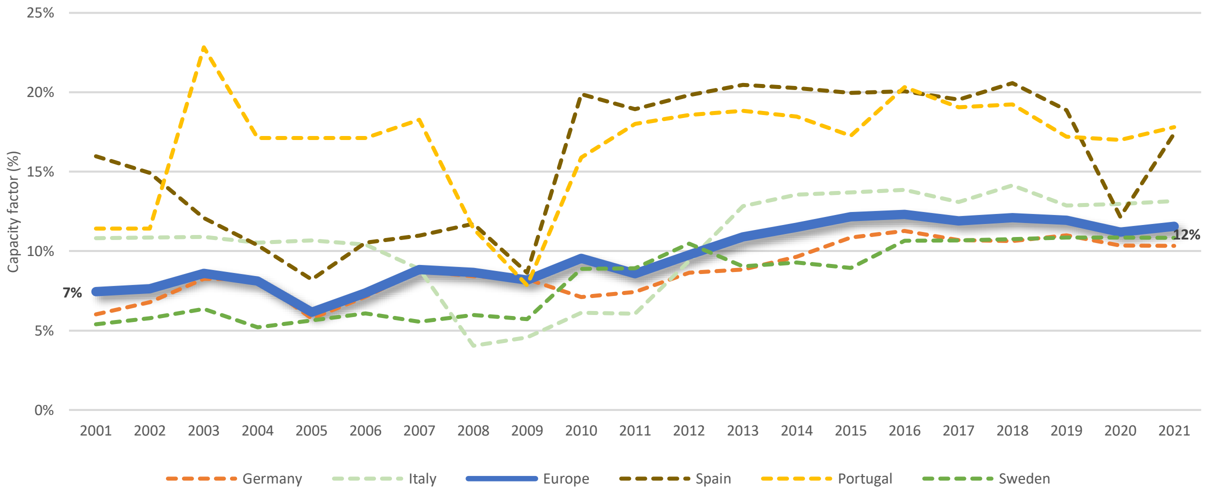


Figure 3-8 Capacity factor of Solar PV in different European countries (IRENA, 2022a).

3.1.1.3 VRE at European perspective

According to Prol (2023), optimizing the shares of solar and wind installed capacities in an integration European power system, by maximising the use of the best deposits, could reduce its hourly variability by 25.6% and increase its CF by 21.6%. This would require stronger European coordination.

The advantage of developing both wind and solar on the European territory is that these technologies are complementary, having a negative correlation (they more often complement each other than the opposite). This negative correlation is all the more important the larger the time step considered (Prol, 2023) (the monthly correlation is weaker than the daily which is weaker than the hourly).

3.1.2 Flexibility

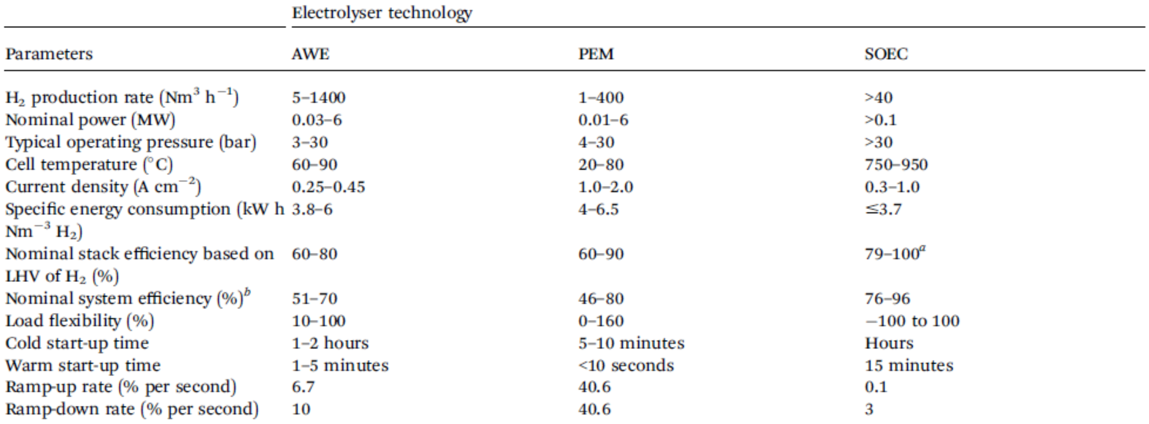
3.1.2.1 Electrolysers

Electrolysers are the main technology to produce H2 from electricity (equation 4.2).

Coupled with low-carbon electricity, they can produce low-carbon H2, which is one of the cornerstones of the strategy to decarbonize the energy mix through electrification, as I will show in more detail below.

$$H_2O + electricity \rightarrow H_2 + \frac{1}{2}O_2 \qquad (4.2)$$

The 3 most mature technologies are, in order of maturity, Alkaline water electrolysis (AWE), Proton exchange membrane electrolysis (PEM) and Solid oxide electrolysis (SOEC). The first two have a technology readiness level (TRL) of 9 and the last one of 7(IEA, 2022a). The different characteristics are presented in the literature review (Table 1). Although the AWE electrolyser is the most mature and least expensive today, the ability of PEMs to be more flexible synergizes particularly well with the variable output of VREs. The management of variability by electrolysers will be a particularly important issue in industry (see 4.3.2) and in energy storage.



	Electrolyser technology		
Parameters	AWE	PEM	SOEC
H_2 production rate ($Nm^3\ h^{-1}$)	5–1400	1–400	>40
Nominal power (MW)	0.03–6	0.01–6	>0.1
Typical operating pressure (bar)	3–30	4–30	>30
Cell temperature (°C)	60–90	20–80	750–950
Current density ($A\ cm^{-2}$)	0.25–0.45	1.0–2.0	0.3–1.0
Specific energy consumption ($kW\ h\ Nm^{-3}\ H_2$)	3.8–6	4–6.5	≤3.7
Nominal stack efficiency based on LHV of H_2 (%)	60–80	60–90	79–100^a
Nominal system efficiency (%)^b	51–70	46–80	76–96
Load flexibility (%)	10–100	0–160	−100 to 100
Cold start-up time	1–2 hours	5–10 minutes	Hours
Warm start-up time	1–5 minutes	<10 seconds	15 minutes
Ramp-up rate (% per second)	6.7	40.6	0.1
Ramp-down rate (% per second)	10	40.6	3

Table 1 Literature review of AWE, PEM and SOEC electrolysers. Taken from Mbatha et al. (2021).

Concerning costs, electrolysers have a high learning rate of around 20%. This cost reduction is essential for their good deployment in industry and for seasonal storage (Appendix 3).

3.2 Storage

Energy storage is key to a robust and efficient energy system. Today, the vast majority of energy is stored in the form of hydrocarbons. In comparison, electricity storage is much more expensive. This is why, until now, it has been preferable to vary production according to demand, rather than to store electricity (Letcher, 2022). The only exception to this are hydropower and pumped hydro storage (PHS). The development of VRE, as explained, will profoundly change the pattern of electricity production. Thus, storage will play a more central role as VREs take a larger share in the electricity mix.

Many storage technologies are emerging to meet this challenge. As I will show, these can coexist because they all have different characteristics, which can meet a particular need. Here is a list of the main characteristics that allow storage technologies to be compared with each other(Letcher, 2022):

- Storage duration
- Typical size
- Charge duration
- Discharge duration
- Cycles (discharges per year)
- Response time
- Round-trip efficiency
- Discharge efficiency
- Daily self-discharge
- Energy and power density
- Specific energy and power
- Maturity
- Energy and power capital costs
- Operating and maintenance costs

In addition to the intrinsic technical characteristics of each technology, it is also possible, as with the electricity generation facilities, to define a cost for each technology. The Levelized cost of storage (LCOS) quantifies the discounted cost per unit of discharged electricity (e.g. USD/MWh) for a specific storage technology and application. It corresponds to the total cost of an electricity storage technology during its whole lifetime divided by its cumulated delivered electricity(Schmidt, 2023b). This metric makes it possible to highlight the electrical energy returned by a storage mode. It is also possible to quantify the cost of the power delivered by a storage technology, which is called the Annuitized Capacity Cost (ACC) for a year. The latter corresponds to the discounted cost per unit of power provided by a technology (Schmidt, 2023b).

Schmidt (2023b) proposes 13 archetypical applications which are essential to a power system characterized by a high penetration in VRE (Appendix 4). As can be seen in Figure 3-9, characterizing the least expensive technology for a given discharge frequency and duration, the majority of these archetypical applications (circle on graph) can be supplied, by 2040, by lithium-ion batteries. Hydrogen seems to be the preferred solution for long-term storage, while flywheels are used for high cycling. The share of PHS will be marginalized, in particular because of its competition with lithium-ion batteries on diurnal cycles, and hydrogen for long-term storage. The conclusion is close considering either LCOS (Figure 3-9) or ACC (Appendix 2).

This characterization is obviously subjective (Figure 3-9), since it makes assumptions about the evolution of technology prices (which are intrinsically uncertain). However, it is based on the very latest assumptions in terms of storage costs and provides a good understanding of the current dynamics in the storage field. A summary of cost trends for the various storage technologies is presented in Appendix 3.

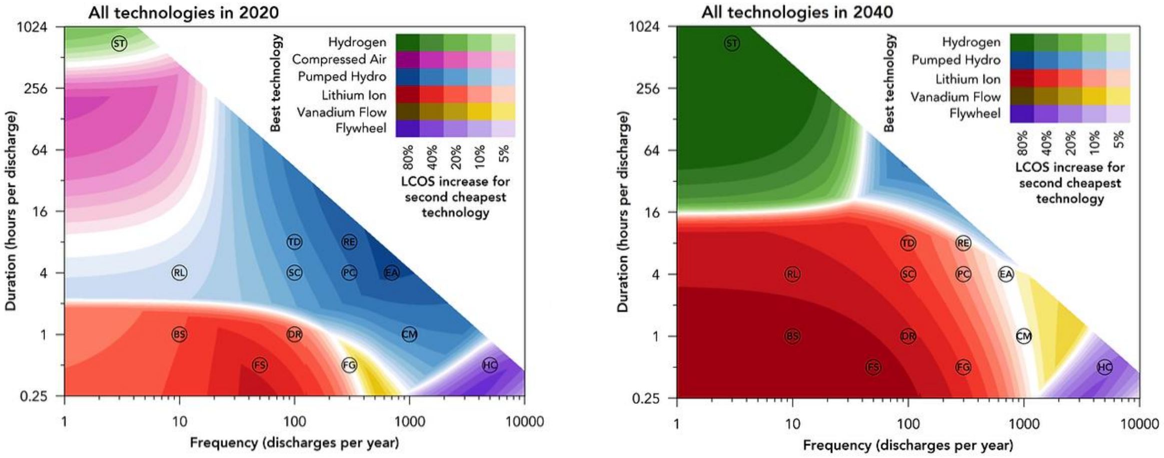


Figure 3-9 Technologies with the lowest LCOS relative to annual cycle and discharge duration requirements. Current situation (2020) and projection (2040) (Schmidt, 2023b).

In Europe, the only storage method that has really been deployed since 1944 is PHS (Figure 3-11). This development, concomitant with the development of the electricity network, has made it possible to offer significant stability at a time when most electricity generation facilities were controllable. Europe is by far the most developed region in the world in terms of hydraulic storage during the second half of the 20th century (Barbour et al., 2016). The distribution of the grid-scale storage capacity available in 2022 between the various European countries is shown in Figure 3-10.

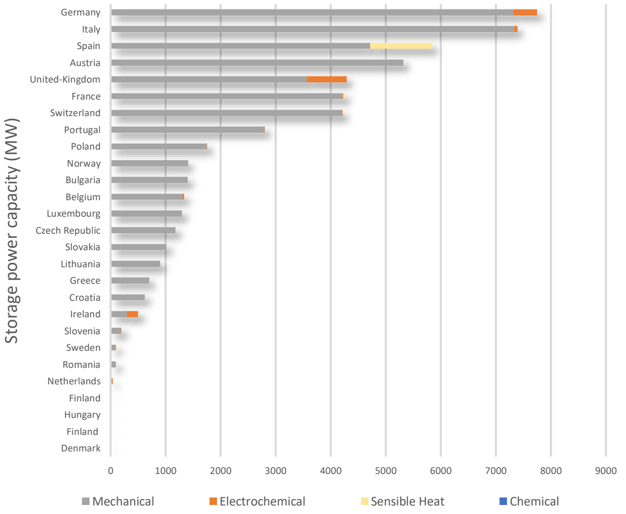


Figure 3-10 Distribution of storage power capacity in Europe in 2022 (Operational + Under construction grid-scale storage)(EuropeanComission, 2023).

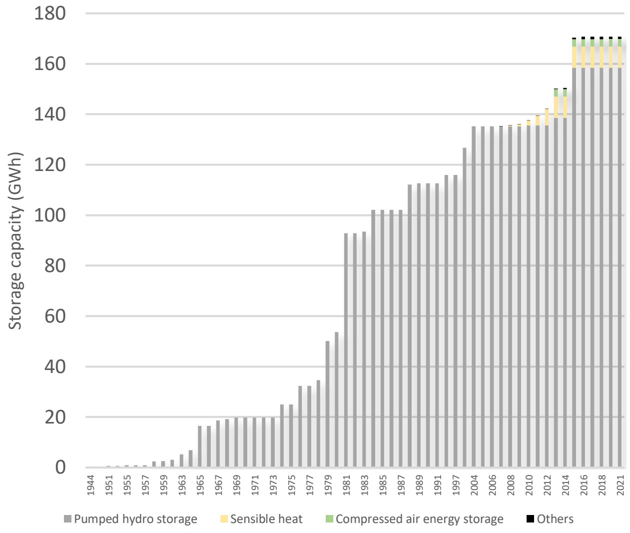


Figure 3-11 Evolution of storage capacity in Europe since 1944(DOE, 2023).

3.2.1 Diurnal Storage

3.2.1.1 Battery lithium ion

A battery stores electricity in electro-chemical form. Lithium-ion batteries have been the subject of much R&D and are now considered to be one of the leading daily storage solutions, notably due to their high energy density, fast and efficient charging capability (compare to other battery technologies) and long life cycle(Letcher, 2022). This technological development has paved the way for its use in a variety of applications, including portable, electric vehicles and stationary storage. The increase in the specific energy of lithium-ion batteries makes their use in transport easier over time (Figure 3-12). Recently, researchers have succeeded in developing (at the laboratory stage) batteries with 711 Wh/kg (CleanTechnica, 2023).

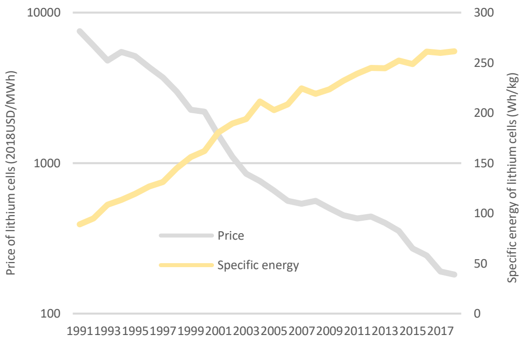


Figure 3-12 Evolution of representative lithium-ion cells price and specific energy (1991-2018)(Ziegler & Trancik, 2021).

In parallel, this technology has seen a particularly large drop in cost. Since its commercial introduction in 1991, the price of lithium-ion cells has declined by 97% (Figure 3-12). Indeed, lithium-ion is the storage technology with the best learning rate of all (Appendix 3). Like VRE technologies, the cost of batteries is very CAPEX-intensive, with very low OPEX(Frazier et al., 2021).

The capital cost of a battery needs to be assessed in terms of its capacity to power ratio, which is sometimes defined simply in terms of duration. In euro/kWh terms, longer batteries have a lower capital cost. In euro/kW, however, the opposite is true (Cole et al., 2021).

3.2.2 Seasonal storage

Seasonal storage becomes an indispensable element when VREs take a large part of the electricity mix. Today, large hydro dams offer seasonal storage but there is little potential to expand. Over the next few decades, hydrogen seems to be the most suitable energy carrier to achieve this storage.

3.2.2.1 Hydrogen

Low-carbon hydrogen, once produced during peak of production, must be stored for consumption when needed. Underground storage is already in use and functional. In this category, three main options exist: storage in depleted gas reservoirs, aquifer formations and salt caverns, each of which has unique properties. Salt cavern storage is particularly suitable for hydrogen(Letcher, 2022). In addition, the European territory potentially has 23.2 PWh of onshore salt cavern storage capacity, which is several orders of magnitude more than the seasonal storage needs (even if the latter are not homogeneously distributed)(Caglayan et al., 2020). According to Chen et al. (2023), the levelised cost of hydrogen storage in salt caverns is of the order of 2.5 dollars per kg. Moreover, storing hydrogen in steel tanks is around 40 times more expensive (IEA, 2022b) and is therefore not considered to be the main route for seasonal storage.

The use of hydrogen in the form of ammonia can also be useful for storage and transport, thanks in particular to its high density (Andersson & Grönkvist, 2019; Bañares-Alcántara et al., 2015; Giddey et al., 2017)

3.3 Transmission

Transmissions play a central role in the stability of the electricity grid and are particularly developed in Europe(ENTSOE, 2022b). In addition to their role of transporting electricity from the production area to the consumers, they also allow exchanges between different neighbouring countries. These exchanges make it possible to coordinate the production of electricity in order to ensure the cheapest electricity mix.

Exchanges between European countries are mainly provided by alternating current (AC) lines, and a few direct current (DC) lines mainly provide links between territories not directly connected by land (mainly submarine cables). (Figure 3-14).

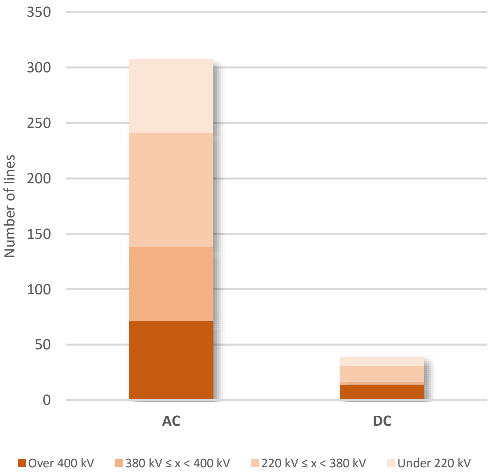


Figure 3-13 Cross-Frontier Lines per voltage and current in 2022, Europe (ENTSOE, 2022).

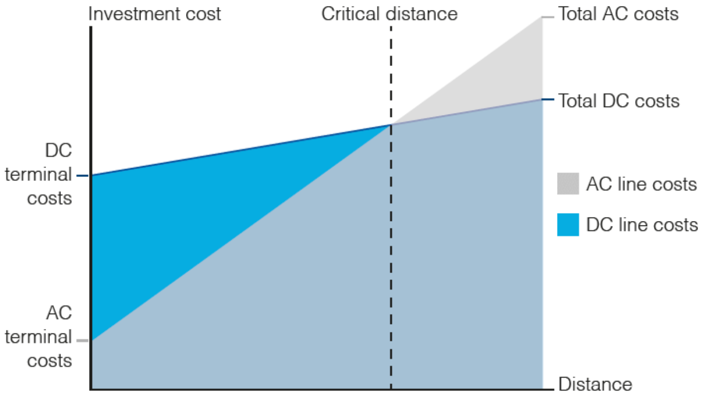


Figure 3-14 AC/DC total costs in relation to the distance (Grant, 2017).

The construction of transmission lines is a process that, like for the development of power generation facilities, faces several important technical, regulatory, and social constraints. In Europe, the construction of these networks can take from a few years to more than ten years, depending on the type of installation (Appendix 9).

AC lines have many advantages, not least that they transport electricity directly into the form produced by synchronous generators (SGs) (although these are set to decline). However, the advantage of DC lines is that they do not have skin effect, they have a smaller footprint, they have no capacitive losses, and their cost per km is lower than AC (Grant, 2017). On the other hand, the installation is more expensive for a DC line because converters are added to the system. Thus, the cost of a DC line exceeds that of an AC line after a certain distance, called critical distance in Figure 3-13. Bussar et al. (2016) estimate that the investment cost of an HVDC transmission system by 2050 in Europe corresponds to 130 €/kW for converter stations and 0.77 €/(km.kW). Over the same time horizon, ETRI (2014) estimates that an HVAC transmission system represents an investment cost of between 1.08 and 0.7 €/(km.kW), with a most likely estimate of 0.9 €/(km.kW).

These transmissions between countries allow a significant amount of electricity to be exchanged (Figure 3-15). The nature of the various European countries is quite different. While Italy and the UK are net importers, heavily dependent on the electricity produced by their neighbours, France, Germany and Sweden are characterized by their ability to export on a massive scale. With the upscaling of VRE on the territory, these exchanges will increase considerably, particularly in order to manage their variability (see 4.5.3).

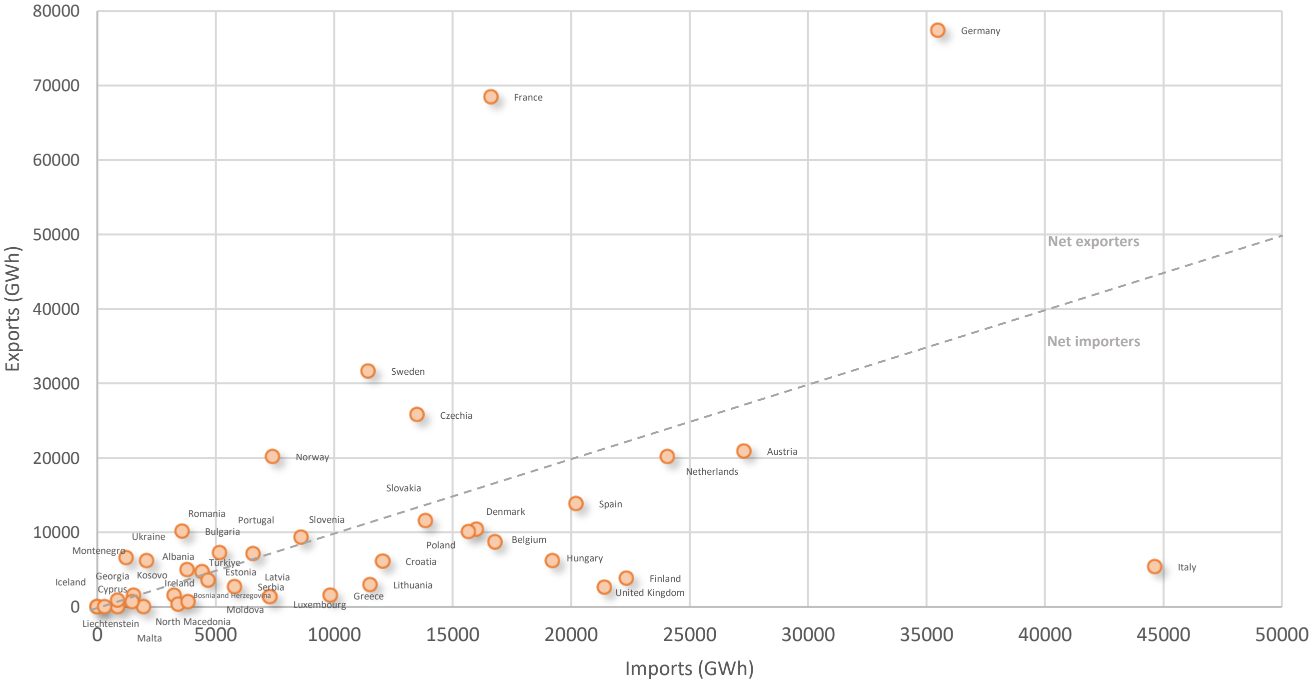


Figure 3-15 Electricity exports and imports in European countries. Average on the period 2015-2020. Own calculations based on Eurostat (2023).

4 Analysis

4.1 Changing perceptions of energy needs

4.1.1 Evolution of energy demand forecasts

The electrification of the energy mix will de facto decrease final energy consumption, even for the same amount of service provided. The reason is that fossil fuel-based processes are considerably less efficient than their electric counterparts (Brown et al., 2018). For example, whenever thermal energy is converted into mechanical energy, the laws of thermodynamics do not allow a certain efficiency to be exceeded. In the case of thermal power plants, the efficiency between the primary energy injected and the useful energy in the form of electricity is around 40%, unlike the VRE, which is 100%. In the same way, the propulsion of an internal combustion engine converts only 25 to 40% of the primary chemical energy used as fuel into useful energy, against 80% for an electric motor. A final example that demonstrates the efficiency of electric processes in energy consumption is in the field of heating. Electric heat pumps have a coefficient of performance that is often higher than 3, i.e. with one unit of electrical energy, it is possible to obtain more than 3 units of thermal energy, allowing a considerable reduction in final energy consumption. These examples are typical of the consequences of electrification of the energy mix: lower final energy consumption for equivalent services. This is why most European transition scenarios predict a fall in final energy consumption, and this fall is only partly based on sufficiency efforts.

On the other hand, the use of the primary energy metric is becoming increasingly ineffective for measuring energy system dynamics as VREs take on a larger share. Apart from the fact that this tends to minimize their share in the scenarios, reasoning in terms of primary energy can lead us to think that it would be necessary to replace all this energy with decarbonized energy. However, this is not the case: it is only the services provided by these fossil fuels that need to be replaced. In this respect, the level of electrification (and therefore changes in electricity demand) has a direct impact on changes in energy demand.

4.1.2 Evolution of electricity demand forecasts

The evolution of electricity needs has gone through three main phases. Firstly, the generalisation of access to electricity at the beginning of the 20th century for rich countries, which today results in the fact that 90% of the world's population has access to electricity (WB, 2020). However, this access remains very low for some African countries, with several countries having extremely limited access to electricity (IEA, 2021a). More generally, this first phase was characterised by increasing energy consumption and high economic growth.

In the early 1970s, the Yom Kippur War (1973), as well as other concomitant events, such as the peak of oil production in the USA (1970) and the exit from the Bretton Woods Agreement (1971), led to the first oil shock, which increased the price of oil from 2.75$ in January 1973 to 11.10$ in March 1974 per barrel (Auzanneau, 2018). This massive increase in the price of oil led to an acceleration in the construction of electricity generation facilities. A particular illustration of this phenomenon was seen in France, with the so-called Messmer plan, which resulted in the construction of 56 nuclear power plants in 15 years (Frontline, 1997). In the same vein, in the US, Marion K. Hubbert (1956), who predicted the US oil production peak, theorised the transition from fossil fuels to nuclear power for the US (Appendix 1). This phase was thus characterised by the response in a (mainly) exogenous element and required an acceleration of the deployment of substitutes to oil (including electricity)(Żuk & Żuk, 2022). However, this phase was cut short by the oil counter-shock of the 1980s, which massively reduced the price of oil and discouraged the development of alternative energy sources (Auzanneau, 2018).

Finally, the last phase, which is very recent, corresponds to a new necessity: the decarbonisation of energy consumption. To meet this challenge, many avenues exist. One of them is to electrify the various industrial processes, transport, heating, and more generally everything that can substitute fossil fuels with electricity. Once coupled with a low-carbon electricity production system, a significant part of the economy can be decarbonised through electrification.

However, mass electrification as a strategy for decarbonisation is a solution that has only emerged particularly recently. Indeed, as shown in Figure 4-1, the IPCC AR 6 (Group 3) mentions it massively only since the very last report, with more than 80% of occurrence of the word among the first 6 ARs. Paradoxically, this is a decarbonisation method that was not part of the initial strategies.

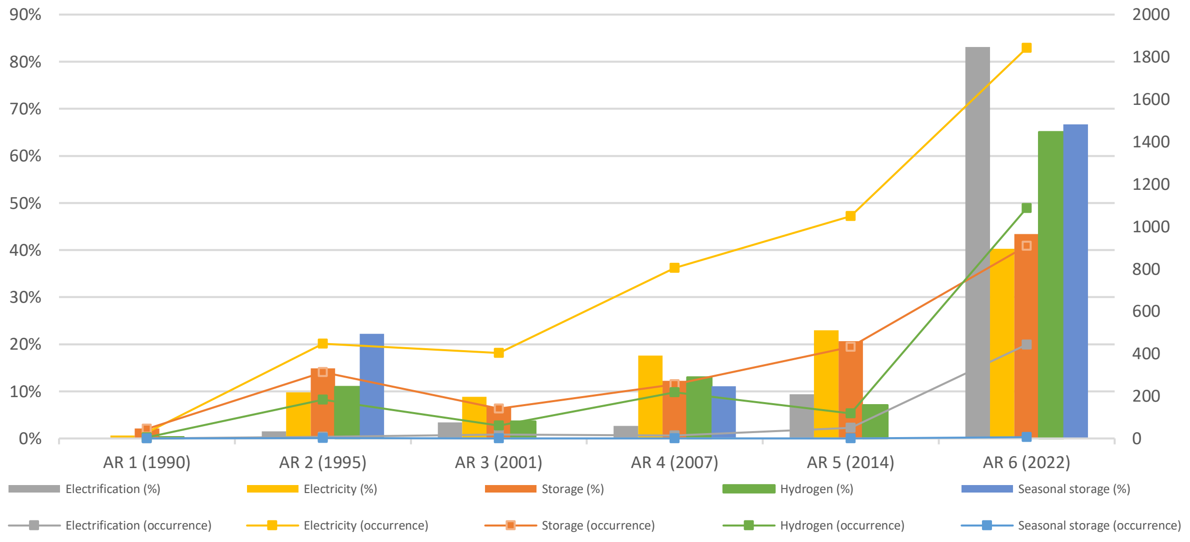


Figure 4-1 Occurrence of different keywords (right-axis) and their proportions (left-axis), in relation to the six reports, in each edition. Own calculations based on IPCC (2022b).

Obviously, substituting energy from fossil fuels with electricity means being able to significantly increase the amount of electricity generation. Thus, different governments (or institutions) have developed scenarios to estimate the necessary requirements. Figure 4-2 presents a summary of the increase in electricity needs in the most recent energy transition scenarios for various European countries, as well as various scenarios for Europe as a whole.

It is possible to say that, in any case, electricity consumption will increase substantially in most countries of the world. However, significant disparities in the degree of increase are visible even within relatively similar countries, such as countries in the European Union. These disparities have multiple causes. To name a few: the current electrification rate (very low in the Netherlands for example), population growth, industrial policy (willingness or not to reindustrialise), the share of electrolysis in electricity consumption, etc. In their energy transition scenarios, most European countries are forecasting an increase in electricity consumption of more than 50% in 2050 (compared with 2018), with some countries forecasting an increase of 150%. At EU level, there is every reason to believe that consumption could more than double over this period (Figure 4-2).

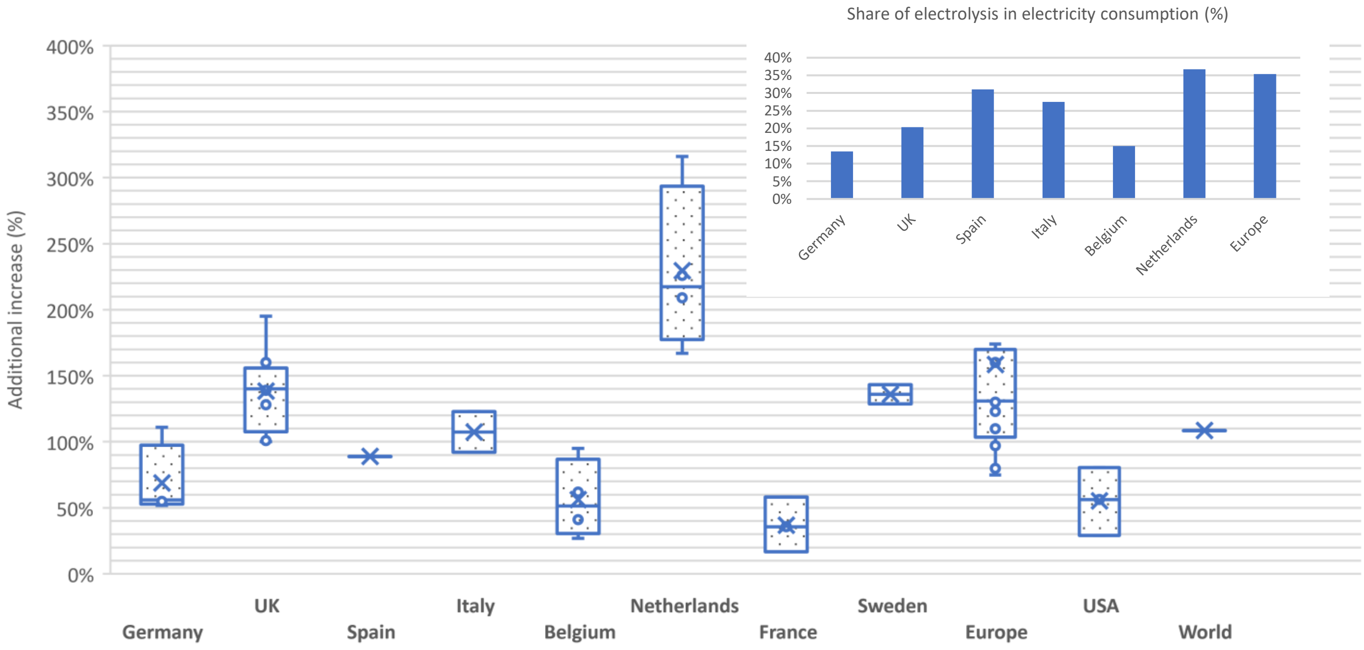


Figure 4-2 Forecasted increase in electricity consumption by 2050 (compared to 2018).

List of institutional scenarios considered in the distribution:

***Germany**: Agora Energiewende (2020), DENA (2018), Transet NW (2020)*
***UK**: CCC (2020), National Grid Eso (2021)*
***France**: Energy Futures 2050, (RTE, 2021)*
***Sweden**: 2045 Forecast : Nytt Högelscenario(2023), Energiföretagen Sveriges Högelscenario (2021).*
***Netherlands**: Tennet/Gasunie (2020)*
***Italy**: Italian strategy on the reduction of greenhouse gas emissions (2020)*
***Belgium:** Scenarios for a climate neutral Belgium by 2050 (2021)*
***Spain**: Decarbonisation Strategy 2050 (2020)*
***EU27**: TYNDP 2022, ENTSO-E (2021), Eurelectric (2018), Gas for Climate (2020), PAC Scenario (2020), Wind Europe (2021), SolarPower Europe (2020), Transet BW (2020), European Commission (2020)*
***USA**: NREL, Electrification future studies (2021)*
***World:** IEA, NZE (2021)*

Top right: average percentage of electricity expected to be dedicated to electrolysis in the scenarios cited. Data missing for Sweden, France, the US and the World. Partially adapted from (RTE, 2021).

It is possible to ask why the upscaling of power generation was not initiated earlier, since the challenges of climate change have been known for many decades. An underestimation of the learning rate of renewable energy sources may be one of the reasons for the low belief in a highly electric future, which is supposedly too expensive. With the case of PV energy, the IEA offered an illustration of this phenomenon, with a very significant underestimation of PV deployment in the world.

As can be seen in Figure5-3, successive WEOs (IEA, 2022d) have not forecast significant growth in PV every year since 2009, while all previous trends have been wrong. BloombergNEF (2023)'s forecast for the year 2022 suggests that the IEA's 2021 proposed scenarios for renewable growth, *Renewable 2022(IEA, 2022c)*, which for once were very ambitious, assume too little growth, with additional capacity in 2022 already well above the IEA's best growth scenario. This underestimation of installation capacity, as with the PV example, may have led to the belief that a massive increase in electricity production was very difficult to achieve. This underestimation of installation capacity does not come from nowhere, it reflects an overestimation of the costs of VREs, particularly solar, and IEA is not alone in this. As Xiao et al. (2021) show, by synthesizing 22 long-term prospective scenarios, published a posteriori to the Paris agreements (2015), the cost of solar is massively overestimated. Among all the scenarios, all but one predicts LCOEs for PV in 2050 that are higher than what is observed today. At the turn of the 2020s, the falling cost of VRE technologies seems to be one of the main vectors of the paradigm shift linked to the energy transition, and the start of a revolution in the way we think about energy systems.

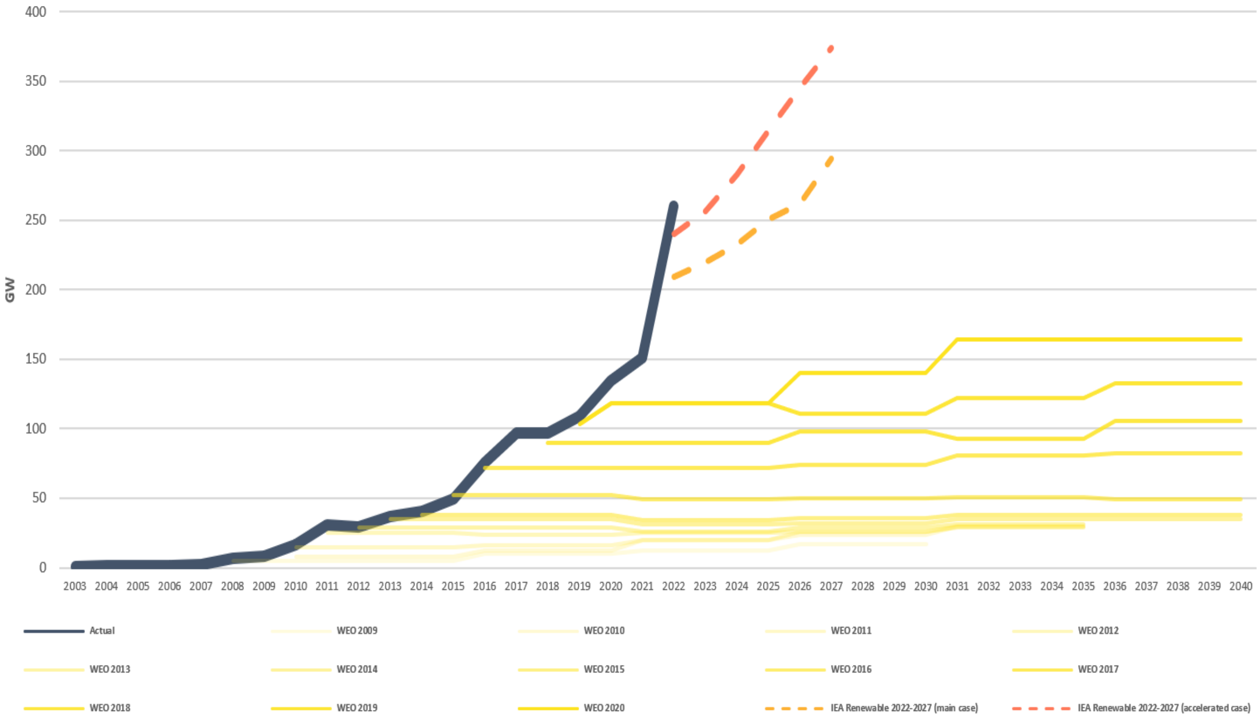


Figure 4-3 PV capacity net additions, World (IEA, 2022d).

4.1.3 Demand paradigm

Finally, the upscaling of wind and solar generation will lead to a change in the way demand peaks are managed. First of all, the electrical systems will no longer be dimensioned by the electricity consumption peak, but by the residual load peak (RTE, 2021). Residual load corresponds to the total consumption load minus VRE and run-of-river hydro. It is this peak that will determine the flexibilities (demand, supply, exchange) required by tomorrow's energy system. The evolution of this residual consumption at day level depends mainly on the mix of VRE. The higher the share of solar, the lower the residual load during the day. In this respect, a high share of solar energy reduces the peak residual load(Blair et al., 2022). Some regions with a high level of solar are in this situation, e.g. California, and face so-called duck curves(Krietemeyer et al., 2021).

4.2 European energy transition scenarios in the literature

In this section, I study the main European energy transition scenarios published in the literature in order to analyse the evolution of trends, as well as the limits of certain studies, notably on storage. They correspond to holistic scenarios that are widely cited in the literature.

Author	Publication year	Scope	Time Horizon	RES generation shares	VRE technologies	Type of storage	Model name	Type of model	Resolution
Inage *	2009	WEU	2050	30%	Wind; Solar	PHS; CAES; Batteries	-	Cost optimised	-
Eurelectric *	2010	Europe	2050	40%	Offshore Wind;Onshore Wind; Solar	No storage	-	-	-
Heide	2010	Europe	2050	100%	Wind; Solar	PHS;H2	-	Physical optimisation	One typical month
Haller	2012	Eumena	2100	75%	Offshore Wind;Onshore Wind; PV; CSP	Generic medium-term and long-term storage, storage integrated in CSP	LIMES	Cost optimised	49 time slices per year
Fursch	2013	Europe	2050	80%	Offshore Wind;Onshore Wind; Solar	PHS;CAES;CSP(heat storage)	DIMENSION	Cost optimised	24 time slices per year
Jägemann	2013	Eumena	2050	85%	Offshore Wind;Onshore Wind; PV; CSP	PHS, CAES, heat storage coupled with CSP	DIMENSION	Cost optimised	4 type days
Nagl	2013	Europe	2050	95%	Offshore Wind;Onshore Wind; Solar	PHS,CAES, H2	-	Cost optimised	Hourly; 30 type days
Pape	2014	Europe	2050	82%	Offshore Wind;Onshore Wind; Solar	Batteries (Li-Ion, lead acid, NaS, redox flow), PHS, CAES, thermal storage coupled with CSP, H2	-	Cost optimised	Hourly, full year
Bertsch	2016	Europe	2050	75%	Offshore Wind;Onshore Wind; Solar	CAES;PHS	DIMENSION	Cost optimised	-
Bussar	2016	Eumena	2050	100%	Wind; Solar	Batteries; PHS;Gas	GENESYS	Cost optimised	-
Després	2016	Europe	2100	65%	Onshore Wind; Solar	Batteries (NaS), PHS, H2	POLES, EUCAD	Cost optimised	12 type days
Cebula	2017	Europe	2050	95%	Offshore Wind;Onshore Wind; Solar	Batteries;CAES;PHS;Gas	REMix	Cost optimised	-
Gils	2017	Europe	2050	100%	Offshore Wind;Onshore Wind; Solar	Batteries;PHS;H2	REMix	Cost optimised	Hourly, full year
Pleßmann	2017	Europe	2050	99%	Wind; Solar	Batteries; PHS;PtG	elesplan-m	Cost optimised	Hourly, full year
Ueckerdt	2017	Europe	2070	>70% (VRE)	Wind; Solar	Generic storage	Remind	Cost optimised	Hourly, full year
Child	2019	Europe	2050	100%	Offshore Wind;Onshore Wind; PV Prosumers; PV utily	Batteries;CAES;PHS;Gas;TES	LUT Energy System Transition	Cost optimised	Hourly; 5-year time intervals

Trondle	2020	Europe	N/A	100%	Wind; Solar	Batteries;PHS;H2	Calliope framework	Cost optimised	1 year recorded at a 4h temp resolution
RTE*	2021	Western Europe (18)	2050	90%	Offshore Wind;Onshore Wind; Solar	Batteries;PHS;H2	Antares	Cost optimised	Hourly, full year
Golombek	2022	Europe	2050	85%	Offshore Wind;Onshore Wind; Solar	Batteries; H2	LIBEMOD,TIMES-Europe	Cost optimised	48 time slices per year
ENTSOE* (DE)	2022	Europe	2050	98%	Offshore Wind;Onshore Wind; Solar	Batteries;PHS;H2	Antares	Cost optimised	Hourly, full year

Table 2 Summary of European clean electricity scenarios published in the literature.

Note: The authors mentioned with a * correspond to institutional scenarios, that have not been published in scientific journals. The - indicates that the information is not available.

4.2.1 Models

A list of the models used is described in Table 2. Most of them use a "cost-optimized" approach, which means that the model seeks to define a range of technologies necessary to achieve its objective, while minimizing the cost of the entire system. The result is therefore strongly dependent on the input data (costs of the different technologies, CF, etc.). For low-carbon transition scenarios, crucial input data is, among other, the cost of VREs. However, this cost has been strongly overestimated (Xiao et al., 2021). It is therefore very important, in order to correctly analyse the scenarios, to put the results of these studies in perspective with the very structuring assumptions they use.

Thanks to improved computing capacity, models are becoming more refined. In particular, it can be seen that the resolution is now regularly on an hourly basis in the most recent scenarios (Table 2). This level of resolution, when used on systems that include a significant dose of complexity (possibility of curtailment, storage, PtG, sector coupling, interconnections) generates a very high level of calculation. For instance, to characterise transmissions between countries, some models use unlimited or vast transmission capacities (also known as copper plates) to simplify modelling. This practice tends to reduce storage requirements (and therefore underestimate them)(Cebulla et al., 2018). Concerning the level of resolution, according to Shirizadeh and Quirion (2022), thinking in terms of hourly steps generates much smaller errors than models using standard weeks, and this is particularly true for storage.

4.2.2 Power generation

A representation of the VRE installed capacity forecasts in the scenarios (Table 2) is presented in Appendix 5. As Table 2 shows, there are many scenarios in the literature proposing a high penetration rate of renewables (up to 100%). In all of them, PV and wind play a major role in the growth of renewables. The role played by VRE in the growth, as well as the distribution between the different VRE technologies, is structured by the cost assumptions (see 4.2.6), and by the role played by storage and transmission in the said scenarios (see 4.2.5).

In this respect, it is difficult to draw up relevant analyses a priori by comparing the amounts of installed capacity in the various scenarios. The fact that data availability in these scenarios is often partial does not help. Nevertheless, it is possible to see that the increase in electricity consumption predicted in the institutional scenarios (see 4.1.2) and in the scientific literature is reflected in an upward trend in installed solar and wind power capacity as the scenarios become more recent.

4.2.3 Storage

A representation of the storage requirements in the scenarios (Table 2) is presented in Appendix 6. The comparison of storage forecasts in the literature is particularly impractical. This is firstly since, depending on the study, data are available in different indicators: sometimes in installed capacity (GW), sometimes in storage capacity (GWh), and sometimes in production over the year (GWh). Sometimes even within the same study, different storage technologies are defined by different indicators. Some (or all) of the data are also regularly not public. It is sometimes possible, by making assumptions about the charging frequency and discharge hour of the technology, to compare the studies more easily, but the quality of the data is strongly affected. I therefore propose, after examining the technological trends in storage, to take a closer look at the reasons why storage needs may be underestimated or overestimated in the European scenarios presented, as well as other scenarios in the literature to support my argument.

4.2.3.1 Technological trends in storage

The use of daily battery storage in scenarios has increased over the years (Table 2). Sometimes absent from the scenarios produced ten years ago, they are now considered indispensable and play a major role in the storage system. By absorbing daily fluctuations, they make it possible to restrict other storage facilities to periods of greater stress(Frazier et al., 2021; Rasmussen et al., 2012). The main reason for their success is the fall in their cost, as well as that of PV, a technology with which batteries synergise particularly well (see 4.2.5). The latest projections (published between 2019 and 2021) suggest that the price of utility scale batteries will continue to fall significantly (Figure 4-4). Batteries with duration less than 6 hours should make up the bulk of tomorrow's utility-scale batteries (Frazier et al., 2021; Golombek et al., 2022; Rasmussen et al., 2012).

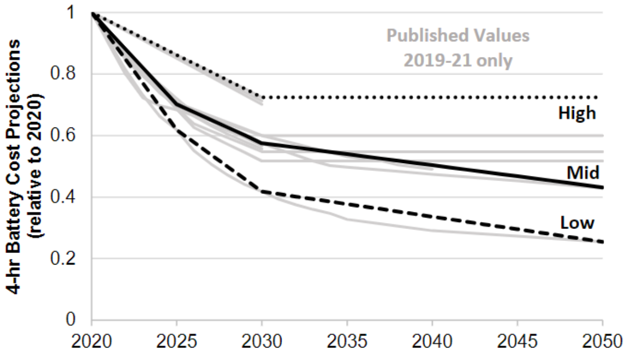


Figure 4-4 Battery cost projections for 4-hour lithium-ion systems. Literature review (grey) and three major trends (black) (Cole et al., 2021). The 2020 starting point is 345$/kWh.

A new consensus seems to be emerging about seasonal storage. Many studies agree that it is only relevant from a very high share of RES in the electricity mix. At the European level, some studies mention a necessity from 70-80% share (Monterrat et al., 2021), others 80-90% (Weitemeyer et al., 2015). Scholz et al. (2017) say that it is not worthy before the VRE reach a 60% penetration level. Denholm et al. (2021b) and Guerra et al. (2021) end up with similar conclusions for the US. This new situation is profoundly changing the perception of VRE deployment. Indeed, in this context, the massive deployment of VREs is no longer conditioned in the short term by the maturity of seasonal storage technologies.

4.2.3.2 Overestimation of storage needs

In all scenarios where solar and wind power play an important role, storage requirements are a key factor. The downside is that when certain scenarios conclude that storage requirements are extremely high, the feasibility of an electricity mix with a high VRE penetration rate is called into question. In Europe, Germany, which is particularly affected by Dunkelflaute phenomena (see 4.3.1), has been the subject of several studies concluding that storage requirements are particularly high.

Sinn (2017) concludes in his work that the share of VRE should not be too high, because the storage needs become too important from a certain stage. This statement is the result of a structuring presupposition: the author wants every potential kilowatt-hour to be captured, without any curtailment. The consequence of this assumption is that storage requirements will be multiplied. For Germany, Sinn (2017), refusing any curtailment, finds a storage need of 16.3 TWh for an VRE penetration rate of 89%, which corresponds to 3.23% of the annual electricity demand. As Zerrahn et al. (2018) analyse in their critique of Sinn (2017), allowing a curtailment dose can significantly reduce storage requirements. To illustrate this, these authors, based on the same perimeter, propose to combine the possibility of curtailment with storage, following a cost-optimization model. The storage needs found by Zerrahn et al. (2018) also grow very strongly from 50 to 90% of VRE, but peak at "only" 1.08 TWh. By adding the possibility of sector coupling, the electricity that is supposed to be lost through curtailment, characteristic of a high VRE scenario, can be used through electric heaters, electric vehicles, P2X, etc.

When modelling storage requirements, it is essential to use many years of input weather data to avoid bias (Staffell & Pfenninger, 2016). Otherwise, it is quite possible to over/underestimate the requirements, as shown by various sensitivity studies(Zerrahn et al., 2018). This allows the proportion of extreme events to be quantified, and the storage system to be designed accordingly.

Using a 35-year database, Ruhnau and Qvist (2022) propose to study the storage needs for a 100% RSE scenario (composed mainly of wind and solar) in Germany. They end of with the result that Germany needs nothing less than 36 TWh of effective storage (56 TWh H2-capacity including combined cycle discharge efficiency). The model proposes a cost-optimised energy system, dimensioning it in such a way that it can absorb the worst period in the 35 years of data. On the other hand, the authors assume that Germany cannot import, and is therefore considered an "island". This argument is defended as valid because, according to the authors, the situation is the same throughout Europe and corresponds to a period when Scandinavian hydro stocks are at their lowest. The dimensioning period for the model is December 1996 - January 1997. Using the model I designed (see section 4.3.1.1 for detailed explanation), which also considers this period as the worst for Europe in terms of VRE potential, and by comparing the situation in Germany with the aggregated situation at European level, it is possible to see that the situation is not as bad (Figure 4-5). The energy theoretically available from VREs over this period is 77% higher if we consider the average wind and solar potential at European level, compared with that of Germany alone ($\frac{\overline{C_{VRE\ Europe}}}{\overline{C_{VRE\ Germany}}} = 1.77$). This period does indeed correspond to a situation of exceptional tension, which requires seasonal storage. Indeed, by smoothing out production on a larger scale, it is possible to mobilise the short-term storage capacities of neighbouring countries to a greater extent, which avoids overestimating the long-term storage capacities in all the countries concerned. This is a characteristic that has been well studied in the literature (Breyer et al., 2022; Brown et al., 2018).

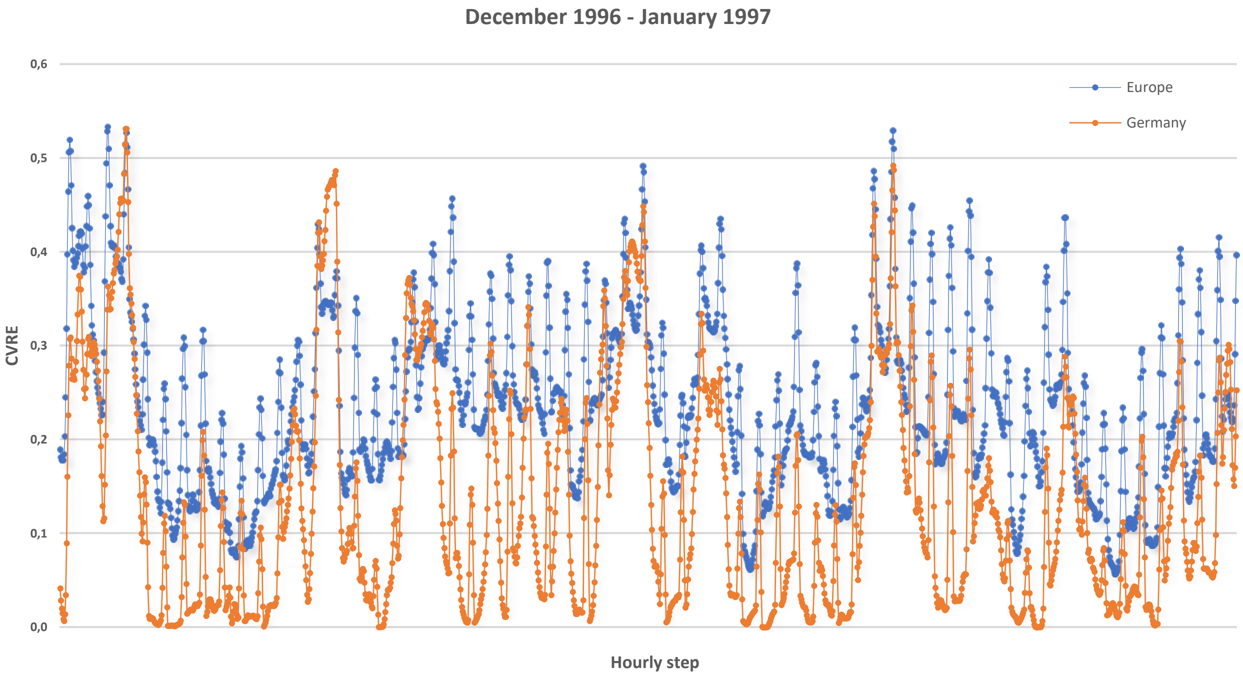


Figure 4-5 Comparison of C_{VRE} in the worst period used in the model of Ruhnau and Qvist (2022) between Germany and Europe with my model developed in 4.3.1.

Heide (2010), one of the first European studies to model a 100% VRE scenario with storage quantification, greatly overestimates seasonal storage needs. Like Sinn (2017), every kWh produced by VRE must be stored, without any sectoral coupling possible. This results, in the same way, in a very large overestimation of storage needs: 480 TWh of hydrogen for Europe (i.e. at least 1 order of magnitude more than most recent studies). The other problem with this study is that it only considers PHS and hydrogen as possible storage technologies. It is therefore impossible to find enough space (for the former) and electricity (for the latter) to store each kWh. Other daily storage facilities, such as batteries, which could avoid wasting PHS and hydrogen reserves and conserve them for longer-term storage, are not being considered. Leonhard and Grobe (2004) concluded the same thing in the mid-2000s, saying that "A future electrical energy supply based on a “wind and water”-model, where the fluctuations of greatly increased wind power infeed are balanced by pumped storage hydro stations, appears as a remotely conceivable possibility”. This desire to rely mainly on PHS for storage is characteristic of the first European energy transition scenarios.

Bussar et al. (2016), who study a low carbon scenario for EUMENA, predict a very high amount of storage needs. They use the assumption that 80% of each country's consumption must come from domestic production, which tend to increase storage. Furthermore, their assumptions on the cost of hydrogen storage are far below all other studies in the same scope. As this is a cost-optimization analysis, this method favors the development of storage over energy production, and therefore tends to overestimate storage capacity requirements. The researchers therefore find a seasonal hydrogen storage requirement of 800 TWh. This low assumption on hydrogen costs is also found in Scholz (2012), which finds 203 TWh of hydrogen storage capacity for the same scope. The first forecasts an investment cost for H2 storage of 0.2 €/kWh, and the second 0.3 €/kWh. As can be seen in Figure 4-7, this is very low. These cost differences with other scenarios can also be explained by the proportion of hydrogen storage that is underground. This assumption is particularly important, because the difference in cost between this method of storage and storage in tanks is around a factor of 40(IEA, 2022b). Storage requirements are therefore strongly influenced by the assumption about the proportion of storage that will be underground. In these two scenarios, all storage is considered to be underground, and the cost of underground storage is particularly low, resulting in over-investment in storage.

A downward trend in storage capacity requirements can be seen in Europe (Appendix 6). This is the result of ever greater integration into the scenarios of the various complexities that enable better management of flexibility: interconnections with neighbouring countries, curtailment, if necessary, PtG and sector coupling. The development of batteries for daily cycles is also playing a growing role, making it possible to concentrate other types of storage over longer periods (and thus avoid wasting resources)(Rasmussen et al., 2012).

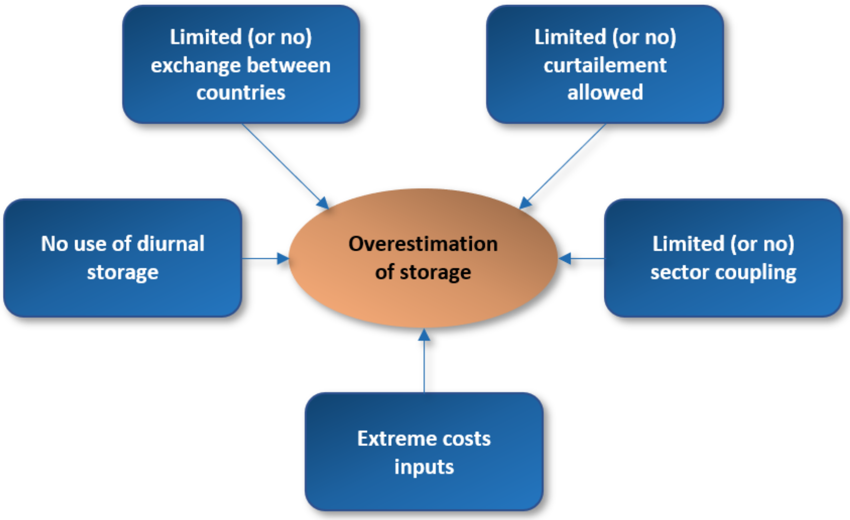


Figure 4-6 Main assumptions leading to an overestimation (which may be slight or lead to totally aberrant results) of storage in scenarios with a high VRE rate in Europe.

To summarise, the scenarios that foresee a very high level of storage assume one or more of these conditions (Figure 4-6): limited (or no) exchange between countries(Bussar et al., 2016; Ruhnau & Qvist, 2022), limited (or no) curtailment(Heide et al., 2010; RTE, 2021; Sinn, 2017), limited (or no) sector coupling(Heide et al., 2010; Sinn, 2017), limited (or no) use of daily storage (typically only PHS and hydrogen)(Heide et al., 2010; Leonhard & Grobe, 2004), or extreme costs inputs (typically low storage costs relative to VREs, which provides an incentive to overinvest in storage relative to electricity generation) (Bussar et al., 2016; Cebulla et al., 2018; Scholz, 2012). These assumptions are therefore particularly structuring for the dimensioning of storage. As such, they require in-depth questioning of the scenarios that admit these possible hypotheses. Are they realistic? This is a question that raises important technical, political and industrial issues. This question raises major technical issues, as well as a number of societal choices.

4.2.3.3 Underestimation of storage needs

On the other hand, several characteristics have been highlighted as contributing to the underestimation of storage requirements. Firstly, as the models are mostly economic optimisations, physical constraints are often relegated to the background of the optimisation(Pezza et al., 2022). Taking into account only a few years (omitting the most "difficult" years) and a large time step tends to lower the storage requirements(Ruhnau & Qvist, 2022). According to Shirizadeh and Quirion (2022), models based on representative weeks are particularly likely to misrepresent storage requirements. Furthermore, scenarios based on deterministic models are often simplistic and do not allow for the quantification of truly difficult periods in terms of storage. In this respect, stochastic models give higher storage requirements (compared to deterministic models)(Golombek et al., 2022; Pezza et al., 2022).

4.2.3.4 Examples of storage needs under different assumptions

For a peak demand of 1200 GW and a consumption of 7000 TWh in 2050 (ENTSO-E projections), Schmidt (2023b) simulates storage power capacity requirements of between 300 and 580 GW and storage energy capacity requirements of between 2.6 and 8.8 TWh for a VRE penetration rate of 80%. If this rate is increased to 100%, the ranges rise to 540-1100 GW and 6.2-21 TWh respectively. This projection corresponds to an extrapolation of their literature review and is based on the open-source model they propose, which makes it possible to assess the most likely level of storage as a function of the VRE rate, peak demand, and annual consumption(Schmidt, 2023a).

In a slightly older literature review, Cebulla et al. (2018) give an approximation of 3 TWh at European level for the amount of storage in the case of a high penetration rate of VRE (>80%). The power capacity results range from 15 GW to 500 GW, depending on the assumed capacities of the scenarios analysed. In view of the recent increase in electricity consumption forecasts, these values may be considered to be somewhat understated, and this is consistent with Schmidt (2023b)'s literature review.

These amounts are much lower than those presented in certain scenarios published in the early 2010s (see Appendix 6).

4.2.4 Transmission

Transmissions, which are often less prominent than other technologies, represent an important part of current and future investments. According to IEA (2022e), 60 billion euros have been invested in electricity grids in Europe in 2022. In the same year, investment in renewable energy amounted to 82 billion euros (IEA, 2022e). ENTSOE (2023a) indicates that, to build 88 GW of additional cross-border capacity by 2040, an additional 3.5 billion euros are needed per year.

Many studies model the ideal transmission level for a 100% clean grid scenario in Europe. The results are very diverse. First of all, the data in TW.km is not precisely available publicly and researchers make approximations, which give different starting points. For example, for Europe, Tröndle et al. (2020) estimate grid capacity at 215 TWkm, while Child et al. (2019) and Schlachtberger et al. (2017) respectively estimate 34.2 TWkm and 31.3 TWkm . In addition to this, the level of transmission depends on the degree of integration taken into account in the scenario, i.e. the extent to which generation and storage are pooled at European level. Obviously, the higher the level of integration, the higher the transmission needs.

Paper	Grid capacity (TWkm)	Comments
Bussar et al. (2016)	503	100% RES, (Eumena)
Gils et al. (2017)	331	100% VRE generation, S20W80
Schlachtberger et al. (2017)	286	Low carbon (Highly renewable)
Child et al. (2019)	145	100%RES
Tröndle et al. (2020)	389	100% RES
Golombek et al. (2022)	5.1*	Low carbon (Higjly Renewable). *Relative to 2015

Table 3 : Grid capacity in different scenarios for 2050.

All forecast a significant increase in transmissions, ranging from a 1.8-fold (Golombek et al., 2022) to a 10-fold (Gils et al., 2017) increase in grid capacity. Given the time constraints involved in building these infrastructures (Appendix 9), such an increase seems absolutely considerable, and in some cases unthinkable. As with storage, this reflects an intrinsic bias in many models, which focus primarily on optimising costs, sometimes relegating technical constraints to second place. This increase is supposed to be achieved by both DC and AC lines, in varying proportions depending on the scenario. In any case, DC lines are set to play a growing role and will no longer be confined mainly to over-sea exchanges.

As well as providing greater interconnection between neighbouring countries, this increase also serves to connect VREs, which are more diffuse and require a larger area, to the network, right up to where they are consumed. This integration into the grid is currently undermined by the impossibility of connecting all the VRE and storage projects to the grid, due to a lack of grid capacity. This problem can be explained by the long lead times required to develop network infrastructures and could even threaten European climate commitments if greater anticipation is not put in place(BBC, 2023). This problem is even more prevalent in the US, where transmission levels are lower(BerkeleyLab, 2022).

Yu et al. (2019), in a prospective work, studies the feasibility, difficulties and benefits of an energy system where transmissions are massively developed between all regions of the world, thus allowing for an integrated energy system at the global level. This integration would allow, as for the European level, to have a lower variability and to use the renewable resources in the best way. On the other hand, this hypothesis assumes reliability between all the links in the transmission chain. Thus, tensions between only a few countries could compromise the global energy supply. While it seems possible to increase integration and transmission at the European level, due to the cooperation and political stability of the different countries, such integration seems highly unlikely at the global level, given the geopolitical tensions.

4.2.5 Storage, Transmission and VRE association

Many studies propose various levels of integration for the composition of the electricity mix at European level, in the form of scenarios(Child et al., 2019; Tröndle et al., 2020). The results, although different, all converge in the same direction: at continental level, transmission capacity is higher, storage and production resources are lower, and the situation is reversed as we move towards the local level.

Storage does not synergise in the same way with wind or solar power. In a highly interconnected European system, the balancing of wind power reduces considerably both short- and long-term storage needs(Cebulla et al., 2018; Roth & Schill, 2022). At the same time, many energy transition scenarios show a strong correlation between the development of solar PV and the development of storage(Gils et al., 2017; Schlachtberger et al., 2017; Scholz et al., 2017). In particular, diurnal storage, with batteries, is becoming more and more promising as solar PV develops (Denholm et al., 2021a; RTE, 2021).

On the European territory, the periods of high tension on the transmission grid correspond to the periods of high wind production, especially during the winter period (Child et al., 2019). Thus, the development of the transmission network favours the development of wind power, to the detriment of solar power. Conversely, if there is a constraint on the development of the electricity grid, the scenarios give a greater share to solar than to wind. (Schlachtberger et al., 2017).

In the case of a scenario with a very high VRE penetration rate, and therefore the need for seasonal storage, the latter makes up a significant part of the storage cost. In these scenarios, the cost of developing transmissions makes it possible to significantly reduce the cost of the system, by reducing the need for seasonal storage(Moser et al., 2020). However, if we look not at the level of the entire system (as in this case at European level) but at the local level, the results need to be qualified. Depending on the geographical location of transmissions and storage facilities, the benefits can be greatly altered (Neetzow et al., 2018). So, to enable an effective storage/transmission system to emerge that does not penalise any region, it is important to have a joint strategy at European level.

4.2.6 Costs

The analysis of the cost assumptions of the different European scenarios presented in Table 2 highlights the great disparity of the input data. Indeed, as shown in Figure 4-7, which shows the assumptions made for different technologies up to 2050, there are often several factors of difference between the different studies. Onshore wind has the smallest discrepancy and solar the most.

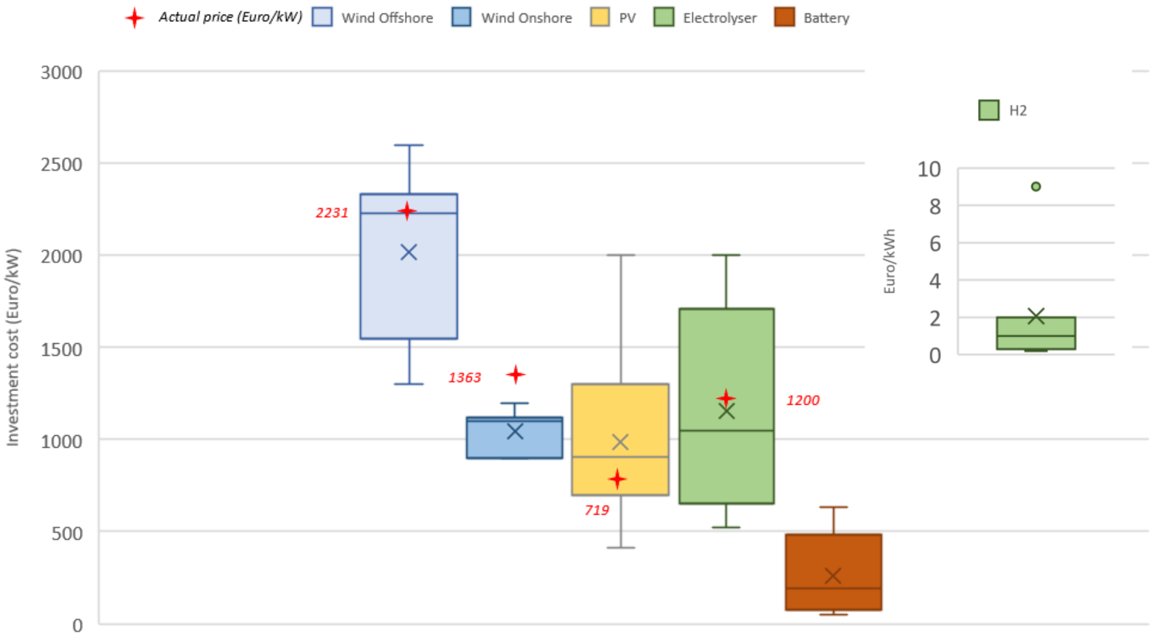


Figure 4-7 Distribution of assumptions of investment costs in 2050 of 5 major technologies for European energy transition scenarios. Own calculations based on public data.

Note: the principal graph display investment costs in €$_{2021}$/kW, whereas the upper-right graph displays investment cost of energy of H_2 in €$_{2021}$/kWh for H_2 storage. The data considered correspond only to those that are public in the studies. The current cost for PV and Wind are those presented in Figure 3-1 (correspond to 2021). Current electrolyser cost it is based on Schmidt (2023b)(correspond to 2019). Data is not specified for batteries as scope and category considerations make a single price irrelevant.

As most of the scenarios are based on a cost-optimisation approach, allowing for a least-cost transition, the inputs to these scenarios are particularly structuring in defining the possible trajectories. As Xiao et al. (2021) has shown by studying the main scenarios on a global scale, the price of renewables has fallen so sharply that it is possible to question, to some extent, the validity of scenarios that are only a few years old. These scenarios studied by Xiao are those on which the IPCC AR6 scenarios are based, whose estimates of storage and VRE installed capacities for the EU are added to the comparison in Appendix 5 and Appendix 6.

I come to similar conclusions by looking at the distribution of the cost assumptions of the European scenarios (Figure 4-7). As with Xiao et al. (2021) study, the scenarios have overestimated the costs of PV technology the most. Logically, the scenarios that overestimate the cost of VRE the most are the oldest ones. Depending on the technology, it can be seen that the costs currently experienced on the market are sometimes lower than those assumed in the input data for the European scenarios for 2050. It is difficult to estimate the real impact of this fact on the conclusions of the studies, but it seems quite clear that, in view of the abrupt evolution of VRE costs, it is necessary to take a step back from the old scenarios. To be complete, the analysis of VRE cost trends must be accompanied by the notion of integration cost.

4.2.6.1 Integration costs of VRE

The integration cost is defined as the additional cost to the system of connecting a marginal unit of VRE to the grid. This may include the costs of storage, transmission, flexibilities, etc. The sum of the LCOE and the integration cost is often defined as the System LCOE(Ueckerdt et al., 2013).

Apart from the fact that there is some debate about the relevant perimeter for defining these costs, it should be noted that the evaluation of the integration cost is intrinsically dependent on the evolution of the costs of the technologies supporting the integration of the VRE(Reichenberg et al., 2018).

The integration cost was estimated to be significant in the early 2010s, especially if it was considered for a country in autarky(Ueckerdt et al., 2013). For example, Ueckerdt et al. (2013) forecasted integration costs of 60 €/MWh for wind and 120€/MWh for solar in Germany (in the long term). Changes in the price of storage, which is particularly important for integration cost (Monterrat et al., 2021), have had the effect of lowering these estimates. By studying integration cost at European level, Monterrat et al. (2021) and Reichenberg et al. (2018) consider that costs increase moderately up to 70-80% of VRE penetration, before increasing considerably when seasonal storage becomes imperative. An illustration of this is presented Figure 4-8. The evolution of the cost of seasonal storage over the next few decades will be decisive in measuring integration cost more accurately with very high levels of VRE penetration.

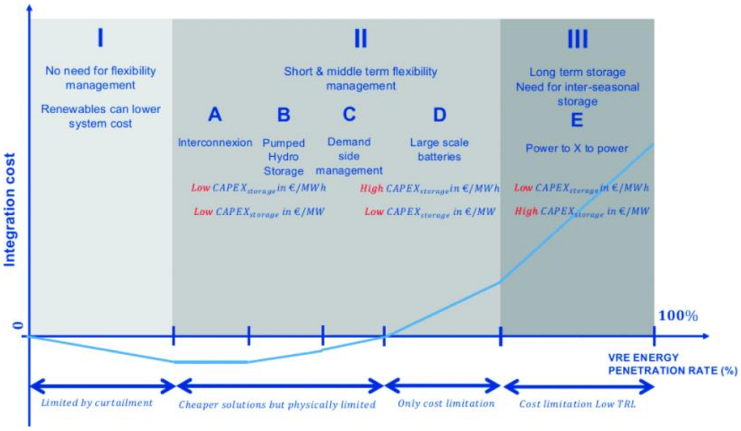


Figure 4-8 Illustration of integration costs in relation to VRE share proposed by Monterrat et al. (2021).

Assessing the cost of integration is highly dependent on the energy system under consideration. First of all, as explained above, the geographical scope has a major impact, as does the level of flexibility that makes up the system. Heptonstall and Gross (2020), who carried out an extensive literature review on the breakdown of the different types of integration costs that make up the overall integration cost, concluded that there is a wide disparity in the results obtained. However, they did identify a number of trends. Costs linked to increased operating reserves are relatively low, and depend heavily on the level of flexibility. The proportion of integration costs linked to grid development varies widely in the literature, but is close to the proportion dedicated to increasing operating reserves. The largest proportion of integration cost is profile cost, i.e. all the costs arising from the system's ability to adapt to meet peak demand at all times. This profile cost also reflects the under-utilization of certain flexibilities due to the high penetration rate of VREs.

According to Breyer et al. (2022), studies that obtain high System LCOE for VRE do not take into account the full range of solutions that exist to meet flexibilities (see 4.3.3), and also that many models use low spatial resolution, and to make up for this lack of precision, they include additional integration costs, which tend to overestimate the total cost of the system. Some studies, with more ambitious cost projections, find a much lower integration cost. For example, for a VRE penetration rate of around 80%, 20 €/MWh for Breyer et al. (2022) and 33 €/MWh for Heptonstall and Gross (2020) in 2050.

4.3 Issues underlying electrification with VRE

In this section, I propose to study the emergence of new issues linked to the development of VREs in Europe. I will focus in particular on dunkelflaute periods, flexibilities in the industrial sector, the need to respond to peaks in demand and the issues linked to inertia and frequency management.

4.3.1 Dunkelflaute period

The name Dunkelflaute comes from German and refers to a period with both little wind and little sun, resulting in a low VRE disponibility. Li et al. (2021) describe them like this:

> “ These events were shown to be typically characterized by near stationary large-scale high-pressure systems and extensive low cloud coverage, with a lower than average cloud base height. This confirms the association of the Dunkelflaute events and blocked regimes arising from the extensive high pressure, which can obstruct the westerly airflow into Europe and further result in the underproduction of wind energy in the neighboring countries. Furthermore, the occurrence of expansive low-level clouds was shown to be another characteristic of Dunkelflaute events, which further corroborates the previous finding that the high-pressure ridges between frontal systems are associated with the occurrence of stratocumulus clouds in mid-latitudes . Due to the relatively low solar radiation and shorter day lengths in winter (during which most Dunkelflaute events occur), the limited solar energy production during the events can thus be well-explained.”

These periods, which often occur around December, can make it difficult to maintain a balance between supply and demand in an energy system where the penetration rate of VRE is very high, particularly as winter is also the time of year when consumption peaks are highest in Europe, unlike in the United States, for example, where the peak occurs in summer (Denholm et al., 2022). The study of the stability of the European grid cannot therefore hide these phenomena. Indeed, if each year, several days or several weeks correspond to these conditions, the efforts on flexibilities and storage would be multiplied.

Recent examples of Dunkelflaute periods exist in Germany (Spiegel, 2017; Welt, 2017), Belgium (Elia, 2017; Meinke-Hubeny et al., 2017) and the Netherlands (NOS, 2018; NRC, 2018). To avoid blackouts, these countries had to resort to demand management policies, large imports from neighbouring countries and the use of all available power reserves(Li et al., 2021).

4.3.1.1 Modeling

To study this phenomenon, and analyse its magnitude, it is possible to use the database provided by Renewableninja.com (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016), providing solar and wind CF data for all years from 1980 to 2019, at a hourly resolution. Although imperfect, this data, using decades of satellite records and accurate simulations, is probably the most accurate (open data) available to date for the European territory. In addition, this database allows the use of future CFs, considering the improvement of wind energy technologies. Based on this historical data, it is therefore possible to estimate both the potential of VREs by 2050, and their propensity to handle extreme events such as Dunkelflaute, with tomorrow's wind technologies.

It seems logical at first sight to think that it is possible to reduce the variability of CFs in each country by aggregating data on a larger scale, thus pooling wind, and solar resources. To quantify this decrease in variability, I define an indicator, called C_{VRE}, which corresponds to the weighted average CF of the VREs for each hourly step. I define a $C_{VRE,Country}$ indicator for individual countries, and a $C_{VRE,Europe}$ indicator for the aggregated indicator at European level. These indicators will make it possible to estimate the vulnerability of a high-penetration VRE electricity mix at the level of individual countries and to compare them to an aggregate mix at the European level.

C_{VRE} for a country i is defined as:

$$C_{VRE,i} = k_{w,i}CF_{wind,i} + k_{s,i}CF_{solar,i} \qquad C_{VRE} \in [0;1] \tag{5.1}$$

$CP_{wind,i}$ being defined by a weighted average of onshore and offshore CP for each country i, and $k_{,i}$ defined as :

$$k_{w,i} = \frac{P_{wind\ installed\ 2050,i}}{P_{wind+solar\ installed\ 2050,i}} \tag{5.2}$$

$$k_{s,i} = \frac{P_{solar\ installed\ 2050,i}}{P_{wind+solar\ installed\ 2050,i}} \tag{5.3}$$

To have an indicator at the European level, the capacity factor of each country should be weighted according to its weight in future electricity production. Thus, the indicator is defined as:

$$C_{VRE,Europe} = \sum_{i=1}^{34} k_{w,i} a_i CF_{wind,i} + \sum_{i=1}^{34} k_{s,i} b_i CF_{solar,i} \qquad C_{VRE} \in [0;1] \qquad (5.4)$$

With a_i being the projected share of the country's wind power capacity in the total wind power capacity of Europe, b_i being the projected share of the country's solar power capacity in the total solar power capacity of Europe. 34 European countries are considered (Appendix 11). Projected share of capacity from Ember (2022). The average values of CFs used are presented in Appendix 12.

This approach makes it possible to standardise the analysis, and thus to be able to make comparisons without judging ex ante the absolute quantity of power that will be installed by the various countries, but rather in relation to the intrinsic variability of the deposits in each country and the consequences that this may have on the Dunkelflaute periods.

The model used is based on hourly data from 1980 to 2019. Basing the analysis on such a database has several advantages. Firstly, it provides a relatively representative view of the major issues of VRE variability, having 40 years of data. In addition, analysing variability over such a long period of time allows highlighting extreme events, which are particularly challenging for an electricity system that is composed of many VRE. Moreover, the hourly time step is a good measure for quantifying energy balancing needs on the power system(Shirizadeh & Quirion, 2022). On the other hand, this time step is not fine enough to draw any real conclusion on the issues surrounding frequency management.

The threshold for qualifying an event as a Dunkelflaute is by nature arbitrary. In line with the scientific literature(Li et al., 2021), I propose to perform several analyses with C_{VRE} thresholds ranging from 10 to 20%. It means that a Dunkelflaute is defined as a period where C_{VRE} is strictly below the threshold defined. Five entities will be studied in particular: four countries, Great Britain, Germany, France, and Spain, and one region, Europe (34 countries).

4.3.1.2 Modelling results

Although it is during the December-February period that the C_{VRE} potential is the least 'variable' on average in Europe (Figure 4-9), it is indeed during this period that Dunkelflaute occur most often. This is characteristic of these meteorological phenomena, localised in time. Figure 4-10 and Figure 4-11 show the distribution of the duration of Dunkelflaute events for two different thresholds. Logically, taking a lower event characterisation threshold decreases the duration of these events for all countries studied and for the European level. However, there are still significant differences in the frequency of these events between countries and regions. It can clearly be seen that in the case of Europe, the Dunkelflaute does not exceed 16 hours in the case of a 10% threshold (Figure 4-10) and very little more than 20 hours in the case of a 20% threshold (with a few longer events, of the order of 44 hours)(Figure 4-11). On the contrary, the countries studied in autarky face many more events of longer duration and are therefore more vulnerable(Figure 4-10) (Figure 4-11). These results are very interesting because they confirm that Dunkelflaute periods can be significantly reduced by pooling production resources.

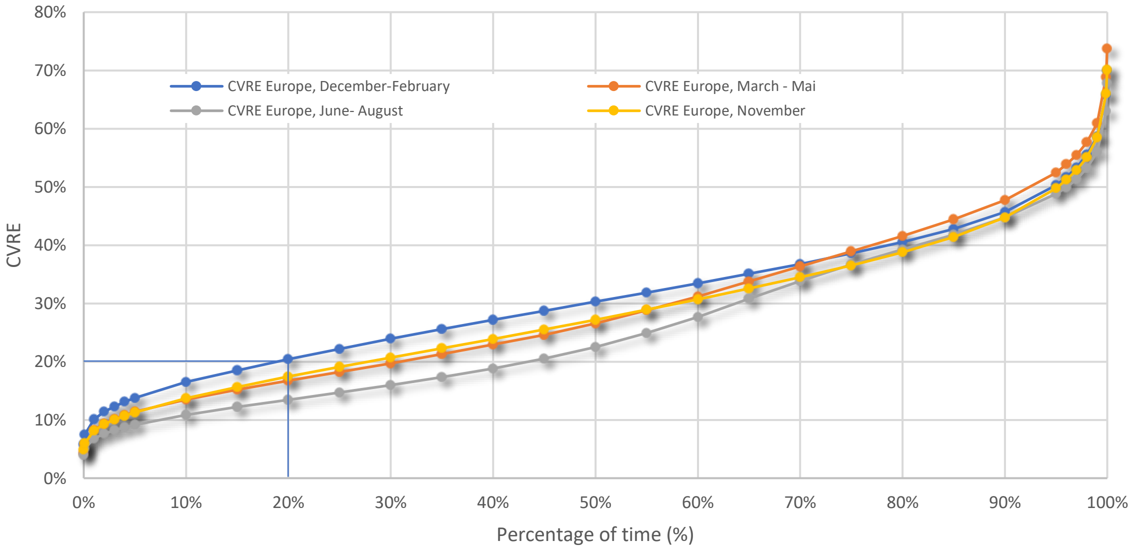


Figure 4-9 $C_{VRE\ Europe}$ in relation to the percentage of time.

Note: The data are constructed by ordering the hourly CVRE data in ascending order and plotting the different deciles. In average, CVRE is lower than 20% one fifth of the time during the period December-February.

It can be seen that, despite the significant differences between the regions, a peak in the frequency of Dunkelflaute is observed around 12 h in the case of a 10% threshold, and around 15 h in the case of a 20% threshold. (Figure 4-10) (Figure 4-11). The frequency of events of shorter duration varies significantly from country to country. These results are in line with those of Li et al. (2021), who carried out these models for Belgium, Germany and Denmark, and who found a similar distribution. The UK follows a peculiar distribution here, notably by having a more squashed distribution and facing many particularly long events. This is due to the fact that the UK has a Wind/Solar ratio of 86%/14% in this model. With little benefit from solar, the country is very exposed to prolonged windless periods.

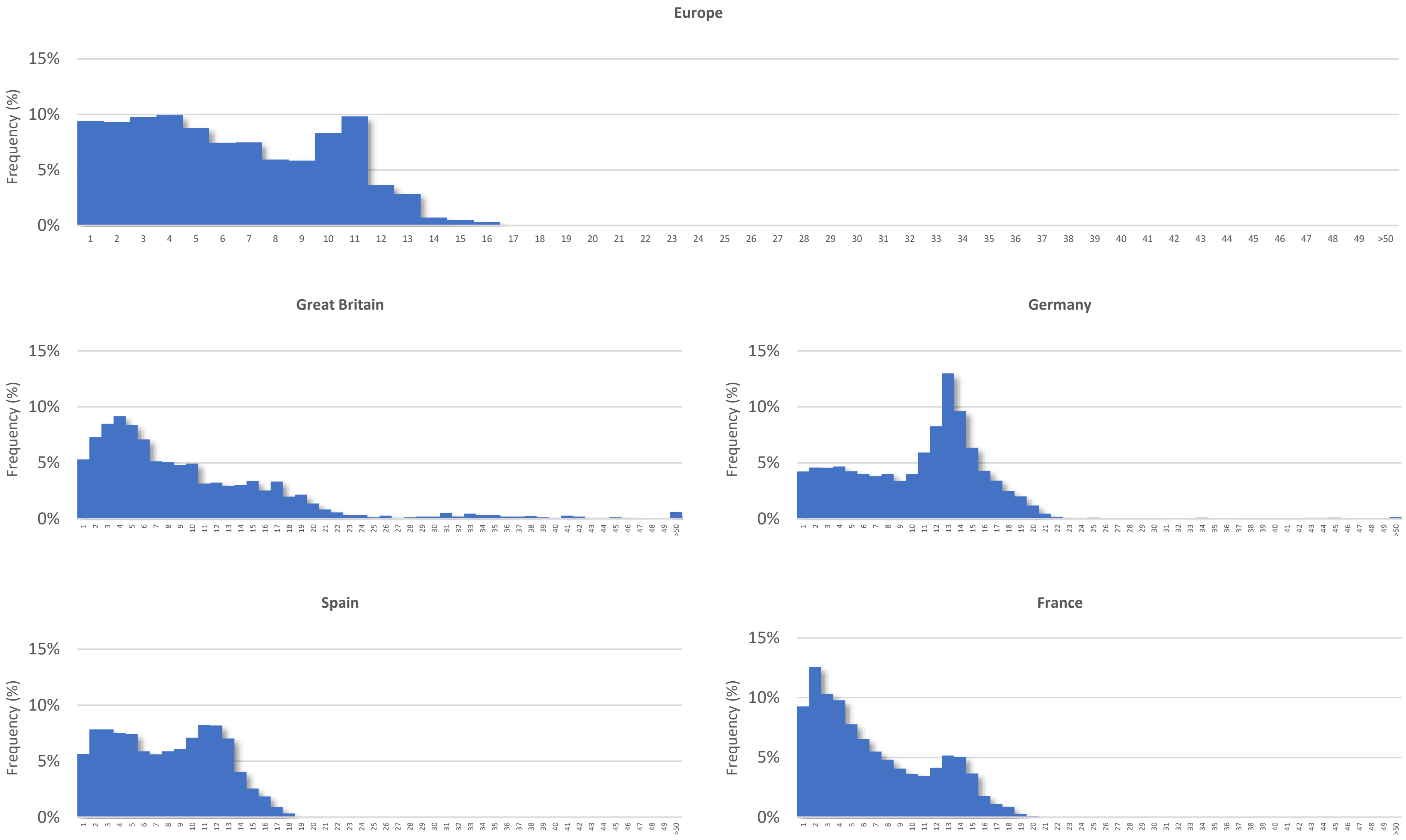


Figure 4-10 Frequency distribution of modelled Dunkelflaute duration (in hours) for 4 countries and for Europe as a whole. The Dunkelflaute threshold is 10% and the data cover the years 1980 to 2019.

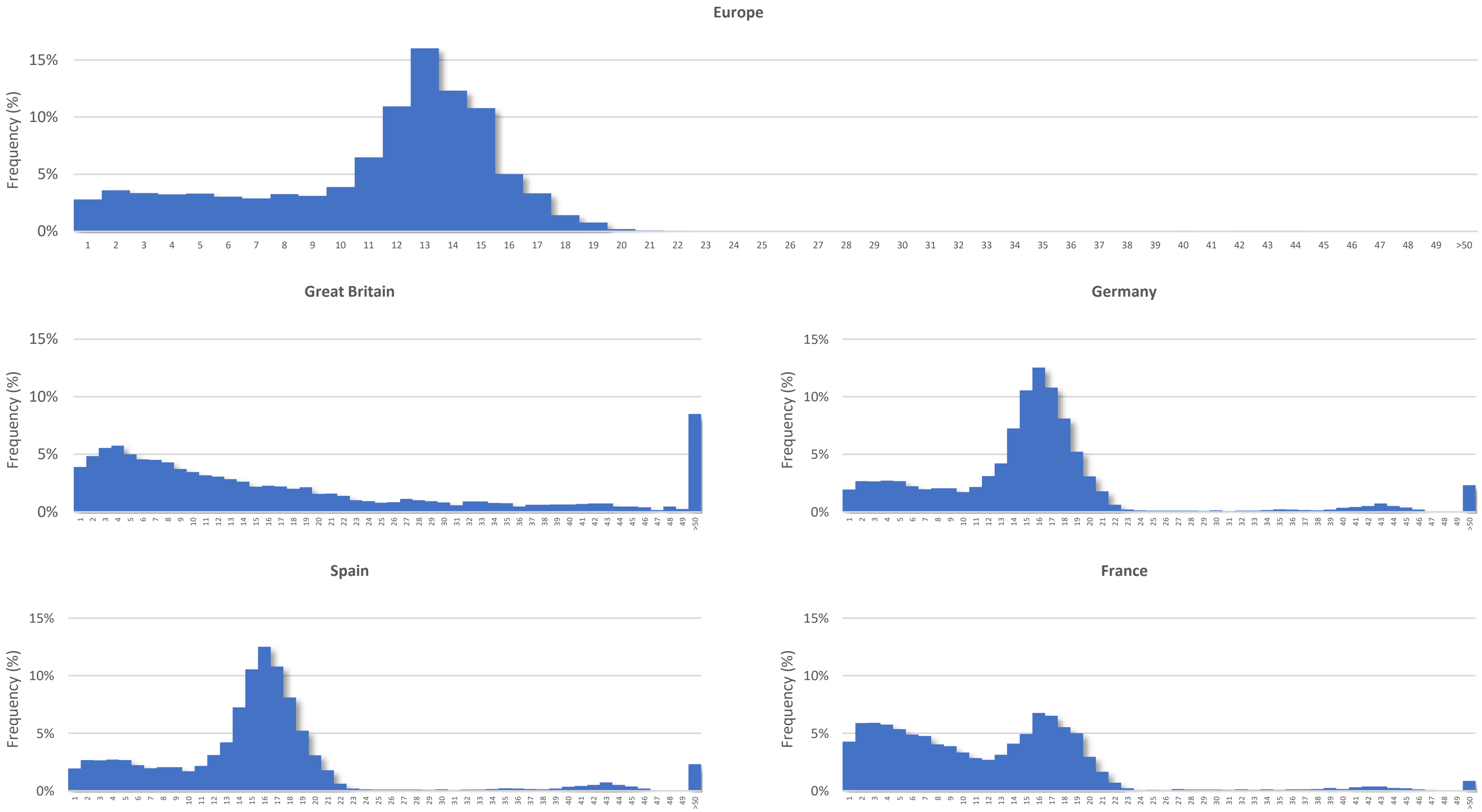


Figure 4-11 Frequency distribution of modelled Dunkelflaute duration (in hours) for 4 countries and for Europe as a whole. The Dunkelflaute threshold is 20% and the data cover the years 1980 to 2019.

As well as reducing the frequency of longer-duration events, Figure 4-12 highlights that aggregating electrical power at European level also reduces the intensity of Dunkelflaute events. For two different thresholds, it is possible to see the duration of the worst Dunkelflaute over 40 years, as well as the number of occurrences of the worst event in Europe in other countries. For example, for a threshold of 20%, the worst Dunkelflaute in 40 years is about 2 days (44 hours) in Europe, while it is about 7 days for France, 8 for Germany and 11 for Great Britain. Moreover, the most extreme event that can occur at European level over 40 years is a common situation in Germany: it occurs about 10 times a year (in average). The same conclusions are drawn for the other countries studied in autarky, albeit in different proportions. These results do not allow us to say what would have happened since the 1980s with a strong development of VRE at that time, since here the wind technologies correspond to what can be expected in the near future. The objective is rather, based on such a large number of years, to estimate the major trends in the future.

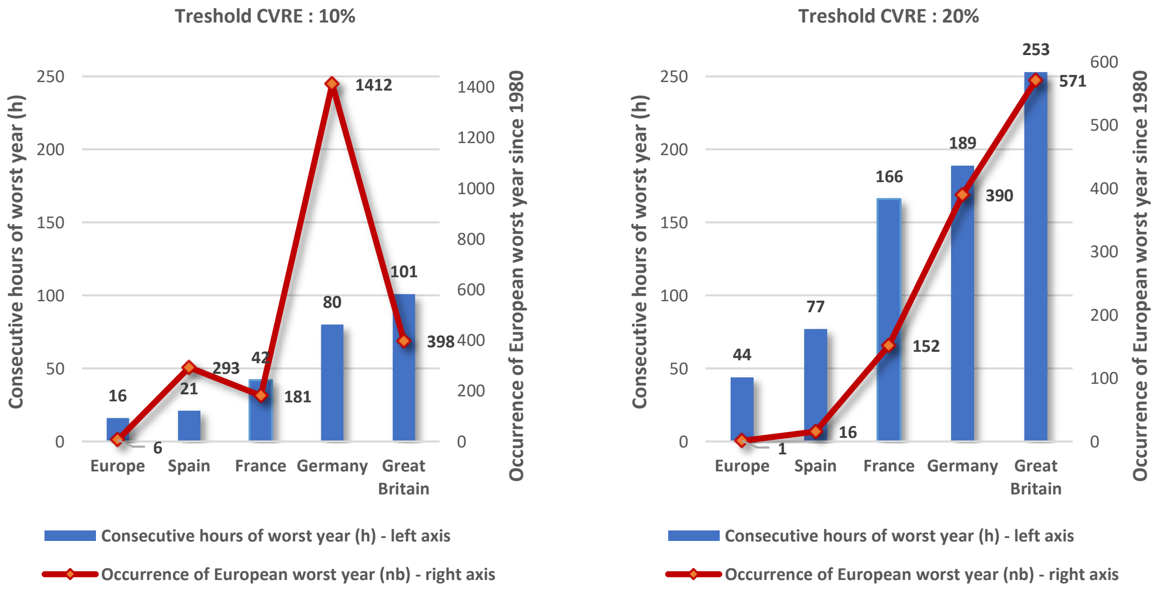


Figure 4-12 Duration of the worst Dunkelflaute duration under two different tresholds, and occurrence of European worst Dunkelflaute in some countries.

These results must be assessed in the light of possible methodological bias. As shown in Appendix 10, the Dunkelflaute periods only take into account the number of consecutive hours below a threshold, and may therefore minimise some Dunkelflaute if the availability of VRE briefly exceeds the threshold. In particular, this tends to minimise the long Dunkelflaute periods of individual countries, which have greater variability (Appendix 10). Another methodological limitation is the scenario used to weight the different country CF (Appendix 11). It appears that certain countries, such as France, are over-represented, particularly in terms of wind energy, and therefore certainly represent too large a share of the $C_{VRE,Europe}$. More generally, the countries of Western and Northern Europe have a predominant weighting in the model and this tends to reduce the potential smoothing and therefore overestimate the impacts of the Dunkelflaute on the continent, but this domination of the electricity generation facilities in this zone reflects an economic reality: it is in these countries that the VRE are likely to be developed the most, even if this is to the detriment of a gain in variability.

In addition to the fact that these phenomena are less extreme at the European level and that their duration is shorter on average, it should be added that the average period per year with a C_{VRE} below 10% is also lower (Figure 4-13), which reflects the fact that production is smoothed over the territory. It is also possible to see that there is no direct link between the duration of extreme events and the average duration with a low rate. Thus, in the model, Spain experiences periods of Dunkelflaute of relatively modest intensity (in duration and occurrence), but regularly has a low C_{VRE} (Figure 4-13). In contrast, Great Britain experiences very intense Dunkeflaute events, but on average spends less time with a very low wind and solar potential. Furthermore, Germany has a significantly longer period of low renewable availability than the other countries studied.

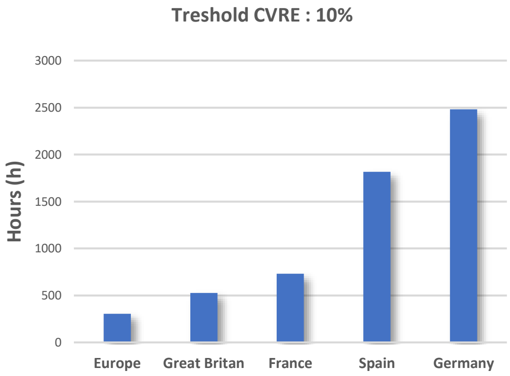


Figure 4-13 Average duration per year below the threshold 10% for different countries and Europe.

Li et al. (2021), on their side, studied the occurrence and impact of the Dunkelflaute phenomenon for 11 countries in Northern Europe and near the Baltic Sea (compare to 34 here). They conclude that although the probability of having Dunkelflaute events between neighbouring countries at the same time is in the order of 30 to 40%, these events almost never occur on the scale of the 11 countries studied. This also argues for the importance of aggregating the production of VRE on a large scale to facilitate their integration to reduce the impact of Dunkelflaute.

The model I propose here is even more integrated, as it includes 34 European countries, and extends further south and east, allowing for more diverse deposits. As such, it does not seem illogical that the conclusions follow the same direction, i.e. a very important interest in pooling production sources on a large scale for the integration of VRE. One advantage of limiting the number of nearby countries to 11, as opposed to 34, is that it limits the assumptions needed in terms of transmission needs. Indeed, it is good to know that increasing the scale decreases the variability, but it remains technically difficult to massively supply Northern Europe with production in Southern Europe and vice versa. This does, however, shed light on the question of variability in an area that has received little attention to date, namely the pooling of VRE production resources to deal with Dunkelflaute phenomena.

Knowing that it is possible to have most of the time a suitable availability of wind and solar sources on the European territory makes it possible to answer the argument, often defended, that the phenomena of Dunkelflaute call into question the very interest of a massive development of VRE(Edwards et al., 2022). It seems clear that assessing the difficulty of managing Dunkelflaute phenomena should no longer be assessed on a national scale, but on a European scale. This mutualisation supposes, of course, an increased development of interconnections, which must be done in conjunction with the development of storage and flexibilities explained in this thesis.

4.3.2 Flexibility in the European Industrial sector

The introduction of a greater share of VRE in the grid will require greater flexibility from most consumers, and industry is no exception. Industry already has potential flexibilities (Lund et al., 2015), but they remain small and are not integrated in an industrial strategy that enhances them.

By studying the industrial models proposed in the literature and extrapolating their implementation at the European level, I propose to estimate the power demand, energy requirements and induced flexibilities. The technological models presented below are the subject of major R&D efforts and are currently undergoing industrial development. Their level of maturity is defined by their Technology Readiness Level (TRL), shown in Table 4.

In industry, the two main routes to decarbonisation based on electrification are the use of low-carbon hydrogen and the use of low-carbon heat through Power-to-Heat (PtH) (Andreola et al., 2021). The use of hydrogen from electrolysis in the chemical and steel industries is one of the best possible uses of low-carbon electricity, because the marginal gains in GHG per MWh of electricity consumed are particularly high(Agora, 2023).

Concerning hydrogen, the industrial solutions proposed below assume that hydrogen can be stored. As explained in section (3.2.2.1), underground storage capacity is very important in Europe. However, storage capacity is not evenly distributed across Europe and some countries are much better equipped, with Germany in the lead (Caglayan et al., 2020). The advantage of underground storage is that it is very cheap (Letcher, 2022). However, the lack of geological storage is not a barrier, but it does require another form of storage, like high pressure steel tanks (which are up to 40 times more expansive than underground storage)(IEA, 2021b).

The choice of electrolysis technology plays an important role in the quantification of flexibility. The main electrification works in the industry via hydrogen use in the vast majority PEM or AWE. As explained in 3.1.2.1, the first one has a greater flexibility of use and can operate at lower load, thus allowing to better follow the fluctuation of the production. On the other hand, AWE, although having less operational flexibility, is currently less expensive(Wang et al., 2023). Concerning AWE, it must be operated at a certain load, which is between 10 and 40%. However, it can cause hydrogen contamination, which can be dangerous(Wang et al., 2023). An advantage of using electrolysers in flexible production is that its energy efficiency is better at medium load than at full load (the efficiency is increasing according to the load)(Wang et al., 2023). To estimate the power that can be erased from the grid, I assume in the calculations that the electrolysers can be erased up to 80%, which therefore corresponds to an AWE electrolyser (conservative assumption).

Flexibility for production processes (excluding electrolysis) is often more limited. Making an industrial production process more flexible means varying the temperature and pressure levels more frequently. In addition to the greater fatigue on materials, the combination of all the constraints on the various elements of a production line makes flexibility a challenge. The level of flexibilization assumed for each industry is described below.

In addition to the possibility of absolute flexibility (by how much can the power of a process be reduced in relation to its nominal value), the question of the ramp rate, i.e. the speed with which the power of a process can be modified, is particularly important. Similarly, the processes described below have much lower ramp rates than can be achieved with a PEM electrolyser.

The amount of erasable power is estimated based on the flexibilities of the various processes, while the erasable energy over the year is estimated using the CF of the processes.

Two scenarios are proposed to assess the electricity needs, and the flexibilities provided for the 3 industries. The first one corresponds to a theoretical scenario of transformation of the entire fossil fuel-based production towards an electrified production mode by 2050. This scenario can be described as a maximum ceiling in terms of electricity demand and flexibility (scenario A). The second scenario assumes that the IEA (2021c)'s NZE projections for technological development are in place in 2050 (with assumptions to align global targets with European targets) (scenario B). The results are presented in Table 4.

4.3.2.1 Steel production

Steel production accounts for a significant portion of global GHG emissions. Indeed, the production of primary steel, carried out in blast furnaces, uses coal to reduce the iron (5.5). The process, in LCA, produces about 2tCO2/t of steel. One way to decarbonize the steel industry is to substitute the reduction with coal to the reduction with hydrogen, a process called H-DR (5.6)

$$2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO_2 \tag{5.5}$$

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O, \qquad FeO + H_2 \rightarrow Fe + H_2O \tag{5.6}$$

Sweden is a pioneer in this sector, with the HYBRIT program, whose primary objective is to demonstrate the feasibility of steel production based on the H-DR process, for future upscaling in order to decarbonize the sector. Toktarova et al. (2020) proposes, in the case of Sweden, to replace the entire primary steel production in Sweden with the H-DR process by 2040. Sweden wants to take advantage of its wind energy potential to power its factories. Commercial H-DRI plants are planned before 2030 in many other European countries, for example in Romania (Liberty, 2023), Germany (Thyssenkrupp, 2022) and France (ArcelorMittal, 2020).

The upscaling of the H-DR process works in synergy with the deployment of VREs. Indeed, VREs, whose intermittency causes various difficulties on the grid, are an excellent complement to hydrogen production, since it is possible to produce it when there is a surplus of electricity production. In doing so, the steel industry, by decarbonising itself thanks to the H-DR process, becomes partly flexible.

The primary steel production, which consists of Blast Oxygen Furnace (BOF) and Blast Furnace (BF) corresponds to 56.4% of the steel production in 2021 in the EU, the other part being composed of EAF(Eurofer, 2022). The total amount of crude steel produced in the EU in 2021 accounts for 153 Mt(Eurofer, 2022).

Decarbonising the European steel industry goes hand in hand with increasing flexibility, which in turn facilitates the stability of the European electricity system. According to Vogl et al. (2018), an H-DR steel plant need, for optimal continuous operation, an electrolyser consuming 274 MW/Mt of liquid steel and an EAF consuming 129 MW/Mt (Figure 4-14). By extending what Toktarova et al. (2020) has done to the whole of Europe, i.e. convert all the BOFs to the H-DR process, the continuous electrolysis amounts to 23.6 GW. As part of the Hybrit research project, a cost-benefit analysis concluded that, beyond the benefits of increased flexibility, it is cost-effective to oversize the electrolyser, and to have hydrogen storage, so that hydrogen is produced when electricity costs are lowest(Hybrit, 2021). By achieving 100% overcapacity, which is one of Hybrit option, it is possible to be flexible 50% of the time. This overcapacity of the electrolyser implies the need for buffer storage to withdraw from the grid during periods of high demand, which can be achieved mainly in steel tanks or geological storage. Based on Hybrit's model, taking advantage of the potential of future offshore wind farms in Sweden, a storage period of around two weeks is the most financially advantageous. Such a duration allows to take full advantage of the low costs of wind energy during periods of overproduction. In order to make the analysis consistent, I will consider the same assumption of overcapacity for the other two sectors.

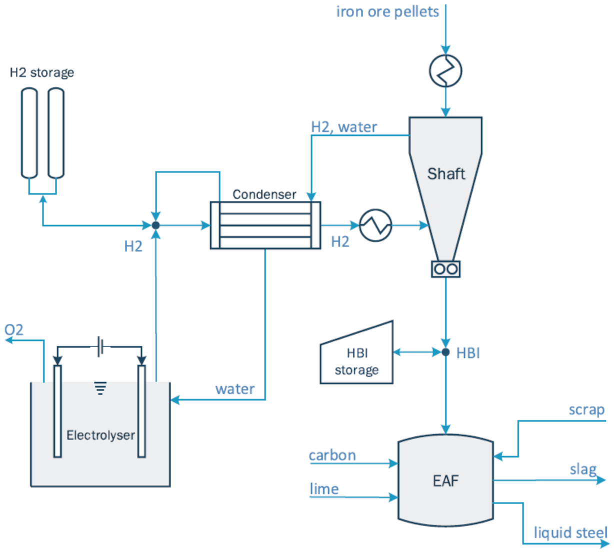


Figure 4-14 Example of H-DRI process for steelmaking(Vogl et al., 2018)

The EAF can also serve as flexibility, of shorter duration. By operating in batches of approximately 1 hour, it is possible to adapt, in particular to the cost of electricity. However, these flexibilities remain marginal and cannot be extended over a long period of time and it is therefore difficult to rely on them to stabilise the electricity grid. I will therefore consider (a conservative hypothesis which corresponds to the testimony of Görnerup (2023)) that the power and energy consumed by the EAF is not flexible for the calculation.

In addition, the use of scrap iron, in the same way, can be used more sustainably during peak demand. This has the effect of relieving the use of the electrolyser(Vogl et al., 2018), and thus it makes it possible to lower the power demand. Constraints on the quality level of the steel can lead to limitations on the use of iron scrap. The steel recycling circuit is of good quality in Europe, and scrap is therefore already massively recovered (EUROFER, 2020). I assume in my calculation (based on (Görnerup, 2023)) that it is possible to increase the amount of iron scrap in 2050 by 5% compared to today (this part of the scrap is entirely diverted to H-DR).

The IEA predicts that H-DR will become a key technology for primary steel production by 2050 and that total consumption from this technology will account for more than 25% of the final energy used to produce steel worldwide(IEA, 2022d). Given Europe's lead, I assume in scenario B that 40% of steel is produced using this method, and that this technology exclusively substitutes BF/BOF (and not secondary steel production).

Finally, hydrogen remains a difficult and expensive molecule to transport, which may make it difficult to generalise in countries that do not have adequate technologies to decarbonise their iron production. (Ma et al., 2023) propose to use ammonia both as a means of transport and directly as an iron reductant. In fact, according to them, this reduction method would be comparable in efficiency to using hydrogen. The manufacturing process for ammonia, like that for iron, can also be made more flexible.

4.3.2.2 Chemicals

One of the main barriers to electrifying the industry is that it means a major change in the manufacturing process. This is particularly the case in the capital-intensive chemical industry. Indeed, the latter has accumulated over the last century several trillion dollars of infrastructure worldwide, making the processes very robust and less risky (in terms of investment)(Mallapragada et al., 2023). In addition, for this industry to be flexible, processes must be designed with capacities above their nominal value. This leads to an increase in CAPEX and OPEX, as larger equipment is required(Cegla et al., 2023). In this respect, it is unlikely that many companies will spontaneously drop massive investments in mature technologies (especially if these investments are recent) without strong financial incentives.

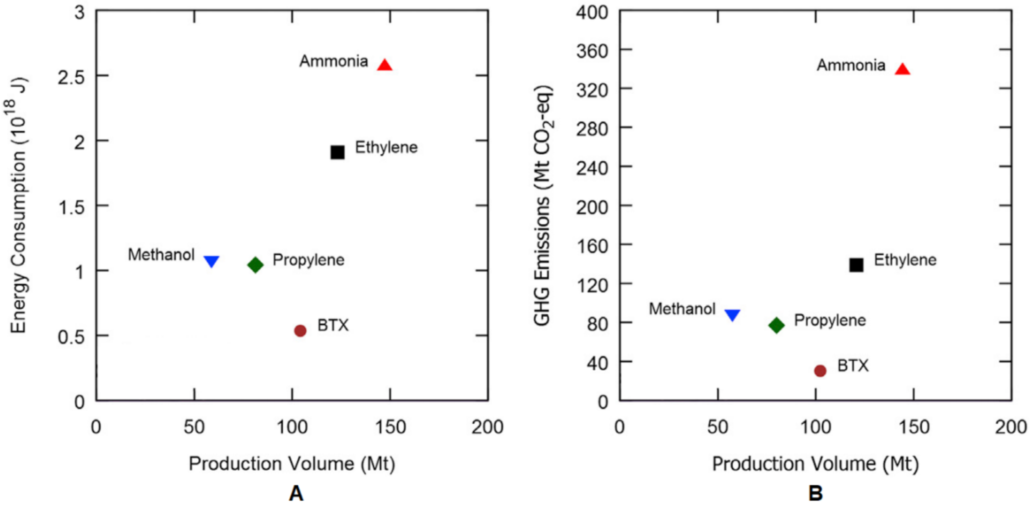


Figure 4-15 Energy consumption (A) and GHG emissions (B) relative to production volume worldwide. Figure from Schiffer and Manthiram (2017).

Figure 4-15 shows the 5 most energy-intensive chemicals in the world.

4.3.2.2.1 Ammonia

Since the development and industrialisation of the Haber-Bosch process by the eponymous researchers in the early 20th century, ammonia has been used extensively as a fertiliser in agriculture to improve yields. According to Smil (2022), the yield gains made possible by ammonia fertilisation would be responsible for around half the world's food.

To produce ammonia, as to produce steel from H-DR, hydrogen plays a central role. But this time, hydrogen does not serve a new process, since it has always been used to produce ammonia, and is the main consumer of hydrogen in the industry (63%)(IEA, 2022b). On the other hand, since most of it is produced from fossil fuels, the objective is, as for steel, to use electrolysis for a significant part of the hydrogen production. This electrification can add flexibility to the electricity mix. Europe is depicted by the IEA as one of the regions where ammonia will be produced most from electrolysis, with 70% of the production by 2050 for the SDS scenarios, and even more for the NZE (IEA, 2021b). For scenario B, I assume that the NZE is more ambitious than the SDS, and therefore that 80% of the ammonia produced in Europe is based on hydrogen from electrolysis. According to IEA (2021b), ammonia production is not expected to exceed current production in 2050 in the EU, remaining at about 20 Mt per year.

Several works have modelled systems to take advantage of the intermittency of VREs to optimize ammonia production, while decarbonizing its production. Some studies assume perfect flexibility in the ammonia synthesis process(Morgan et al., 2014), others assume availability of salt cavern for H2 storage, making the cost of flexibility very low (Fasihi et al., 2016). Others, however, consider constraints in the storage of H2, as well as maximum flexibility in the electrolysis and synthesis process (Armijo & Philibert, 2020; Wang et al., 2023). Like steel production, this kind of system integrates a multitude of facilities that accompany the decarbonizing system level, with, in the first place, a hydrogen storage system(Armijo & Philibert, 2020).

Electrolysis-based ammonia projects can be divided into two broad categories: grid-connected or connected directly to a dedicated VRE network. For example, dedicated VRE projects for ammonia production are being developed in Australia(Yara, 2020), the Netherlands (Yara, 2020) and Chile (PEi, 2020), and grid-connected projects are under construction in the US (Industries, 2021) and Norway (Yara, 2020). In the first case, this means that ammonia production uses electricity from the grid, which is supposed to be stable and continuous, and has a higher CF (IEA, 2021b). In contrast, the second case produces concomitantly with the electrical production facilities, and therefore has a lower CF, which depends on the RES deposit, which depends a lot on the location in the case of wind and solar. Among electrifiable industries, ammonia is probably the most suitable for off-grid installation, because the only raw materials are water and air, in addition to electricity.

I therefore propose, based on the different systems proposed, to estimate the new needs for decarbonising ammonia, as well as the flexibility that this can bring to the European electricity system. Here, I will confine myself to the Haber-Bosch process fuelled by hydrogen from electrolysis. Flexible ammonia production can therefore be simplified to an electrolyser, hydrogen storage, and an ammonia synthesis process composed of an Air Separation Unit (ASU) and a Haber-Bosch process (HB) (Figure 4-16).

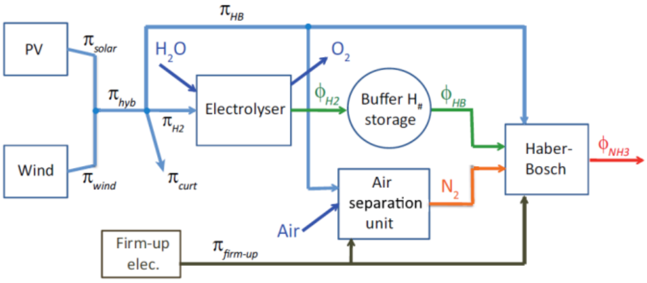


Figure 4-16 Example of a Haber-Bosch process functioning with green-hydrogen.(Armijo & Philibert, 2020)

Contrary to the efficiency of the electrolyser, the Haber Bosch (HB) process is more efficient at full load than at partial load.

The reaction if defined by the equation:

$$3H_2 + N_2 \rightarrow 2NH_3 \tag{5.7}$$

It includes that 177 kg of H_2 is needed per ton of ammonia (Rivarolo et al., 2019).

Based on (Armijo & Philibert, 2020; Wang et al., 2023) and keeping the most conservative assumptions, it is possible to assume that the synthesis process (ASU+HB) can be switched off by 40% respectively (i.e. operate at 60%) of its maximum power. Haldor Topsoe claim that they can design even more flexible processes, up to 90% for ammonia synthesis (Laval & Hanfia, 2022), but I will not use it in order to stay conservative. In addition, I am using the assumption provided by IEA (2021b) for the electricity consumption of a complete HB plant with electrolysis, which is 10 MWh/t of ammonia. The CF is considered to be 70% for ASU+HB.

As Philibert (2017) shows, beyond the benefits to the grid of flexible ammonia production, the cost of production per ton depends mainly on the cost of electricity, and much less on the CF, which once exceeded 40-50%, only marginally impacts the cost of ammonia.

Ammonia's field of application is set to expand in the long term. Its higher density (Andersson & Grönkvist, 2019) and greater transportability make it an interesting fuel for many energy applications. For instance, the NZE predicts that ammonia will cover 45% of energy demand for shipping worldwide in 2050(IEA, 2021c).

4.3.2.2.2 Methanol

Methanol is a multi-purpose alcohol particularly used in the chemical industry. It is used as a raw material to produce plastic, paint, and plywood. It is also used as a supplement to fuels for transport and heating(Philibert, 2017).

The production of low-carbon methanol from CO2 and hydrogen produced by electrolysis is possible thanks to the following reaction. The methanol is synthesised by hydrogenation of CO2, which can replace energy from fossil fuels (Chen & Yang, 2021). Production is also possible from carbon monoxide. The technology used for methanol synthesis is almost identical to that used to produce methanol from fossil fuels. The technology is therefore very mature(IRENA, 2021).

$$CO_2 + 3H_2 \leftrightarrow CH_3OH \tag{5.8}$$

$$CO + 2H_2 \leftrightarrow CH_3OH \tag{5.9}$$

According to the first stochiometric reaction, 188 kg of H2 and 1,370 kg of CO2 are needed to produce one ton of MeOH (CH3OH).

There are several possible ways of meeting the CO2 requirements for the production of e-methanol. Firstly, it is possible to use the CO2 produced by various industrial activities that emit CO2 and that can be captured. This solution is based on maintaining fossil industries. Another option is to use the CO2 from biomass via bio-energy with carbon carbon and storage (BECCS), bio-energy with carbon capture and utilisation (BECCU) or direct air capture (DAC)(IRENA, 2021).

Several commercial projects of e-methanol are planned for the next few years in Europe, for example in Germany (200000 t/y)(Dow, 2021), in Sweden (45000 t/y)(LiquidWind, 2022) and in Belgium (46000 t/y) (Sherrard, 2020), among others.

Numerous works studying the feasibility of the implementation of a Power-to-Methanol technology exist, and were mainly listed in the literature review proposed by Mbatha et al. (2021). However, models based on production flexibility are less numerous.

Hank et al. (2018) propose a model based on the flexibility of the electrolyser, but it is relatively simplified. On the contrary, Chen and Yang (2021) propose a fully electric model, where all processes are electric, and where the flexibility of the electrolyser but also of the methanol synthesis technology are considered. The latter models use excess capacity to produce at the most opportune times, both to stabilise the grid and to use the cheapest electricity possible.

Chen and Yang (2021) explain that their synthesis process can be theoretically flexibilised to 100%, although he has some reservations, explaining that other similar processes were only flexibilised to 80%. To be conservative, I propose to use the latter value. Extrapolating from the work of Chen and Yang (2021), I consider that non-electrolysis processes for methanol production require a power of 955 MW/Mt, of which only half is 80% flexible (in Table 4, Methanol process 1 is the flexible part and Methanol process 2 is the non-flexible part). Likewise, the CF for the methanol process comes from Chen and Yang (2021).

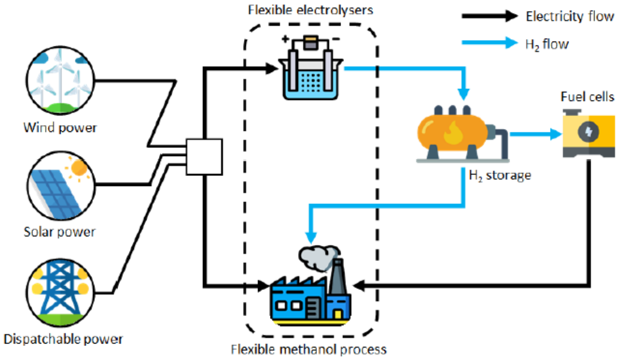


Figure 4-17 Simplified illustration of the e-methanol model proposed by Chen and Yang (2021)

Current European methanol production is around 10 Mt per year, mostly based on fossil fuels. According to (IRENA, 2021) , world methanol production will increase fivefold by 2050, half of which will come from PtM. The IEA assumes that 40% of fuel in the chemical industry comes from H2 by 2050 in its NZE (IEA, 2021c). I use this assumption for scenario B and assume that 40% of current methanol production is produced from hydrogen from electrolysis in Europe. Given the assumed evolution of methanol in the coming decades (IRENA, 2021), there will be a trade-off between methods to produce sufficient decarbonised methanol. Other methods are possible (biomass, CCS in particular).

Methanol's field of application is also set to expand. In addition to its potential as a fuel, the Methanol-to-Olefin (MtO) process can also be used to largely decarbonise the chemical sector. This process makes it possible to obtain ethylene and propylene, the production of which is highly GHG-emitting (Figure 4-15), from methanol(Gogate, 2019).

4.3.2.3 Hydrogen-free industries

Most industries use heat in their production chain (Madeddu et al., 2020). Power-to-Heat is an effective way of reducing the GHG emissions from this heat. Various methods can be used: direct electrification (resistive or inductive heating), high temperature heat pump(Bauer et al., 2022), and others that for the moment do not appear to be low hanging fruit, such as hydrogen combustion, electrochemistry or plasma(Mallapragada et al., 2023). There is very little literature on potential flexibilities, and the only publications that mention them are very recent.

An example of a model is proposed by Bauer et al. (2022) to make heat production in the chemical industry flexible. By coupling PtH, thermal energy storage (TES) and a combined heat and power steam turbine, it would be possible to obtain a flexible process with an energy yield around 10% lower than the process without heat storage (with only electrode boilers) (Figure 4-18). According to the authors, high CO2 prices and the use of low-cost electricity from VREs can make this technology viable. Spatial constraints may constrain this type of device.

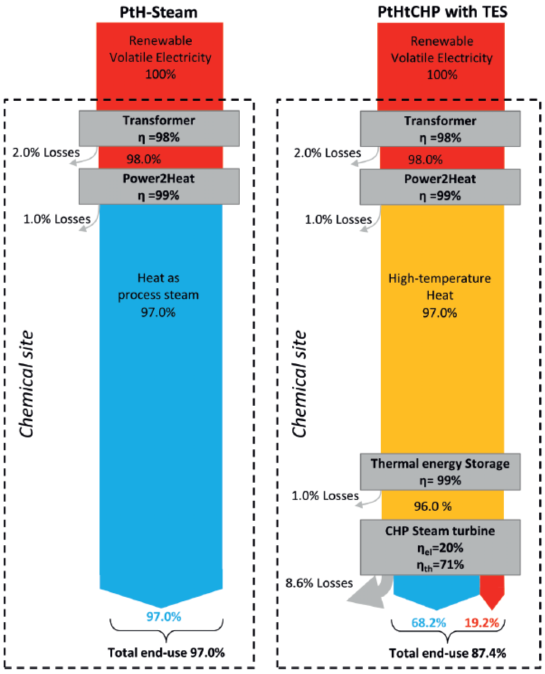


Figure 4-18 Energy Sankey diagrams of PtH technologies : direct steam generation without storage (left) and Power-to-Heat-to-Combined-Heat-and-Power with TES (right). Taken from Bauer et al. (2022).

Further studies are needed to assess the true level of flexibility that this type of process can offer.

4.3.2.4 Summary of flexible potential

		Scenario A					Scenario B					TRL
		Pw (GW)	Pw Flex (GW)	En (TWh)	En Flex (TWh)	H2(Mt)	Pw (GW)	Pw Flex (GW)	En (TWh)	En Flex (TWh)	H2 (Mt)	
Steel												6
	H-DRI - Electrolyser	45	36	196	98	4.2	32	25	139	70	3.0	
	H-DRI - EAF	7	-	88	-	-	5	-	63	-	-	
Ammonia												8
	Electrolyser	40	32	166	83	3.5	32	26	133	67	2.8	
	HB+ASU process	5	2	34	10	-	4	2	27	8	-	
Methanol												7
	Electrolyser	21	17	88	44	1.9	9	7	35	18	0.8	
	Methanol synthesis 1	5	4	14	9	-	2	2	5	4	-	
	Methanol synthesis 2	5	-	14	-	-	2	-	5	-	-	
	Total	129	91	600	245	9.6	86	61	408	166	6.5	

Table 4 : Power and energy needs in 2050 for primary steel, ammonia, and methanol, as well as the flexible share.

Note: Scenario A corresponds to a 100 % shift towards electricity-based process. Scenario B is adapted from IEA's NZE forecasts. Pw is the power in GW, En is the energy in TWh, and Pw Flex and En Flex correspond to the flexible share. TRL are from IEA (2022a). Energy requirements for hydrogen storage are not included in this table.

Scenario A is used as a ceiling reference but does not currently appear to be achievable by 2050. For these three industries, this would require an additional 600 TWh of electricity and 129 GW of processes (electrolysis + other processes). Scenario B, which is an adaptation of the IEA's NZE, seems to correspond to a technological ceiling, in that it corresponds to a very ambitious strategy for the development of technologies. I therefore consider scenario B to be the target.

For scenario B, the level of production achieved by these flexible production methods in 2050 amounts to 61, 16 and 4 Mt of steel, ammonia and methanol respectively. For this production to be available, the grid must be able to accommodate a further 85GW of electrolysers and related processes. Of this 85 GW, 61 can be removed from the grid in the event of peak consumption, thus providing flexibility. Additional electricity consumption for these 3 sectors amounts to 408 TWh and the amount that is flexible (whose use can be shifted to stabilise the network) is 166 TWh.

The power levels of different industrial processes are highly dependent on the CF of the process. The lower the CF, the greater the potential flexibility, but the more overcapacity the process must have to produce the same amount. In the case of electrolysis, this leads to a greater need for storage and higher CAPEX. The benefit of further decreasing the CF of electrolysers will depend mainly on the development of electricity prices in the coming years (Philibert, 2017). It is clear that the latter will benefit particularly from periods of high VRE production. For industrial processes, further increasing flexibilities leads, in addition to a higher capex, to technical problems (pressure and temperature phenomena that can damage the installations) that it is not certain that they can be resolved by 2050. What's more, the vast majority of potential flexibility is confined to the electrolyser, and the levels of flexibility offered by ancillary processes are relatively marginal.

So it seems that while taking advantage of the flexibility of electrolysers to follow the production of VREs is clearly a central avenue to follow for the low-carbon industry of the future, the flexibility of the ancillary processes of steel, methanol and ammonia is less of a low hanging fruit, although it could make it possible to add a level of flexibility to the grid.

In scenario B, the amount of H2 consumed are 3, 2.8 and 0.8 Mt respectively for steel, ammonia, and methanol. These results are consistent with Andreola et al. (2021) for electrifying these sectors on an EU scale, although the need is greater for methanol in my calculation.

Within the scenarios presented in section 4.2, flexibilities in industry are not (or hardly) considered. While the flexibilities brought by smart grids (BEV, heat pumps, etc...) are being addressed, the flexibilities brought by the electrification of industry require further research. By way of comparison, the amount of flexibility given by my scenario B is comparable to the flexibility defined in ENTSOE's scenario for V2G, which is the main flexibility of the scenario.

This estimate corresponds to an average of what can be expected in these sectors under the assumptions cited, but does not take into account the constraints that may exist, for example on the ramp rate or other complex industrial constraints. This tends to overestimate the results. On the other hand, under certain conditions, the EAF could be included in the flexibility calculation, and taking into account better part-load efficiency could help to reduce marginal electricity requirements. In addition, assuming that PEMs (instead of AWE) can be used increases the power that can be removed from the grid. To obtain more detailed results, a more detailed dynamic study, as initiated by Toktarova (2023), is required.

4.3.3 Meeting the last portion of clean electricity

4.3.3.1 100% carbon-free grid

One of the main challenges in managing the electricity grid is to meet peak demands. These events are characterised by the fact that they occur only a few times a year. Thus, it is necessary to have a significant proportion of assets available that only work during these peaks. In order to be profitable (and to pay back the capital costs), these assets must be highly remunerated during these periods(Mai et al., 2022). In Europe, as in other parts of the world, fossil-fired power plants are used extensively to meet these peaks.

Achieving a 100% decarbonised electricity mix requires replacing these fossil-fired power plants with low-carbon assets. Several means, more or less adequate and mature, can be used to meet what is sometimes called "the last 10%", which is this last increment of demand. As well summarized by Mai et al. (2022), "The challenges of achieving a 100% carbon-free grid are disproportionately driven by the difficulty of solving approximately the last 10%".

One solution, which is supported in many scenarios(Mai et al., 2022; Scholz et al., 2017; Ueckerdt et al., 2017; Zerrahn et al., 2018), is to overdrive the VRE, transmission and diurnal storage triptych, so as to increase production during peak periods. The advantage of this method is that it is based on relatively mature technologies. As presented in "4.3.1", this method is all the more relevant to manage winter peaks as electricity production is integrated at European level. However, in all cases, having excess capacity leads to a significant amount of curtailment.

Seasonal storage, based on hydrogen (see section 3.2.2.1), is widely cited as the technology that would allow the completion of 100% RES scenarios. Its use seems necessary (and cost competitive) from a renewable share in electricity generation of around 80-90%(Denholm et al., 2021b; Guerra et al., 2021; Weitemeyer et al., 2015), and may correspond to the majority of storage capacity in the case of 100% RES scenarios(Bussar et al., 2016; Guerra et al., 2021; RTE, 2021). Electricity can be generated via combustion turbines (reformed from gas turbines or newly built) or fuel cells(Mai et al., 2022).

Renewable energy other than VRE and H2 can also be useful. In Europe, increasing geothermal and hydropower production can make a moderate contribution to meet peak demand. Moderate because, for the former, the deposit remains limited in Europe, although many projects are being developed (Dalla Longa et al., 2020; Morales Pedraza, 2015). According to Dalla Longa et al. (2020) between 100 and 210 TWh could be produced by geothermal energy by 2050. For the latter, a large part of the deposits has already been exploited(QUARANTA et al., 2022). According to Stocks et al. (2021), it would be possible to upgrade the current fleet by 8%(~30TWh) and there is 67 TWh of closed-loop hydro potential in Europe (excluding Russia) that can be built at a cost comparable to past projects. Some fossil gas power plants can also run on biomethane. Sulewski et al. (2023) literature review concludes that more than 1000 TWh of biomethane can be developed in Europe by 2050. The share that can be allocated to the power sector will depend on technological arbitrage. Biomethane can replace natural gas in electricity production, but it can also be used for heating, transport, and non-energy applications in the industry.

Nuclear power, which accounts for 19% of Europe's electricity in 2022(Ember, 2023), is likely to be part of the European mix in 2050, as several countries have decided to have new nuclear power in their electricity mix, including France, Finland, Poland, Hungary, Bulgaria, Croatia, the Czech Republic, Romania, the Netherlands and Sweden(Euronews, 2023a). However, this technology is very capital intensive and is used more as a base load technology, with a high CF, rather than as a flexibility. Furthermore, as Lynch (2022)'s work shows, nuclear reactors are often wrongly modelled as any other thermal power plant. In reality, there are technological constraints that limit flexibility, especially operational schedules and minimum power evolutions. The impact of these omissions is all the stronger when the model considers a high share of VRE in the mix. This makes its use as a flexibility for the last 10% potentially expensive technically difficult. On the other hand, smaller and more flexible reactors that may arrive in the future may be more appropriate to meet peak demand(Mai et al., 2022).

Finally, demand response can also be an interesting way to facilitate the last 10%. Many possibilities for demand-side flexiliby exist, e.g. with EV batteries, heating through heat pumps, sufficiency measures(Mai et al., 2022). However, it is difficult to precisely quantify the robustness and the amount of energy that can be saved by these measures. Indeed, the complexity of human behaviour as a society creates significant uncertainties about the level of application of this type of measure(Mai et al., 2022). New regulations and market incentives are being studied to promote these approaches. Beyond the solutions mentioned below, there will also be flexibilities in the part of the industry that will be electrified, as discussed in section 4.3.1. This type of flexibility is really underestimated in the European scenarios for decarbonization (ENTSOE, 2022b).

None of these technologies corresponds perfectly to the typical profile of a flexibility that can only respond to peaks, i.e. a low OPEX, low CAPEX technology that is very mature and has no constraints on the resources it can deploy(Mai et al., 2022). In fact, a combination of all/or some measures seems to be the preferred way to solve this problem. However, the problem of peak demand in the last 10% in a scenario approaching carbon neutrality remains a distant horizon for most countries in Europe and the world, given the electrification needs to decarbonise the entire energy mix. Thus, the above-mentioned tracks must be articulated in the medium-long term strategy of countries to reach their 100% clean grid, but these difficulties should not be a barrier for the massive deployment of VREs which, by being deployed in parallel with storage and transmission, will allow to reach a 80-90% clean grid.

4.3.3.2 100% RES grid

The 100% RES scenarios differ from the previous scenarios by the absence of nuclear in the electricity mix. This means doing without this controllable production base and therefore adds technical constraints on the management of flexibility. Although, as explained above, such a scenario is unlikely to happen in 2050 (given the de facto revival of nuclear power for some countries), there is a lot of work proposing 100% RSE scenarios, in Europe and in other parts of the world. The feasibility of these scenarios relies on the ability to address many technical, industrial, legislative, and political issues, which are sometimes, but not always, shared with 100% clean grid scenarios. It appears that the technical constraints inherent in 100% RSE scenarios are becoming more and more accessible, and that the issue is shifting more to financial feasibility(Breyer et al., 2022; Brown et al., 2018).

4.3.3.3 Curtailment of VRE

Increasing the share of VRE in the electricity mix, if not done in conjunction with massive investment in interconnections and storage, will lead to periods when production exceeds demand (Bird et al., 2016). These periods are often characterised by low or negative prices and potentially require curtailment of production. Some propose an overhaul of market design to combat this phenomenon, by promoting financial incentives to invest in interconnections and storage(Newbery et al., 2018). In the case of the European electricity market, such a reform is not without challenges as it implies a fair return on investments in infrastructure at the local level, but which will be used at the global level(Newbery et al., 2018).

Although curtailing production is a costly and potentially delicate action, it is sometimes part of a deliberate strategy to increase the share of VRE in the mix. Indeed, many studies (Guerra et al., 2021; Ueckerdt et al., 2017; Zerrahn et al., 2018) consider it beneficial to allow a significant amount of curtailment (more than 10% of VRE production), in particular because this reduces storage requirements compared with other scenarios which, for technical or economic reasons, would like to limit curtailment to very low values, by seeking to store all (or almost all) the energy produced(Heide et al., 2010; Sinn, 2017). Nonetheless, the marginal contribution of VRE to meeting peak demand in a mix that is already heavily weighted towards wind and solar becomes smaller and smaller as this rate tends towards 100%. So the more the electricity mix is decarbonised by the deployment of VREs, the less the increase in new capacity will contribute to meeting peak demand, and the greater the curtailment will be(Mai et al., 2022).

4.3.4 Inertia, frequency, and voltage control

For a power grid to function, it must have several characteristics, allowing it to satisfy both the power balance on an hourly scale (balancing) and on the scale of the second(frequency control). The main characteristics can be summarised as follows: the availability of flexibility for balancing (storage or flexible power), the control of frequency, inertia, reactive power for voltage control, sufficient short circuit level (SCL) to face short-circuit faults and the ability to do a black start. The past electrical system, based almost exclusively on synchronous generators (thermal power plant, hydraulic power plant, etc.), provided for all its needs.

In Europe, every synchronous generator (SG) works at 50 Hz and all of them are synchronize together. Their rotational masses provide kinetic energy, resulting in inertia, and their output consist of three AC signals, phase-shifted by the same period. To gain a better understanding of the issues involved in upscaling VREs on the frequency and inertia of the power grid, I propose first of all to define the characteristics governing SGs.

4.3.4.1 Definition SG

The motion equation of a SG is defined this way (Boldea, 2016):

$$2H\frac{d\omega_r}{dt} = T_m - T_e \tag{5.10}$$

With:

Tm : Turbine torque (p.u)
Te : SG torque (p.u)
H : Inertia (s)

H is given by:

$$H = \frac{1}{2} * \frac{J * \omega^2{}_{base}}{S_{base}} \tag{5.11}$$

With J the moment of inertia, ω_{base} the base frequency and S_{base} the base power. H is defined by the duration in which the generator is able to deliver its rated power by only using the kinetic energy stored in the rotational masses of the generator (Fernández-Guillamón et al., 2019).

It is possible to define equation (1) in terms of power(Boldea, 2016). For small deviations:

$$P = \omega_r T = P_0 + \Delta P \tag{5.12}$$

$$T_m = T_{m0} + \Delta T_m; T_e = T_{e0} + \Delta T_e \tag{5.13}$$

$$\omega_r = \omega_{r0} + \Delta\omega_r \tag{5.14}$$

In steady state, $T_{m0} = T_{e0}$. Equation X and Y results in:

$$\Delta P_m - \Delta P_e = \omega_0(\Delta T_m - \Delta T_e) \tag{5.15}$$

Steady state also imposes $\omega_0 = 1\ (p.u)$.

$$2H\omega_0\frac{d\Delta\omega_r}{dt} = \Delta P_m - \Delta P_e \tag{5.16}$$

Thus, for each deviation of the power balance, the power is first taken by the kinetic energy force present in the rotating masses, in other words, the inertial energy, and then it is the frequency control that reacts. If there is more energy called by the network than injected, then the rotating mass of the SGs decreases their speed somewhat, which will decrease the frequency very slightly. A higher inertia allows the frequency not to drop in case of disturbance on the network.

By aggregating all rotating mass, it is possible to define an equivalent inertia H_{eq}, defining the inertia of a whole power system.

$$H_{eq} = \frac{\sum_{i=1}^{GCPS} H_i E_{g,i}}{E_{g,total}} \tag{5.17}$$

Where E_g is the annual electricity value and $E_{,gtotal}$ the total electricity supplied (SG+RES) within the year.

4.3.4.2 Consequences for VRE integration

Fernández-Guillamón et al. (2019) proposed an estimation of the evolution of the equivalent inertia in the EU-27 + UK. They estimated that the inertia equivalent constant was reduced by nearly 20% between 1996 and 2016 (H_{eq} in 2016 without WPP in Figure 4-20). During this period, RES began to be deployed.

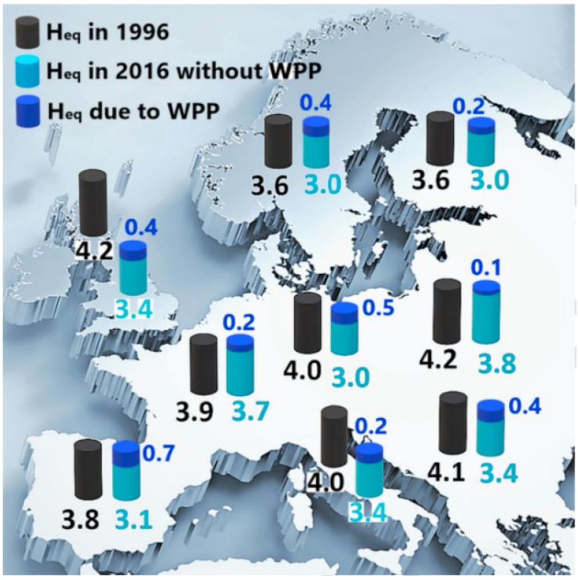


Figure 4-20 H_{eq} estimated in EU-28 considering hidden inertia provided by WPPs (1996–2016) (Fernández-Guillamón et al., 2019).

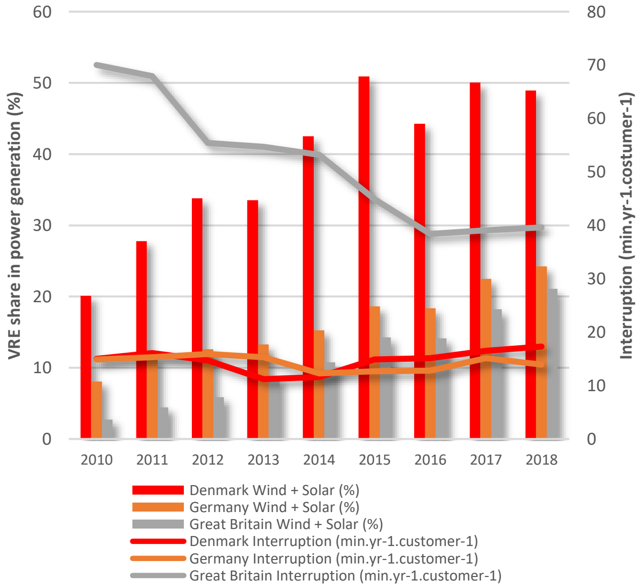


Figure 4-19 Evolution of unplanned interruption duration and penetration rate of VRE in the electricity mix, from 2010 to 2018, in Denmark, Germany & Great Britain (CEER, 2022; Ember, 2023).

Wind and solar PV, unlike SGs, are connected to the electricity grid through power electronics(Kenyon, Bossart, et al., 2020), using the maximum power point tracking (MPPT) technique to maximise the power obtained (Muyeen et al., 2009). They are defined as “decoupled” from the grid, as this power converter prevents wind and PV power plants to contribute directly to the inertia of the power system (Zhao et al., 2016). They are sometimes defined as inverters-based resources (IBR). The purpose of power converters is to convert the DC output into an AC signal that is able to integrate in the power system. The signal converted is defined as asynchronous(Kenyon, Bossart, et al., 2020). However, VRE through power electronics can still produce inertia, which is often defined as synthetic, emulated or virtual inertia (Vokony, 2017).

The 5.18 equation, by adding the part of the synthetic inertia to the equivalent inertia, allows to re-estimate the evolution of the inertia. (Figure 4-20, H_{eq} due to WPP)(Fernández-Guillamón et al., 2019).

$$H_{eq} = \frac{\sum_{i=1}^{GCPS} H_i S_{g,i} + \sum_{j=1}^{EVG} H_{EV,j} S_{EV,j}}{S_{base}} \tag{5.18}$$

The inertia present in wind turbines is defined as hidden, because it corresponds to the inertia present in the rotating blades, although these are not directly connected to the grid. Indeed, wind turbines do have rotating elements (a rotor), but they are not synchronized with the grid, since it does not operate at 50 Hz. The inertia constant of the wind turbines produced today is close to the SG's inertia constants (Fernández-Guillamón et al., 2019). On the contrary, solar PV has no rotating mass, resulting in the fact that its inertia constant is close to 0. In the context of grid integration of solar PV, the inertia is defined as emulated/virtual. Once taken into account the hidden inertia from the WPP, the reduction of inertia in the EU is halved as Figure 4-20 shows (Fernández-Guillamón et al., 2019). However, these authors only consider electricity generation from VREs via the grid-following connection strategy. As I will show, grid-forming inverters will play a crucial role later on to increase the penetration rate of VREs in the electricity mix.

To study the impact of changes in the inertia of a power system, it is interesting to compare trends of decreasing inertia with trends of unplanned outages on the system. By looking at this trend in 3 European countries (Figure 4-19) that have particularly developed VRE, and are therefore among those that have seen their Heq decrease the most(Fernández-Guillamón et al., 2019), Denmark, Germany and the UK, it is possible to see that the cause and effect link does not seem at all obvious, and that these countries have rather seen their robustness increase or stagnate as the integration of VRE into the network has increased.

4.3.4.2.1 Grid-following and grid-forming connection

The two main grid connection control strategies for IBRs are grid-following and grid forming. Grid following is defined by the fact that it adapts to an existing grid. By matching the reference signal of the grid, the IBR allows the electric production facilities (solar or wind) to contribute to the grid. As shown in the analogy in Figure 4-21, it is commonly accepted that the increase in grid following IBR, and therefore the decrease in SG, decreases the robustness of the grid. Grid-following, shown as a tagalong bicycle, can produce basic propulsion (energy) and speed control (frequency response, synthetic inertia); but it cannot steer the whole power system(Kenyon, Bossart, et al., 2020). To maintain a sufficient level of robustness, a certain level of grid forming is necessary.

Figure 4-21 Illustration of the issues underlying the stability of the network. The size of the bear corresponds to the power level. Grid forming can correspond to a SG or an IBR operating with grid-forming control. A high proportion of grid-following can lead to instabilities (Kenyon, Hoke, et al., 2020).

On the contrary to grid-following inverters, grid-forming inverters can generate an AC waveform independently and act by so, act as a voltage source(Kenyon, Bossart, et al., 2020). As well described by The Economist (2023), "Grid-forming inverters offer a step change away from the world of instantiated electromagnetism and into a realm of code and electronics". As well as being a voltage source, grid forming inverters can provide inertia, frequency stability and black start capability(Rathnayake et al., 2021). The deployment of grid-forming inverters is a prerequisite for a very high penetration rate of VREs in the future electricity mix(MIGRATE, 2019). Although the first successful deployments have been made in Australia, the UK and the US, further research is still needed before they can be rolled out more widely(Rathnayake et al., 2021).

4.3.4.2.2 Frequency issues

Maintaining a certain frequency stability on the network is essential to its smooth operation. If production exceeds or falls short of demand, this results in a difference in frequency with respect to the nominal value: 50 Hz. If the frequency changes by more than 0.2 Hz, the network may experience a brownout or even a blackout. Europe has a market mechanism to manage these fluctuations: the FRC Cooperation(EuropeanComission, 2017). The TSOs of Austria, Belgium, Switzerland, Germany, Denmark, France, the Netherlands, Slovenia and Czech Republic (which joined the alliance on 1 March 2023) coordinate to stabilise the network. The frequency containment reserve (FCR) consists of a cumulative power on the European territory of 3000 MW which can be deleted or added to the network at any time. In the event of a frequency drift of more than 10 mHz on the network, this reserve is activated to contain the frequency drift and must be available within 30 seconds. This amount of power is dimensioned to withstand the loss of 2 large generation plants (typically 2 nuclear plants). After the power drift is contained by the FCR, the automatic frequency restoration reserve (aFRR) gradually takes over after 30 seconds, to converge the network back to 50 Hz (Figure 4-22). The tertiary reserve then comes to the rescue if this is not sufficient. These frequency fluctuations damage the elements connected to the network, whether on the consumer or producer side, hence the interest in stabilising the frequency on the network as much as possible.

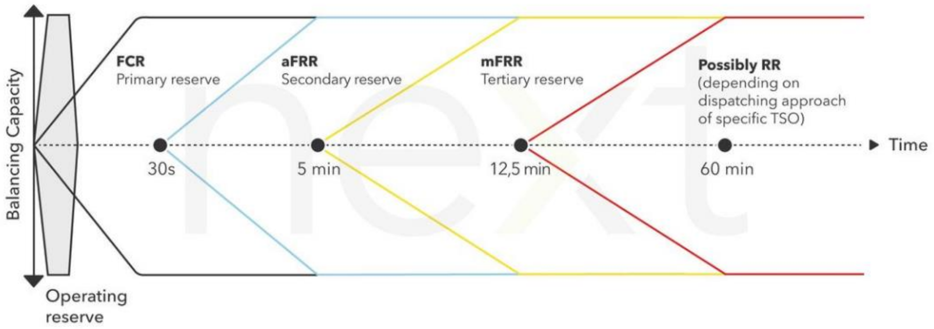


Figure 4-22 Balancing services according to the system envisaged by ENTSO-E (Next, 2023).

As explained above, replacing SGs with IBRs tends to reduce the inertia of the system. As a result, the rate of change of frequency (ROCOF) will tend to increase in the case of a power disturbance(Kenyon, Bossart, et al., 2020). This means that the drop (or increase) in frequency will be more abrupt (since the energy available in the rotating masses can be used less to 'absorb' the shock). In this context, the role of the primary reserve in stemming the drop in frequency is likely to increase as SGs are replaced by IBRs.

4.3.4.2.3 Frequency control by VRE

In order to provide additional active power during imbalanced situation, allowing a control of the frequency, both PV power plants and wind turbines can be combined with batteries, or other types of storage (Salim et al., 2017). Another technique to control the frequency is de-loading. This method consists in deliberately reducing the power, so as to operate under the nominal power, in order to have a power reserve in case of a frequency drop. The VREs operate most of the time with MPPT, i.e. maximizing the power at any time, so they are not able to have this active power reserve. For PV, one of the strategies can be to operate a curtailment, in order to operate at a voltage that generates a power drop. Wind power can also use de-load techniques, by doing a pitch angle control or over-speed control(Yingcheng & Nengling, 2011).

4.3.4.2.4 Faults

Faults can occur on the electrical system for many reasons (e.g. a tree falling on a line, hurricane, problem on a power plant, etc.). In this case, the network must be able to provide the necessary power very quickly, so that the network does not collapse. When a fault happens in a power system, IBRs can only achieve a doubling of its current rate, for a duration of approximately 1ms (Keller et al., 2011). For longer period of time, IBRs cannot go beyond 120% of its rated current(Bhattacharya et al., 2013; Keller et al., 2011). A higher percentage of IBR penetration can tend to decrease the short-circuit level (SCL), which can put the electrical system in trouble in case of a fault(Kenyon, Bossart, et al., 2020). One way to improve the SCL of a network is to add reactive power sources, such as synchronous condensers (SC). A SC is a DC-excited synchronous machine whose shaft is not linked to any driving equipment. The role of this device is to improve SCL and frequency stability by providing synchronous inertia. It also improves voltage regulation and stability by generating and absorbing adjustable reactive power continuously (ENTSOE, 2023b). This technology, which is now mature, does not significantly increase the cost of the electrical system (Brown et al., 2018).

4.3.4.2.5 Summary

To sum up, although the increase in the penetration rate of IBRs will lead to greater complexity in managing the electricity network, there does not appear to be any technological barrier (from a theoretical point of view). In fact, with the increase in control strategies and the deployment of grid-forming devices, reaching a significant proportion of IBRs seems entirely feasible (Kenyon, Bossart, et al., 2020). The technologies still need to be deployed on a large scale to validate these theories.

Some countries are embarking on very ambitious programs, such as the United Kingdom, seeming to explain that grid-forming inverters, coupled with other frequency control, inertia generation and SC, could replace SG (see 4.3.4.3). Numerous research projects are underway to study the feasibility of systems relying on very high inverted-based solutions, until 100%(ESIG, 2022).

4.3.4.3 Examples

In Europe, the United Kingdom is one of the countries that have seen a significant increase in VREs in recent years. In 2010, solar and wind power accounted for 3% of the UK's electricity production (the same level as the European average), compared to 28% in 2020 (15% average in Europe) (Ember, 2023). The increase of solar and wind comes up with the decline of SG connected to the grid. The Stability Pathfinder program, lead by ESO, the TSO of Great Britain, aims to find the most cost-effective way to address the stability issues resulting from this new electricity mix. This program, conceived in three phases, aims to deploy the most effective means to improve inertia (through energy storage) in Great Britain initially (phase 1), then inertia and SCL in Scotland (phase 2) and, in England and Wales (phase 3).

The commonly used approach is, to promote grid stability, to make each generator, using inverters, behave as close as possible to an SG. Stability Pathfinder proposes a different approach, by trying to treat the power system as a whole. According to ESO, phase 2 will demonstrate, in 2024, for the first time in the world, the use of new grid forming converters placed throughout Scotland, improving inertia and SCL to respond to disturbances on the power system(ESO, 2022b). Other technologies, such as synchronous condensers and ultracapacitors will be installed during phase 2 and 3, completing the various storage systems implemented in phase 1 (ESO, 2022a). With the implementation of these technologies, ESO will be able to significantly increase the penetration rate of VREs, and thus meet its objectives of reducing greenhouse gas emissions in electricity production. Indeed, in addition to the substantial increase in SCL in the grid, making it more robust in case of fault, the cumulative inertia added to the grid during the three phases will be of the order of 20 coal-fired power plants(ESO, 2022a).

According to Urdal et al. (2015), 9 GVA of SC could stabilise the British grid even during the worst fault with a share of instantaneous VRE reaching 95%. Investing in such an amount of SC for the UK should cost around 0.3 EUR/MWh(Brown et al., 2018), which is very little compared to the range of possibilities to stabilize the grid.

Further east, Denmark has equipped itself with SC and HVDC VSC transmission with Norway, allowing it to operate without major SG share in its network(Orths & Borre Eriksen, 2016). For example, in 2017, the power grid operated 985 hours without relying on any SG to maintain grid frequency and voltage. That same year, the longest period of operation under these conditions was one week(Green, 2018).

Out of Europe, the state of South Australia has undergone a drastic change in its energy mix, sharply reducing its level of SG on the grid. In November 2022, VRE generation reached 91.5% of generation at the same time as its only synchronous interconnection with a neighbouring state failed. The use of four SC, strategically placed around the territory, stabilised the grid(Parkinson, 2023).

4.3.4.4 Risks of blackouts in Europe

The coordination of the different national TSOs led by ENTSOE allows the European network to carry out joint actions to stabilize the network. Thanks to the high level of interconnection between the different European countries, they can, in case of deviation on the production or on the demand, which would generate a frequency disturbance, exchange between countries to smooth the disturbance in a first step, and then use various methods to regulate the frequency in a second step(ENTSOE, 2016). These interconnections therefore play an important role in preventing blackouts. The size of the European network is a strength for maintaining the stability of the network. Due to its larger number of generating facilities, the inertia is greater than on an island, for example (ENTSOE, 2023a). Smaller and less interconnected networks are more likely to experience blackouts.

Although the European electricity network is one of the most stable and robust, this has not prevented it from encountering, over the last 20 years, more than a dozen major outages, having cut off access to the network for millions of people for several hours(Fotis et al., 2023). The causes leading to such a problem can be multiple (network management problem, accident on a line, extreme weather conditions, cyber-attacks, etc...). Integrating the management of these outages into the energy transition strategy is crucial to achieving a resilient electricity network.

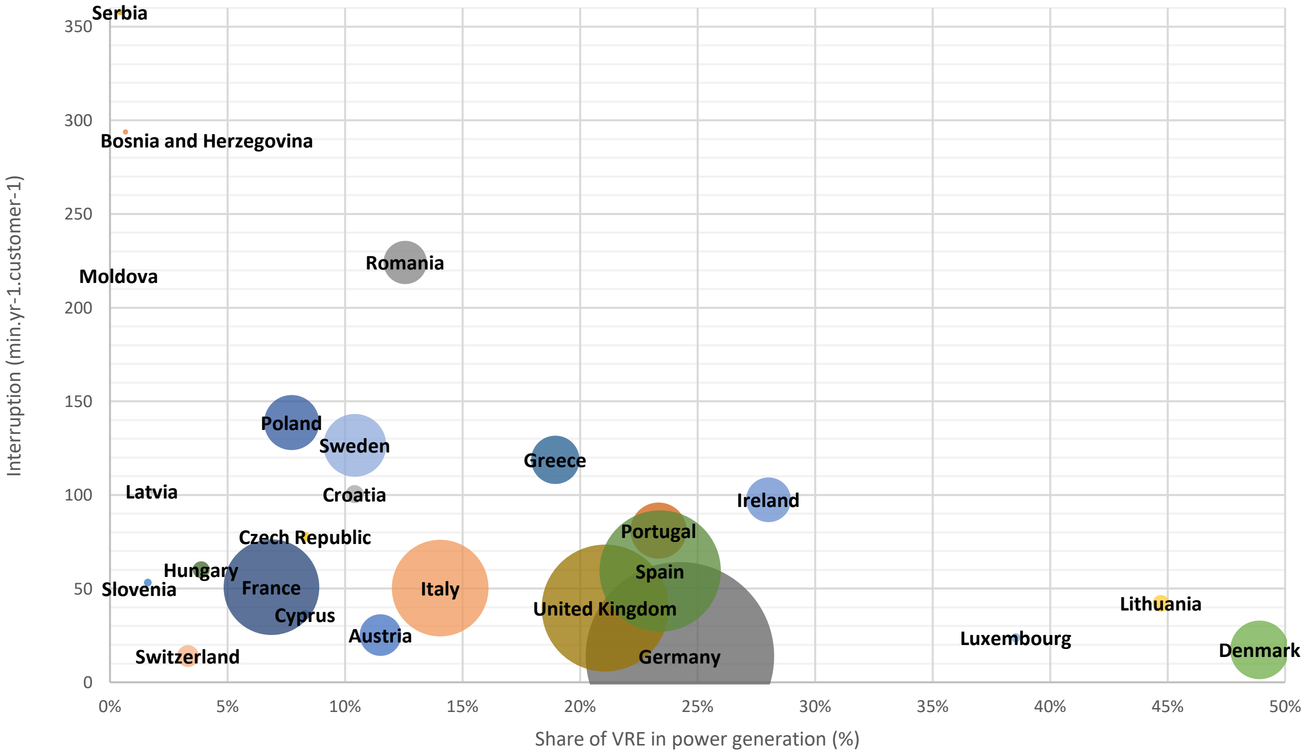


Figure 4-23 Unplanned interruptions (without exceptional events) and share of VRE in European countries.

Note : System Average Interruption Duration Index (SAIDI) used for interruption(CEER, 2022). Data from interruptions and VRE share (Ember, 2023) are for 2018. Circles size correspond to the volume of electricity generation from VRE.

Figure 4-23 shows the average time of unplanned network interruptions as a function of the VRE rate on the network of the country in question. It can be seen that, a priori, it is not possible to conclude that a higher penetration of VREs in the network leads to a higher level of interruption. However, this does not allow for any conclusions to be drawn about the results for much higher VRE rates (>60%). Further work on this subject is needed in the coming years to study the evolution.

Although the deployment of VREs does not seem to be correlated with a greater number of blackouts, it is nevertheless important to deal with the possibility of blackouts with electricity grids supplied to a significant extent by wind and solar power. In the event of a blackout, it is necessary to carry out what is known as a blackstart to restart the network. Storage technologies can be very effective in restoring the network. According to Zhao et al. (2022), lithium-ion batteries and PHS are currently the most promising storage technologies, thanks in particular to their short response time and large storage capacity (in terms of power and energy), respectively. Beyond the technical aspects, lithium-ion batteries are also the least expensive technologies for meeting this black start requirement (Figure 3-9).

4.4 Fuel the transition

In this section, I briefly analyse the main issues relating to resources for electrification, as well as the issue of EROI for the integration of VRE.

4.4.1 Resources

4.4.1.1 Worldwide

To meet future electricity needs will therefore, as I have shown, require the construction of a significant number of new power generation facilities, mainly solar and wind. In this respect, it is necessary to ask ourselves whether, beyond the technical difficulties caused by a greater number of VREs on the network, mentioned above, the need for metal resources is not a constraint that could jeopardise this transition.

One way of looking at it is to compare the extractivist model of society as it exists today, i.e. based on fossil fuels, with a counterfactual scenario of decarbonisation. Indeed, criticism of the deployment of new electricity generation facilities in terms of the quantity of metals needed often overlooks the significant extractivism of the fossil-based society. Watari et al. (2021) propose to compare 2 such scenarios, based on the decarbonisation scenario proposed by the IEA (2017) (Beyond 2 Degree Scenario). By comparing the Total Material Requirements (TMR), which accounts for both the extracted resources that are going to be used in the production process, and the unused resources in the economic system (waste rock for example) (Appendix 7), the power sector decreases its fossil resource extraction by 75%, while metal consumption increases dramatically (Figure 4-24). Adding up the needs for fossil resources and metals, Watari et al. (2021) conclude that resource extraction for the power sector will decrease by about 60% by 2050 compared to 2015. However, electrification in the decarbonisation scenario is not limited to the power sector. Another sector, transport, for which decarbonisation is a major issue (given its high proportion of GHG emissions) and for which electrification is one of the main levers(IPCC, 2022a), will require a doubling of the quantity of extracted materials(Watari et al., 2021). Updating this work in line with the NZE (and not the B2DS) would almost certainly result in even lower extraction figures, further reducing the proportion of coal needed by 2050. Such a study is desirable if we are to gain a better understanding of the issues involved in metal extraction.

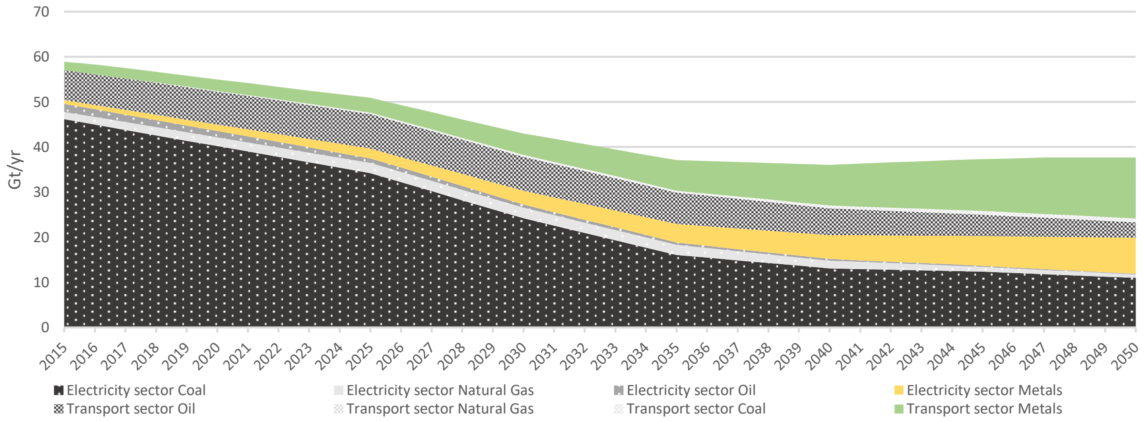


Figure 4-24 Total material requirements induced by the global energy transition. Adapted from (Watari et al., 2021).

The fact that the extraction of fossil resources is decreasing drastically should not obviate the need for new metals. Many studies evaluate the most critical minerals for the energy transition. At the world scale, cobalt, lithium, neodymium and dyspromium are identified as critical by Junne et al. (2020). Lundaev; et al. (2022) explains that antimony, nickel, silver, zinc, zirconium, and manganese may be a problem for the transition if numerous actions (intervention, substitution, new discoveries) are not implemented.

4.4.1.2 In Europe

In 2023, the European Commission published a study summarising the main metal requirements, their evolution, and their criticality (CARRARA et al., 2023). A projection of metal requirements for the EU by 2030 and 2050 for solar panels, wind turbines, electrolysers and batteries is presented in Appendix 8.

Lithium will be a particular focus among strategic raw material for the EU, as its demand will grow strongly to provide the batteries needed for tomorrow's energy system(CARRARA et al., 2023). It is possible, in order to reduce the pressure on lithium, to force the recycling of batteries to a level close to 100% (Breyer et al., 2022), so as to have a circular economy for batteries, as is the case for lead batteries. This may be at the expense of energy consumption and GHG emissions, as in most cases the recycling optimum (the share at which marginal energy consumption for recycling is higher than primary production) is well below 100% (Rochette, 2022). Others propose to extract lithium from the ocean (where lithium is 6000 times more concentrated than on land)(Liu et al., 2020). Deep-sea mining is the subject of much debate, particularly with regard to its impact on marine biodiversity, and some European countries, such as France, have already explained that they will not be mining it (Euronews, 2023b). The development of batteries with new chemistries can also reduce the strain on materials. Na-ion batteries can be used both for stationary storage and for moderate-sized vehicles (260-450 km range). Their main advantage is that they are based on a much more abundant resource, for which there are fewer supply tensions and which is also more cost-effective(Rudola et al., 2023). The energy density of these batteries is still significantly lower than their lithium-ion equivalent, but progress is being made(MITTR, 2023). The fact remains that, like other technologies, it is difficult to accurately predict their ability to scale up.

In addition to lithium, the European Commission mentions the four REEs (neodymium, praseodymium, terbium, and cerium), borates, gallium, natural graphite and cobalt as particularly important strategic raw materials(CARRARA et al., 2023).

Beyond the question of the availability of stocks of the various resources, an extraction, logistics and recycling chain must be designed to meet the flows required for the transition. In fact, the problem is much more one of flow than of stock. (Rochette, 2022).

4.4.2 EROI

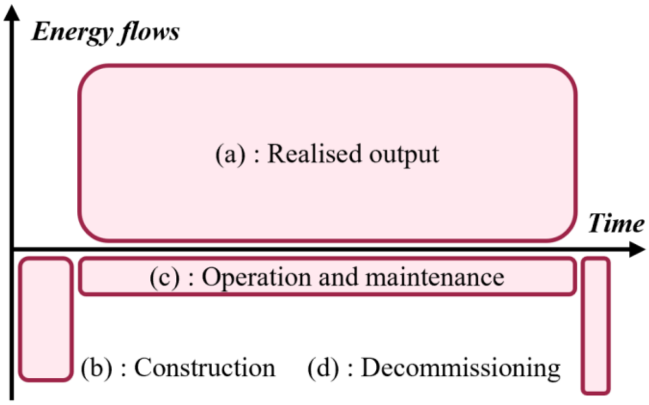


Figure 4-25 EROI of an energy system(Pahud & De Temmerman, 2022).

$$EROIp, POD = \frac{a}{b + c + d} \tag{5.19}$$

The EROI measures the equivalent of a return on investment in an energy system, by expressing the ratio of the potentially recoverable energy of an energy production facility, divided by the energy mobilized for its construction, operation, and end of life (Figure 4-25). Today's energy model is in a transition phase(Pahud & De Temmerman, 2022). The future electricity generation facilities (mainly wind and solar) will be built with the energy facilities of this society in transition, that is to say with fossil energies. The EROI of fossil energies is strongly declining, which has a negative impact on the EROI of VREs. Over the years, the electrification of the system will allow to decrease the losses, and will thus contribute positively to the EROI of VREs(IEA, 2021c).

According to Pahud and De Temmerman (2022), a system composed of VREs and storage has a better EROI than a fossil energy system with CCS. This justifies, from an energy point of view, in the sense of EROI, using fossil fuels to transition to a wind and solar based electricity system. More simply, it means that it is "profitable" to use fossil fuels, fossil transportation, fossil industry, etc. to design a massively electric system. This comparison only serves as a justification if one considers the reduction of greenhouse gas emissions as a necessity, of course.

The EROI calculations for renewables are subject to wide variations, not least because of the scope considered. For example, Ferroni and Hopkirk (2016) give an EROIext of 0.8 for PV in Switzerland, while Raugei et al. (2017), based on the IEA recommendations(Raugei et al., 2016), give an EROIext of 7-8 (EROIext corresponds to a broader scope, taking into account the energy used throughout the supply chain.). In Europe, the southern countries have a higher EROI due to their sunshine. Similar discussions exist for wind power. In contrast, the northern European countries, and in particular the regions near the North Sea and the Baltic Sea, have the highest EROI(Dupont et al., 2018).

The EROI of VREs has increased significantly in recent decades(Diesendorf & Wiedmann, 2020). Using the EROI,POD metric (equation 5.19), Steffen et al. (2018) estimate that over the period 1990-2015, the EROI of solar PV rose from 1 to 9, and that of wind from 12 to 23. The results differ significantly if we consider the EROI of an installation (a wind or PV power plant) or of an industrial sector. In the latter case, the term PROI is used (a graph showing its evolution is presented in Appendix 13).

Including storage in the calculation of the EROI of an energy system tends to lower the latter. Its impact depends very much on the storage technology considered. Indeed, a technology used at low frequency and with low efficiency will have a significant impact on the system's EROI, whereas storage used very frequently and with very good efficiency will have very little effect on the EROI (Diesendorf & Wiedmann, 2020). The lifetime of storage facilities is also an important characteristic. Furthermore, as I have shown, the storage requirements necessary for the deployment of VREs are revised downwards. All this suggests that the EROI issue of a system with a high penetration of VREs coupled with storage does not appear to be a brake on the transition.

4.5 Role of Europe in the transition

Finally, I would like to conclude this analysis with the role that Europe has to play in this electrification.

4.5.1 Cooperation between countries

4.5.1.1 Interdependency

The increase in interconnections allows, as I have shown, to reduce the need for storage and flexibilities, to reduce curtailment, all of which results in considerable technical and economic benefits. However, each country, by building less flexibilities and storage, in order to maximize the use of VREs where the deposit is the best, increases its dependence on imports, and therefore decreases its "electrical independence". Although exchanges are not new, and European countries have already been exchanging for a long time, an increase in interconnections amounts to bequeathing part of their sovereignty to a group of countries. According to RTE (2021), France, for example, will more than double the frequency electricity imports strictly necessary for security of supply in a 100% RES scenario.

However, this increase in inter-state dependence must be put into perspective in relation to current energy dependence, which is characteristic of a mix that is mainly composed of fossil fuels. In 2020, the EU was dependent on imports for 58% of its energy(Lu, 2022). The war in Ukraine has not changed the EU's dependence, but it has reduced the proportion of energy coming from Russia. The electrification of the energy mix therefore generates a very strong decrease in the dependence on imports. For example, France, by switching to a very strongly renewable mix (close to 100% in 2050), can be heavily dependent on only 2% of its total consumption, against about 61% in 2018(RTE, 2021).

Numerous past political conflicts, such as the Gulf Wars and the Yom Kippur War, have profoundly restructured the relationships of influence that the various countries involved had with regard to their energy strategy. As Żuk and Żuk (2022) note, the war on European soil in Ukraine sheds light on 2 energy policy responses, which can sometimes be contradictory. On the one hand, a greater emphasis on the country's energy security, and on the other, the acceleration of the energy transition away from fossil fuels. Expenditure mobilised to deal with possible exogenous crises, such as the search for new fossil deposits or the deployment of new fossil fuel capacities, cannot be used to finance renewable energies. Within European countries, the strategy to be followed may diverge because the interests of all are not the same in the short and medium term. Substituting fossil fuels from Russia is, by definition, much more costly for the countries that rely most on them, such as Germany, Poland and Italy. The trade-off between these two strategic lines is the result of many factors, but it neatly sums up the issues that European countries will have to face in the event of future geopolitical conflicts.

In this context of greater electrical interdependence, electricity transmission networks are among the infrastructures that will play a growing role in the geopolitics of energy. As Europe was reminded in 2022 by the episode of the destruction of Nordstream 2, the challenges of energy transmission infrastructures are not simply a technical matter, but also raise questions of vulnerability and dependence. For example, electricity transmission networks were one of the targets of the war in Ukraine (The Economist, 2023). Thus, delegating part of the electricity production that one wishes to consume to neighbours implies considering the potential tensions that these neighbours could face.

4.5.1.2 Inequalities

Effective transition requires cooperation at the European level, also because the benefits and vulnerabilities of transition are uneven across countries. In their model, Sasse and Trutnevyte (2023) quantify these inequalities in terms of investments/divestitures, electricity prices, employment, GHG emissions, particulate emissions and land use between the different countries in Europe. They find that the benefits of a low-carbon transition are mainly reaped by the northern countries, the Baltics, Germany, Ireland, Scandinavia, and Scotland, due to an improvement in the above-mentioned criteria. On the contrary, according to them, the countries of the Balkans, southern Italy, Portugal, Poland, and Spain will be the most vulnerable to job losses, rising electricity prices and particulate matter, divestment, and land use. Thus, a European policy must consider these inequalities to ensure an effective transition, for example through compensation mechanisms between regions. Such mechanisms already exist in Europe for the energy transition, with the Just Transition Mechanism of the European Union (EuropeanComission, 2020), to help coal mining regions.

4.5.2 Share of key industrial markets for Europe.

The ability to achieve electrification requires an industry capable of building the necessary technologies. I propose to summarise the situation in Europe with regard to the production resources for the main technologies needed for the energy transition.

4.5.2.1 Wind market

Worldwide, the wind energy market is relatively concentrated. In 2020, 96% of wind turbines were produced by 15 companies (Figure 4-27). Europe is an important player in this market. Indeed, 4 European companies, Vestas, Siemens Gamesa, Nordex and Enercon represent 29.7% of the world market in 2020 (WoodMackenzie, 2021). Representing only 18.6% (GWEC, 2022) of the world's demand for wind turbines in 2021, Europe is therefore able to avoid being heavily dependent on other regions of the world for its industrial production of wind turbines. The main elements of the production chain are produced on the territory (Figure 4-26).

Figure 4-26 Market share (%) of wind turbine in 2020 per company (WoodMackenzie, 2021).

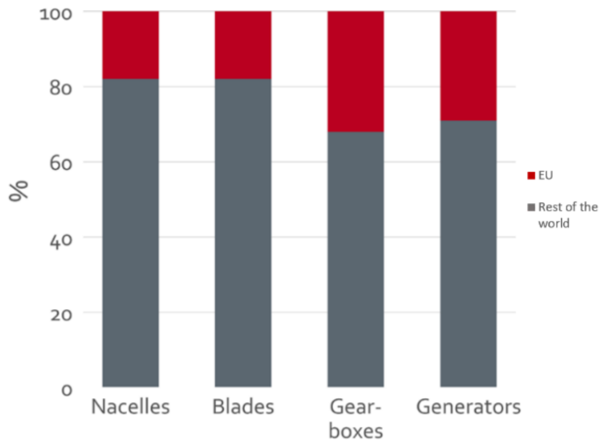


Figure 4-27 Market share (%) of major wind turbine components in the EU (Jansen, 2023).

4.5.2.2 Solar market

Europe, which had been a major photovoltaic producer since the early 1990s, now represents virtually nothing on a global scale, and is entirely dependent on Asia for its supply. The Chinese photovoltaic industry has accelerated rapidly and now occupies a dominant position on the world market. There are many reasons for this development (Huang et al., 2016). Firstly, China's entry into the WTO. Secondly, technology transfers from European countries, which were leaders in the sector at the time, led to the massive development of the PV industry in China. Europeans wanted to take advantage of the large Chinese market, so they helped them install PV systems and contributed to China's rise in skills. Finally, the large European market has encouraged Chinese entrepreneurship, aided by a government setting up extremely advantageous policies for investment in this sector(Huang et al., 2016). Companies have been massively created, developing in parallel the technological level of the country in this field. The Chinese companies have finally flooded the European market with PV at very competitive prices, reducing to nothing the European industry, which was one of the biggest a few years ago (Figure 4-28). Only polysilicon exceeds the few % of market share in EU (Figure 4-29). In this context, European countries cannot rely on their domestic market and must ensure a resilient supply chain.

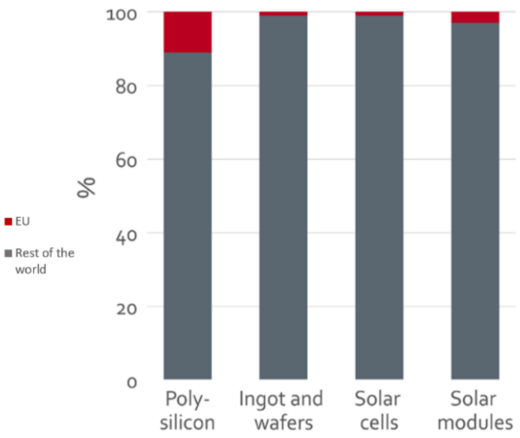


Figure 4-29 Market share of EU by major components (Jansen, 2023).

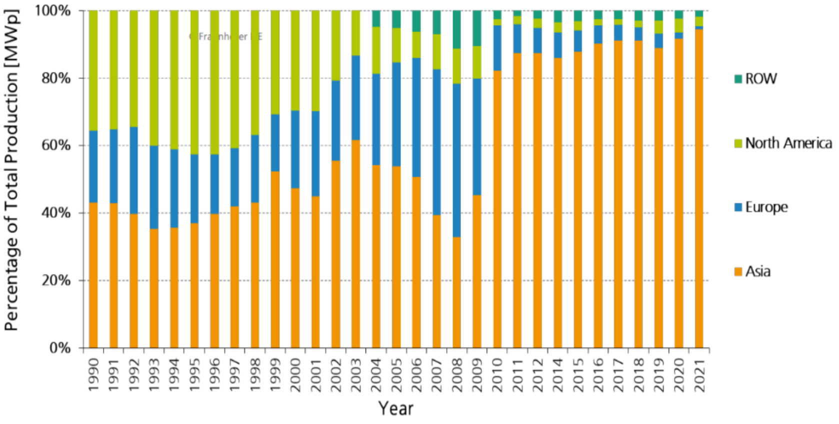


Figure 4-28 PV Module Production by Region 1990-2021 (FraunhoferInstitute, 2023).

4.5.2.3 Battery market

The lithium-ion battery market is still in its infancy, and the EU currently has few battery production facilities in the country. The European Battery Alliance (EBA), launched in 2017, aims to build a battery industry on the continent. By 2025, 20% of the world's lithium-ion batteries should be assembled in Europe (Figure 4-30). In the short term, the EBA's aim is to develop a large part of the battery industry's value chain, beyond assembly, in order to meet the decarbonisation needs of mobility and grid-scale batteries. However, Europe faces a number of structural challenges, including a shortage of 800,000 skilled workers by 2025, and the fact that only 1% of key battery raw materials come from the continent(EBA, 2023).

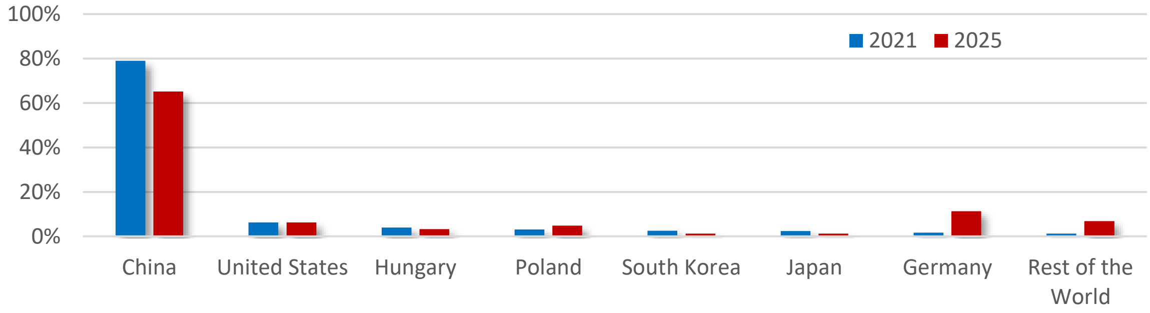


Figure 4-30 Share of the global lithium-ion battery manufacturing capacity in 2021 with a forecast for 2025, by country (in gigawatt hours) (Statista, 2023).

4.5.2.4 Hydrogen market

In the hydrogen market, Europe could have significant manufacturing capacity by 2030 (Figure 4-31). In particular, in the short term, Europe is set to become the leader in terms of PEMs, which, as I mentioned earlier, have considerable advantages for integrating VREs, in particular thanks to their greater flexibility than Alkaline.

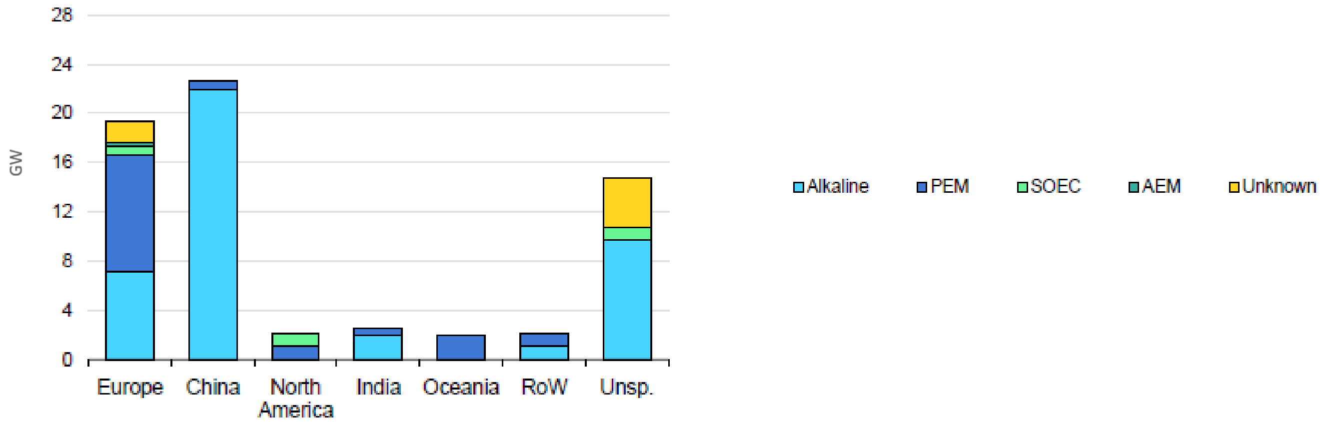


Figure 4-31 Electrolyser manufacturing capacity by region and type in 2030 (IEA, 2022).

4.5.3 Comparison between Europe and other regions

Large-scale deployment of clean technologies requires the ability to mobilize significant levels of investment. Indeed, the various components of tomorrow's electricity mix are highly CAPEX intensive. Achieving carbon neutrality will therefore require redefining many market mechanisms, business models and development policies. In this context, the Inflation Reduction ACT applied to the US appears to be an interesting avenue, although its implications for the global economy go far beyond the scope of this thesis. Indeed, NREL (2023b) estimates that the Act (in addition to the BIL) will increase the share of low-carbon electricity from 41% in 2022 to between 71-90% in 2030, which corresponds to an increase of 25 to 38% compared to the case where the Act would not have been enacted. This federal law, by delivering a mix of tax incentives, loan guarantees and grants, is expected to have a significant impact in just few years(McKinsey, 2022).

This policy will have an important impact on the EU and the Net Zero Industry Act aims to be a response to develop green industry in Europe. Jansen (2023) advocates a coherent response at European level, focusing mainly on technologies where Europe has a card to play (hydrogen and batteries) and developing common financing instruments to engage all EU countries.

5 Conclusion

As I have shown in this work, the electrification of processes, and more broadly of the energy we consume, is at the heart of the European decarbonisation strategy. Over and above the reduction in final energy consumption that this enables, a very large number of sectors of the economy can be decarbonised solely through this electrification. However, awareness of the need for electrification is only fairly recent in Europe, and more widely around the world. Today, in their national scenarios, most EU countries are forecasting an increase in electricity consumption of more than 50% by 2050, with some exceeding +150%. At EU level, electricity consumption is likely to more than double by the same date. This sudden increase reflects the sharp fall in the price of VREs and batteries, which will enable electrification to take place at a much lower cost than was projected in the European energy transition scenarios proposed in the literature. In the early 2020s, this fall in costs seems to be the start of a revolution in the way we see the future energy mix.

In fact, the fall in the price of VREs, which is particularly significant for PV, is creating new prospects for the structure of the energy system. Batteries, which synergise in a special way with PV, will come to play an increasingly important role in the management of the electricity grid. This greater accessibility of solar and wind power is changing the structure of storage needs, compared with what they might have been in the early 2010s. Indeed, daily storage seems to be becoming the cornerstone of tomorrow's storage system, while seasonal storage does not actually seem to be necessary in Europe until the penetration rate of renewable energy is very high, at around 80%. The scenarios based, at European level, on several hundred TWh of storage capacity, characteristic of the literature of the early 2010s, greatly overestimated these needs. More recent studies, which include more complexity and more credible input data in their models (more interconnection, possibility of curtailment, daily/seasonal storage duality, sector coupling, reasonable cost for VRE) suggest that the order of magnitude of storage capacity in a scenario with a very high penetration rate (>80%) of renewables is in the order of tens of TWh.

This electrification through the massive development of VREs gives rise to technical difficulties in relation to their intrinsic characteristics. To overcome their intermittency and manage the supply-demand balance at all times, it is essential to make the most of the different wind and solar potentials present on the European continent. The massive development of the grids, which is sometimes overlooked, is central to the transition scenarios, since they call for an increase in grid capacity by several factors. This development of interconnections, which in particular enables generation resources to be pooled on a continental scale, is particularly interesting in terms of dealing with the Dunkelflaute phenomena that exist in Europe. Although these are very problematic in the case of autarkic countries, because they are potentially both intense and long-lasting, they do not affect all European countries at the same time. Thus, while the occurrence of Dunkelflaute periods of more than 2 days is not negligible at national level, the duration of such events at European level almost never exceeds 20 hours. In short, the worst Dunkelflaute events at European level correspond to a relatively recurrent situation for an autarkic country. This argues in favour of pooling VRE resources as widely as possible, so as to make the European electricity system more resilient. This pooling at European level applies to the entire electrification strategy. In fact, many economic mechanisms need to be re-examined, particularly as many key links in the chain, such as various storage and transmission systems, which are essential to the development of VRE, sometimes do not correspond to profitable investments.

Tomorrow's electricity system, which will be heavily dominated by VREs, will in any case require greater flexibility. Certain heavy industries that depend on hydrogen as part of their decarbonisation strategies can benefit from this increase in flexibility. By building overcapacity in their electrolysers, they can stand down when demand peaks and produce when production peaks, which are characteristic of low prices. Considering the steel, ammonia and methanol industries, I estimate that it is possible, over one year and at EU level, to have 166 TWh of flexibility in electricity consumption (electrolysers + other processes), based on the IEA's NZE projections. These flexibilities will play an increasing role as the penetration rate of VRE increases. Other flexibilities discussed in this work include geothermal, hydro, biomethane and nuclear. It is likely that a combination of all these flexibilities, in proportions yet to be defined, will be the most effective way of supporting the development of VRE.

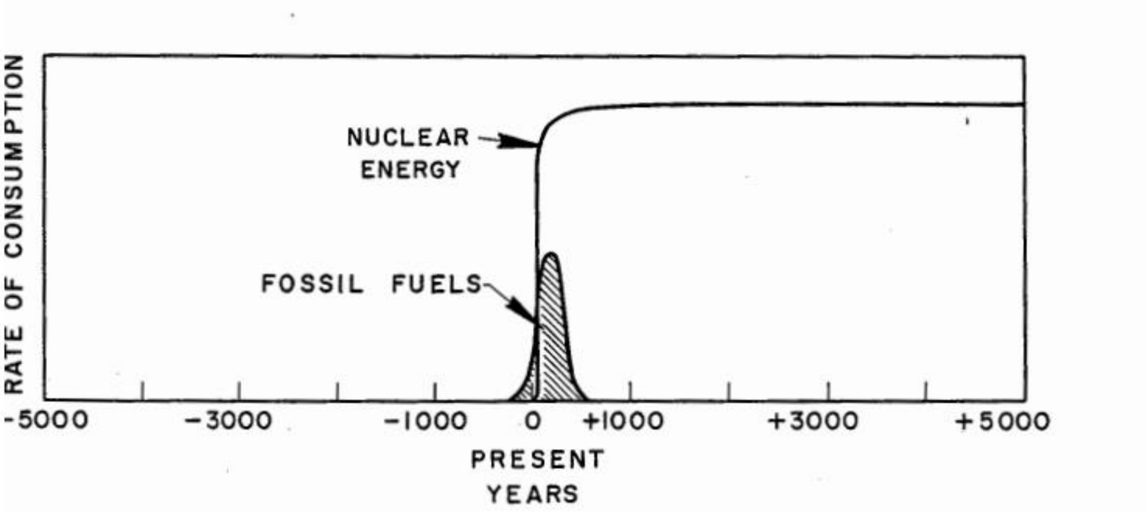
In addition to the greater hourly variability that needs to be satisfied, VREs also pose new challenges in terms of frequency management, in particular by reducing inertia in the power system. The development of VREs since the early 2000s, although effectively reducing the inertia of the power system, does not seem to be leading to a reduction in the robustness of the system in Europe. Technologies such as SCs and grid forming inverters, coupled with storage resources, appear to be theoretically capable of stabilising the grid, and their implementation in the near future will make it possible to quantify this difficulty.

Finally, this transition to a much more electric model will greatly reduce the extraction of materials in general, but will on the other hand massively increase the demand for certain metals, especially over an unprecedented timescale. The EROI of VREs, while still lower than some other energy production technologies, is increasing, and the reduction of fossil fuels in the European energy mix will have a positive effect on the EROI of VREs.

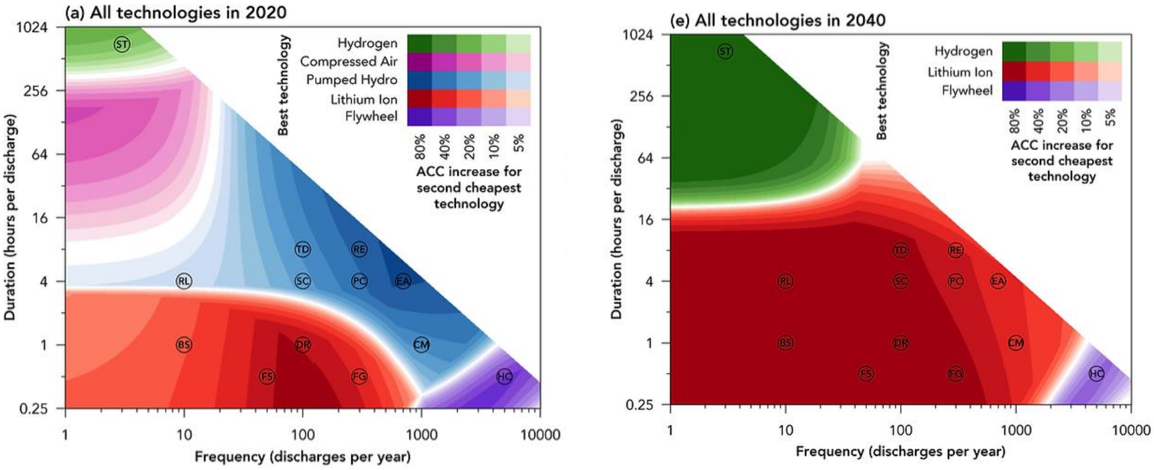
All the difficulties presented above regarding the massive deployment of VRE argue in favour of a strategy that is as coherent and integrated as possible at continental level. Although creating greater dependence between European countries, the electrification of the energy mix considerably reduces dependence on fossil fuel producing countries, enabling Europe to massively reduce the potential exogenous constraints that can result from geopolitical tensions.

The massive development of VRE in Europe, given the low short-term constraints that such deployment implies, is a no-regrets path, and once articulated with a coherent energy transition strategy enabling its integration, the main means of complying with the Paris agreements.

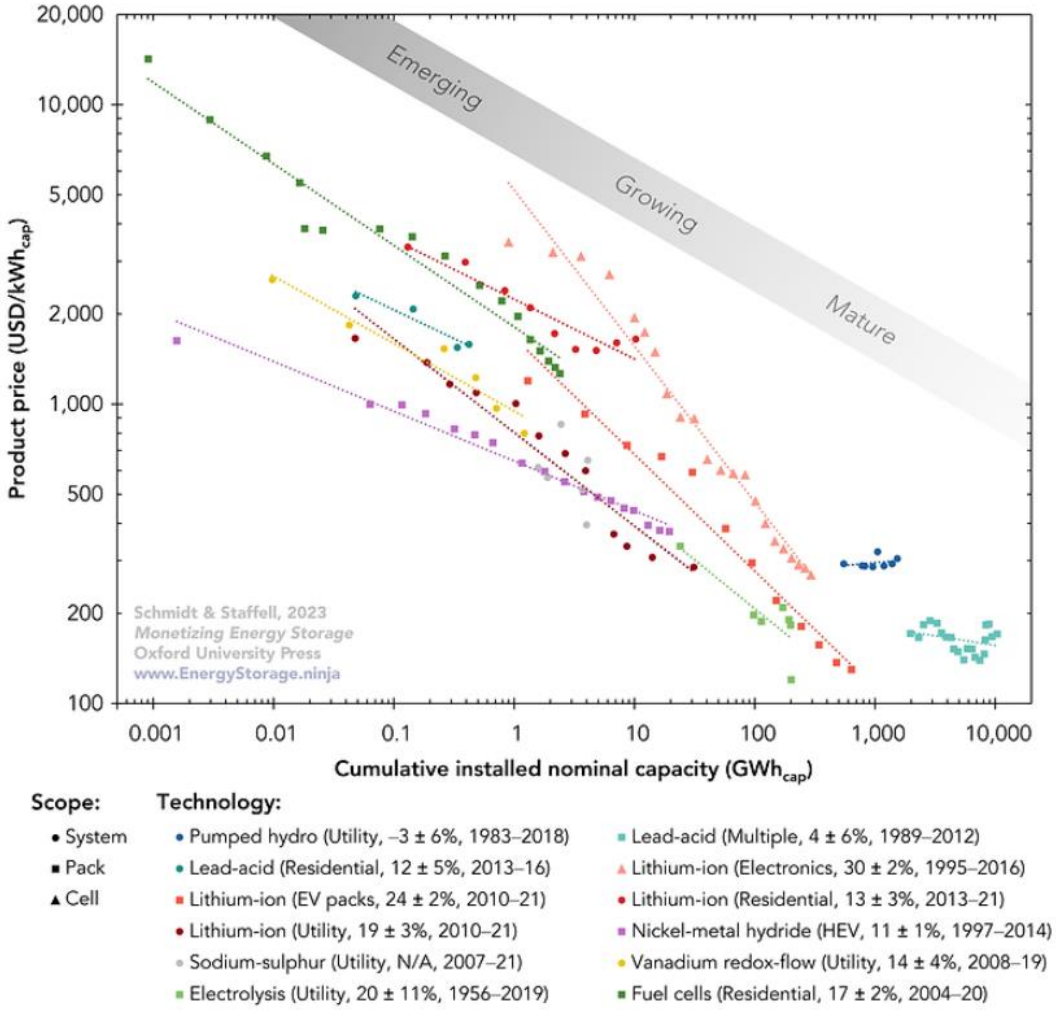
6 Appendix



Appendix 1 Relative magnitudes of possible fossils fuels and nuclear energy consumption according to Hubbert (1956).



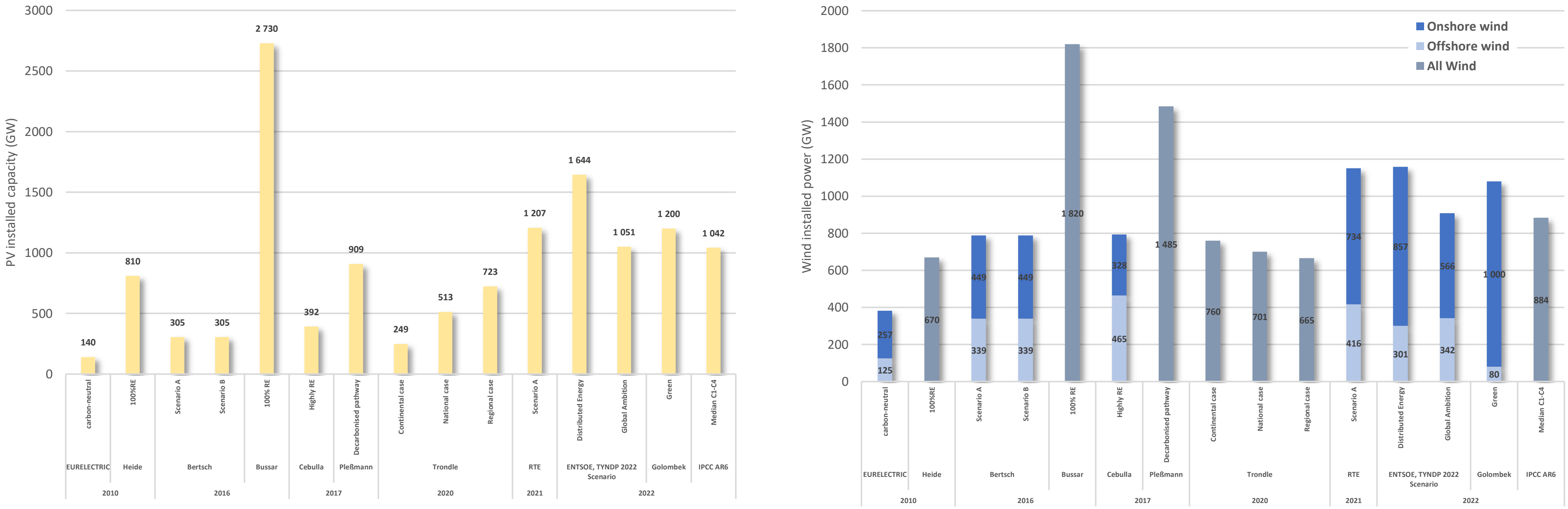
Appendix 2 Storage technologies with lowest ACC relative to their annual cycle requirements and discharge duration (Schmidt, 2023b).



Appendix 3 Price reduction of different storage technologies (Schmidt, 2023b).

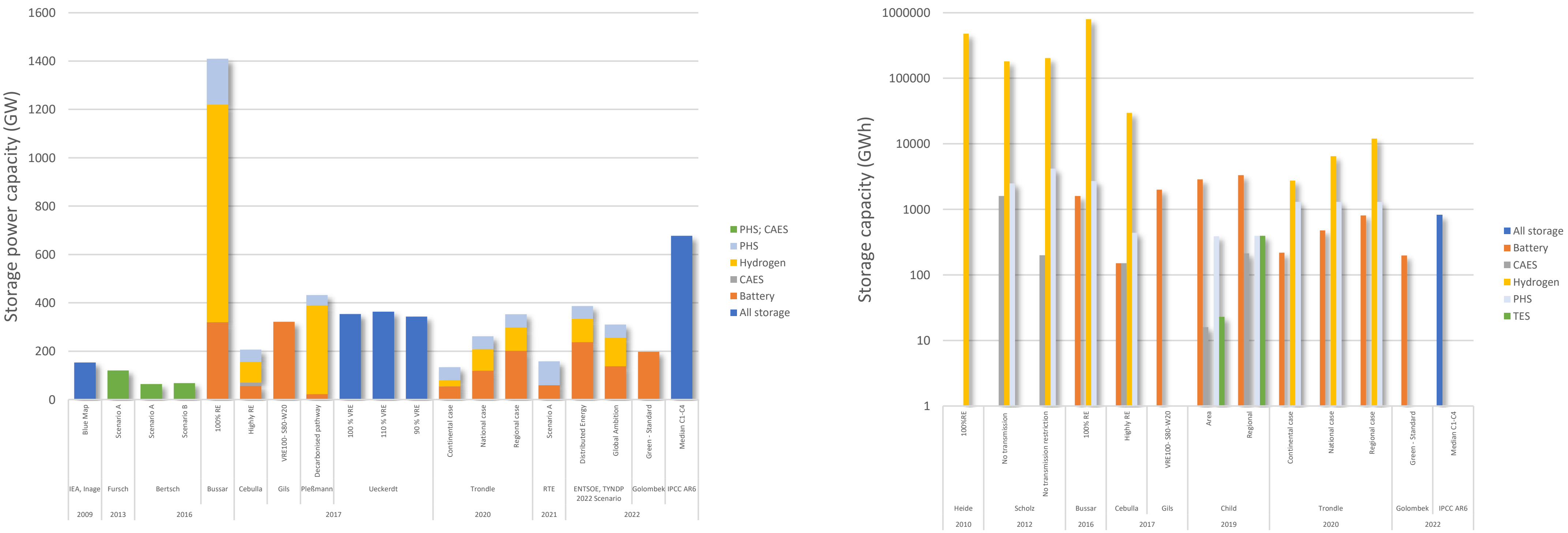
Archetype	Application	Description	Alternative name
1. Frequency regulation (FG)	Frequency regulation	Automatically correct the continuous changes in supply or demand within the shortest market interval	Frequency control, Automatic generation control
	Renewables smoothing	Smoothen output from variable supply resources when generation is out of line with short-term forecasts	Correcting forecasting inaccuracy
	Power quality	Condition frequency and voltage of power supply for sensitive loads in unstable grids	
2. Frequency response (FS)	Contingency reserve	Automatically stabilize frequency after unexpected, rare, instantaneous change in supply or demand	Primary / Secondary / Tertiary reserve / response, Frequency response, Non-spinning reserve, Spinning reserve, Replacement reserve
	Ramping reserve	Automatically stabilize frequency after unexpected, rare, non-instantaneous change in supply or demand	
	Inertia services	Instantaneous and inherent active power response, not dependant on measurement, to rapid changes in frequency after frequency disturbance	
3. Black start (BS)	Black start	Restore power plant operations after network outage without external power supply	
4. Peak capacity (PC)	Peak capacity	Ensure availability of sufficient generation capacity at all times	Electric supply capacity, System capacity
5. Seasonal storage (ST)	Seasonal storage	Compensate longer-term supply disruption or seasonal variability in supply and demand	
6. Power reliability (PR)	Power reliability	Fill regular, sustained gap between supply and demand (e.g. microgrid)	Off-grid, Microgrid
	Backup power	Fill rare, unexpected, sustained gap between supply and demand (e.g. total loss of power from grid)	Home backup, Emergency supply, Resiliency
7. Renewables integration (RE)	Renewables firming	Storing large amounts of excess renewable electricity supply to be used at a later time	Variable resource integration, Renewable generation shifting
8. Congestion management (CM)	Congestion relief	Avoid risk of overloading existing infrastructure that could lead to re-dispatch and local price differences	Network efficiency
	Load following	Maintain balance between supply and demand, while allowing generators to operate at optimal capacity	Balancing reserves
9. T&D deferral (TD)	Transmission upgrade deferral	Deferral, reduction or avoidance of transmission and/or distribution network upgrades when peak power flows exceed existing capacity	Network efficiency, Transmission support, Distribution substation
	Distribution upgrade deferral		
10. Demand reduction (DR)	Demand charge reduction	Reduce demand supplied by the network during periods of highest network charges	Peak reduction, Demand shifting, Retail demand charges
11. Self-consumption (SC)	Renewable energy self-consumption	Increase self-consumption of energy produced by non-dispatchable distributed generation	
12. Energy arbitrage (EA)	Renewables arbitrage	Storing energy produced by variable renewable plants when prices are low to sell when prices are high	
	Wholesale arbitrage	Purchase power in low-price periods and sell in high-price periods on the wholesale market	Electric energy time-shift, Price arbitrage, Time-shifting
	Retail arbitrage	Purchase power in low-price periods and sell in high price periods on the retail market	End-consumer arbitrage
	Time-of-use bill management	Purchase power in low-price periods and use during high-price periods	Retail energy time-shift, Energy management, ToU charges
13. Voltage support (VS)	Voltage support	Maintain voltage levels across networks via supplying or absorbing reactive power. Note that as no active power is drawn from the device, there are no cycle or discharge duration requirements.	VAR support

Appendix 4 Archetypical applications of storage (Schmidt, 2023b).



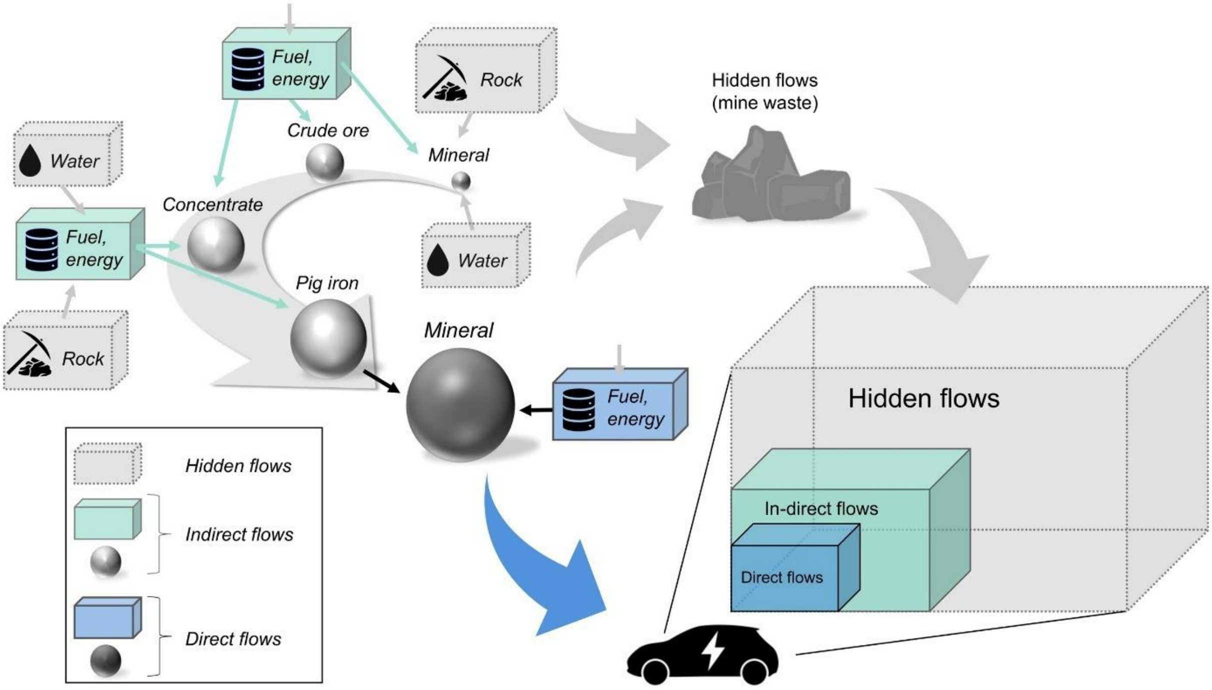
Appendix 5 Wind and PV installed capacity of different studies according to their publication years in 2050.

Note : Scenarios publishing complete public data are shown. The value corresponding to the IPCC corresponds to the median scenario of all the C1 to C4 scenarios (<2°C) used for the AR6.

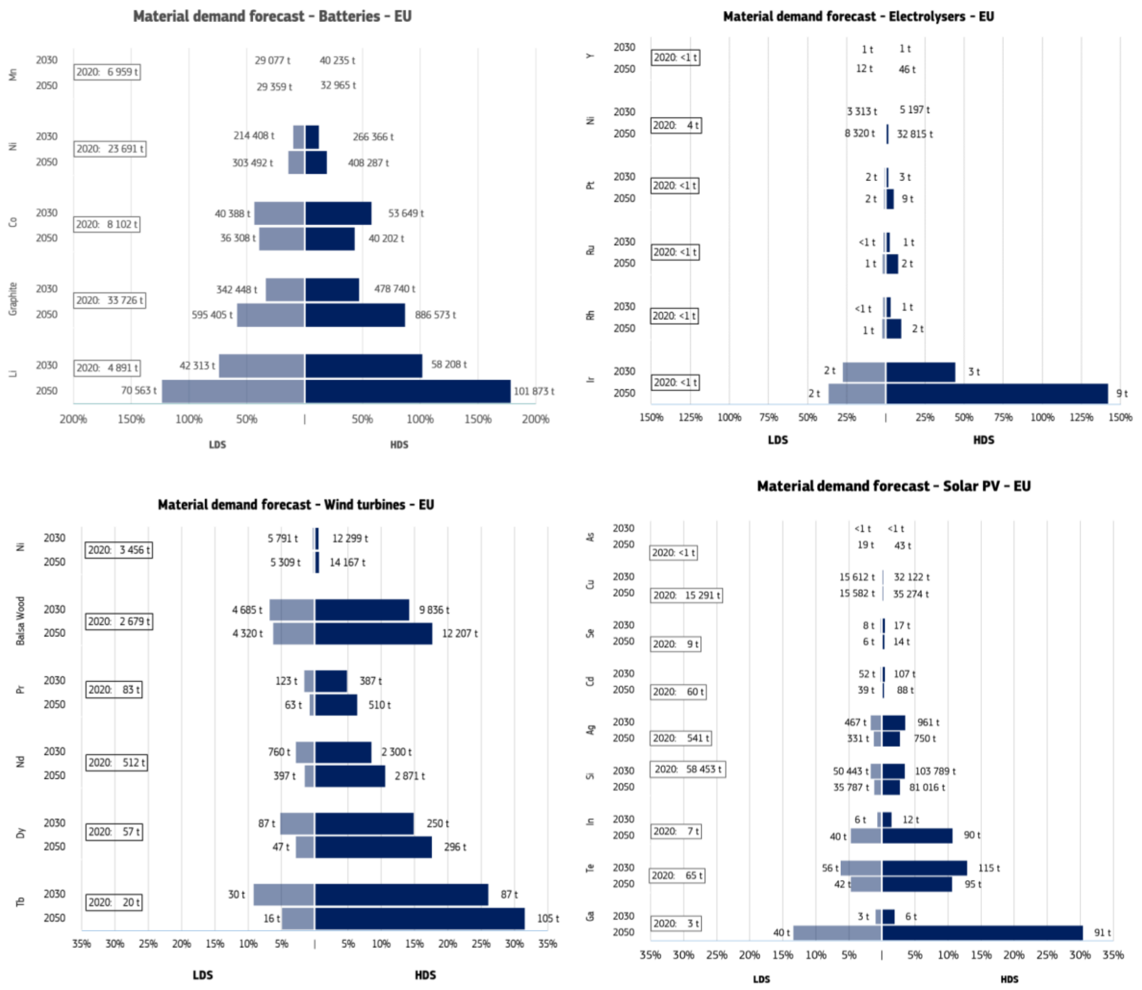


Appendix 6 Storage power capacity and storage capacity of different studies according to their publication years and technologies in 2050.

Note : The data below correspond to the available and usable data, which explains why not all studies are represented in the two graphs. This is due firstly to the fact that, depending on the study, the data is available in several units: sometimes in installed capacity (GW), sometimes in storage capacity (GWh), and sometimes in output over the year (GWh). It even happens that within the same study, different storage technologies are defined by different indicators. For example, RTE, Child and Golombek have hydrogen in their scenarios, but this could not be included in the above graphs due to lack of information. The value corresponding to the IPCC corresponds to the median scenario of all the C1 to C4 scenarios (<2°C) used for the AR6.



Appendix 7 Conceptual framework of Total Material Requirement (Watari et al., 2019).



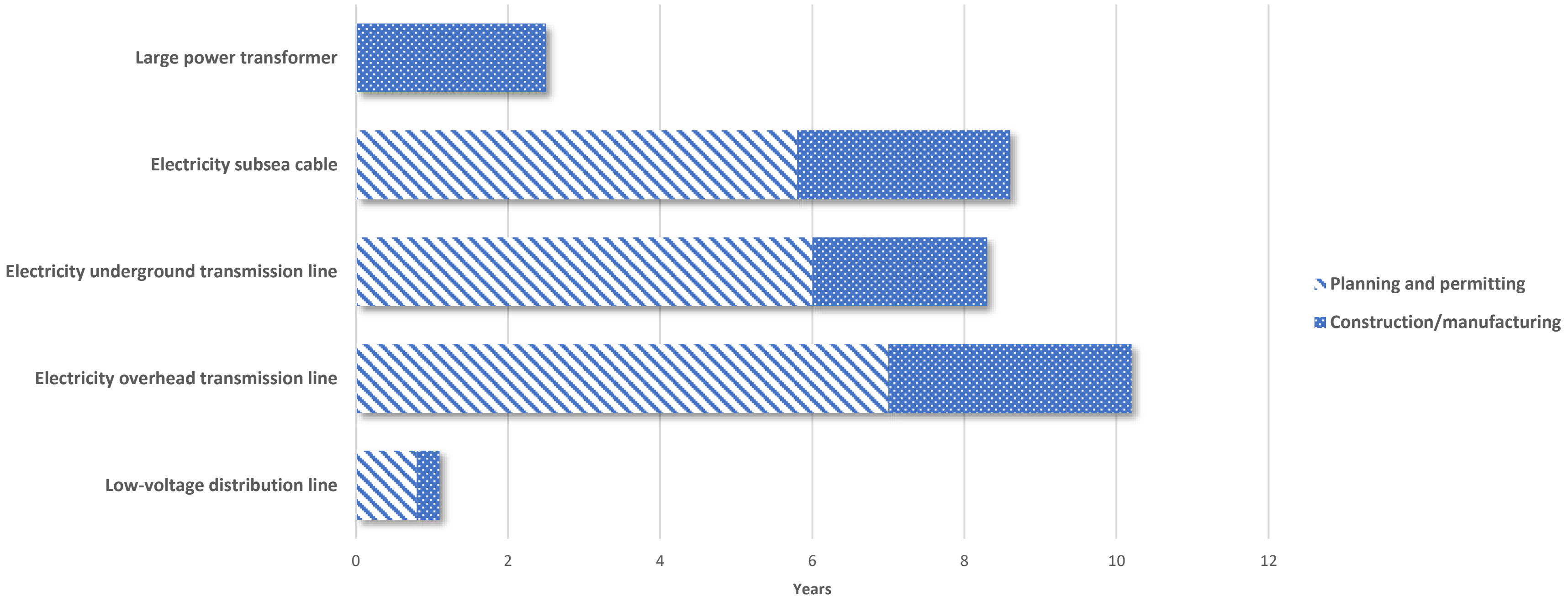
Material demand forecast - Batteries - EU

Material demand forecast - Electrolysers - EU

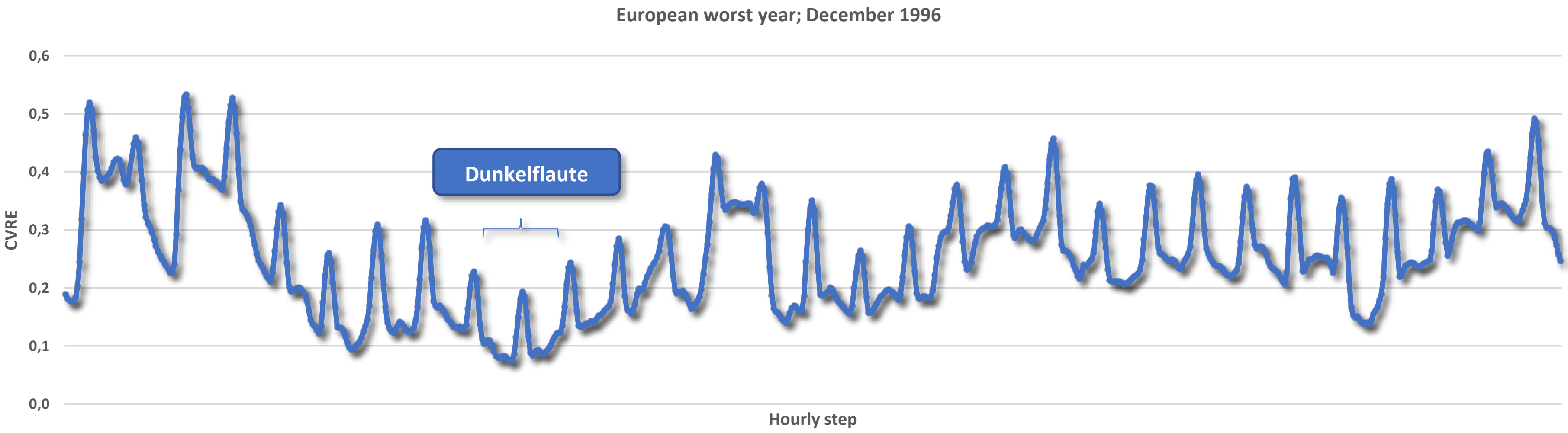
Material demand forecast - Wind turbines - EU

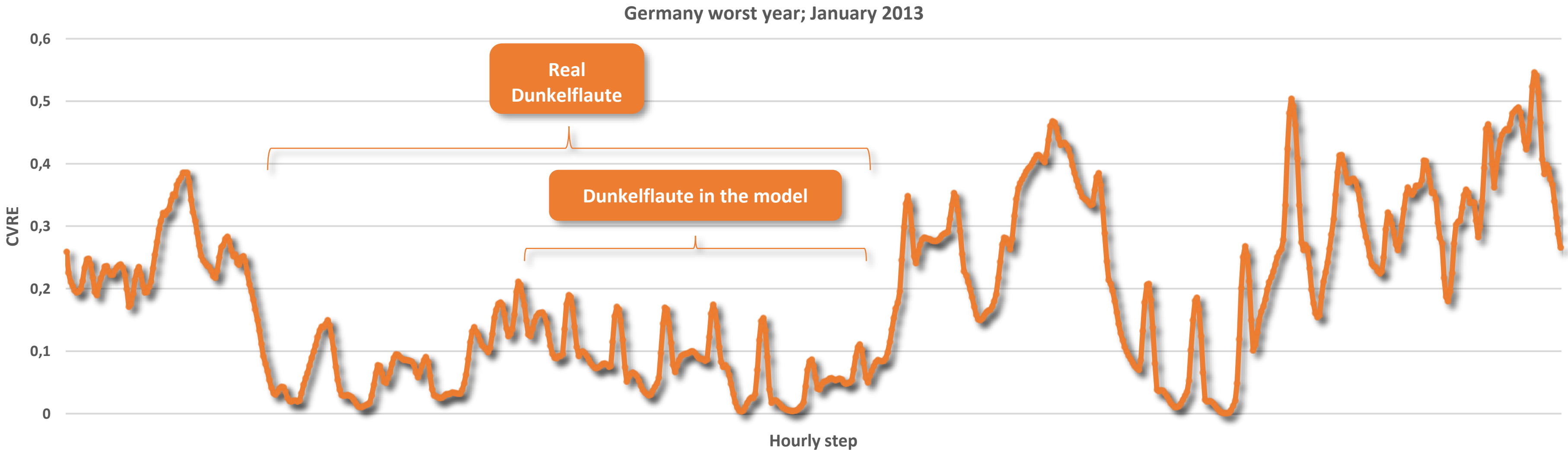
Material demand forecast - Solar PV - EU

Appendix 8 Material demand forecast for the four principal technologies of the energy transition in the EU(LDS : Low Demand Scenario; HDS: High Demand Scenario) (CARRARA et al., 2023).

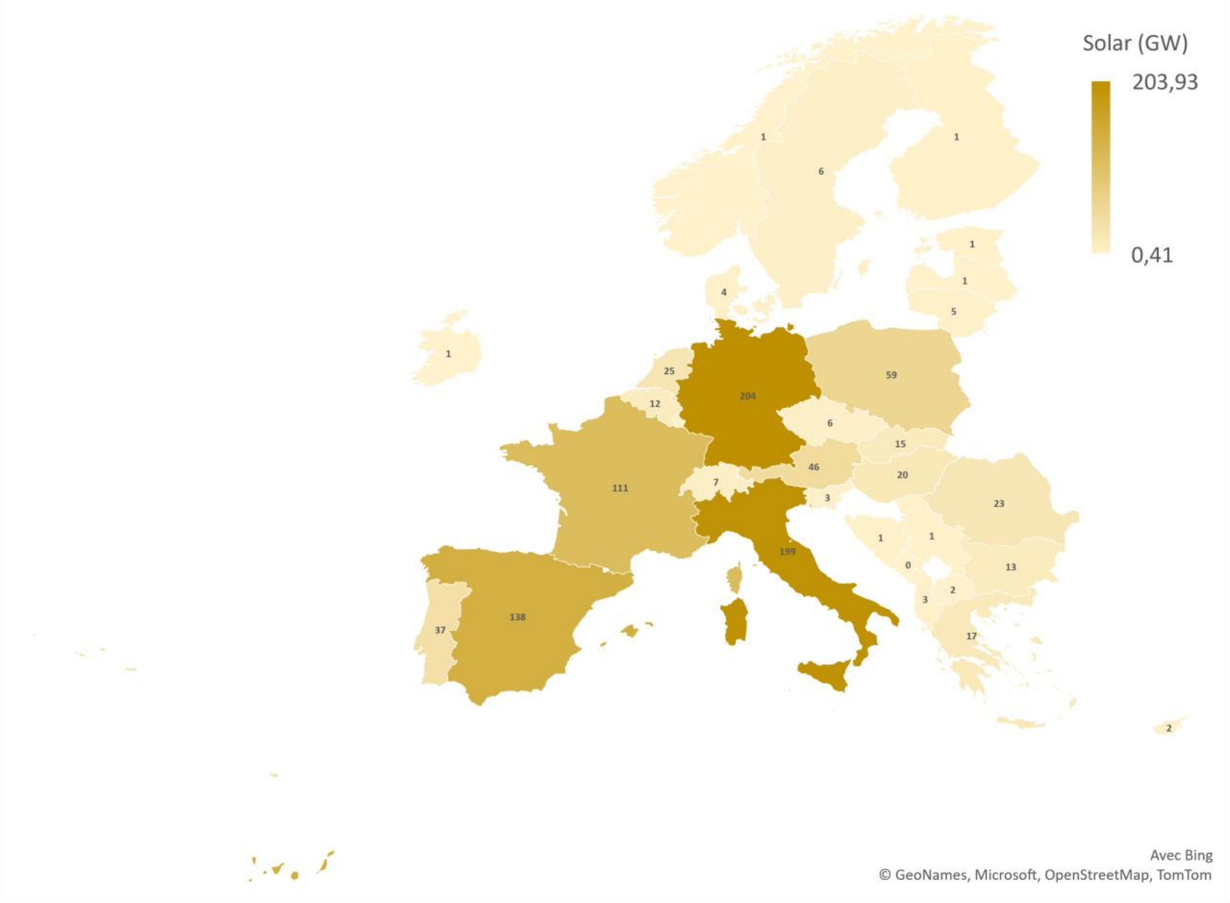


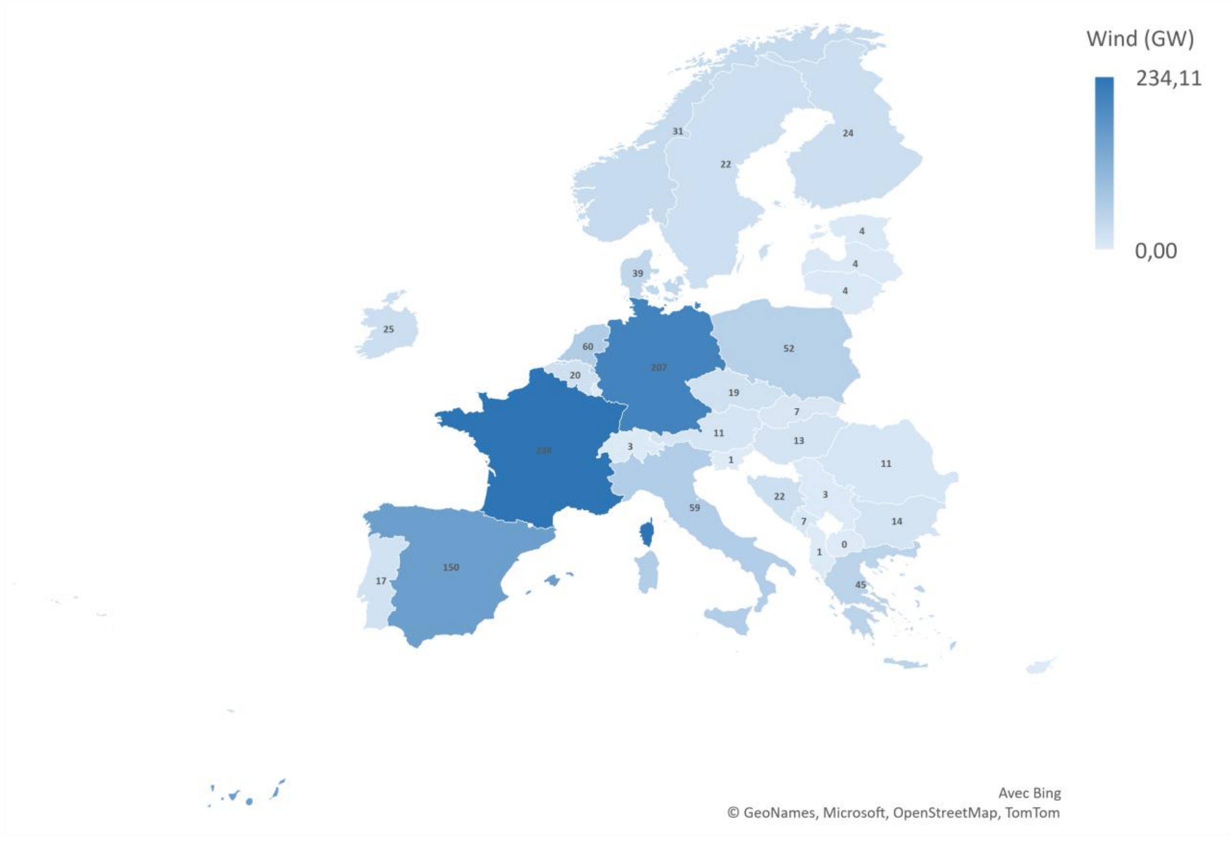
Appendix 9 Average lead times to build new electricity grid assets in Europe 2010-2021 (IEA, 2023).





Appendix 10 Month of the worst year for Europe and Germany





Appendix 11 Power capacity of solar (up) and wind (down) in GW, taken from the Ember (2022) scenario. The model only uses relative data (relative share of wind and solar in the country's VRE mix, and relative share of wind or solar for the country compared to the aggregated power at European level).

Appendix 12 Average capacity factor from Pfenninger and Staffell (2016); Staffell and Pfenninger (2016)

Note : Wind is aggregated between offshore and onshore

	PV	Wind
Albania	16%	
Austria	14%	26%
Bosnia	15%	
Belgium	12%	33%
Bulgaria	15%	23%
Switzerland	15%	18%
Cyprus	18%	13%
Czech Republic	13%	22%
Germany	12%	29%
Denmark	11%	33%
Estonia	11%	31%
Spain	17%	40%
Finland	10%	34%
France	14%	34%
Greece	16%	41%
Crotia	14%	14%
Hungary	14%	25%
Ireland	11%	37%
Italy	16%	20%
Lithuania	11%	34%
Luxembourg	13%	35%
Latvia	11%	25%
Montenegro	16%	
Macedonia	15%	11%
Malta	17%	
Netherlands	12%	30%
Norway	10%	41%
Poland	12%	30%
Portugal	17%	44%
Romania	14%	24%
Serbia	15%	
Sweden	10%	40%
Slovenia	14%	9%
Slovakia	14%	15%
Great Britain	11%	40%

Appendix 13 PROI (industry-scale EROI) of Wind and PV in relation to facility scale EROI and industry growth rate (% per year)(Carbajales-Dale, 2019).

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