European Power Sovereignty through Renewables by 2030

A Meta-Analysis Commissioned by

AQUILA
GROUP

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Note:

With regard to the data on electricity and energy consumption in Europe discussed in the report, the attentive reader will not fail to notice that minor inconsistencies occur in some cases. This is due to the fact that data sources sometimes provide different entries. This is especially true when information is communicated from sectors, like wind, solar, or hydropower business. International databases, on the other hand, often enter data with a delay. In addition, differences arise when data is provided for the EU27 or Europe as a whole. Wherever possible, the differences are also referred to in the text to ensure overall coherence.

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Foreword by Aquila Group

Aquila Group is generating and managing essential investments. To us, essential assets are anything related to expanding or rebuilding the world's infrastructure in a sustainable way. Clean energy has played a key role in our activities since 2006. We are developing and operating an asset fleet of approx. 21 gigawatts in solar PV, onshore wind, hydropower, and battery storage systems. Today, clean energy is the cheapest, most sovereign, and only energy resource able to solve the climate problems that the world is facing. In the debate on the energy transition, we stand for pragmatism and fact-driven action.

The geopolitical events of the past year have changed European energy markets like no other event in the past 50 years. For the first time since the oil crisis in the 1970s, the public has become aware of the importance and value of energy supply. It was previously taken for granted, something that would always be available, but today we all realize that this availability is the basis for our economic prosperity and social well-being.

Our strong belief is that using complementary European resources (e.g. sun in the south, wind in the north), together with a consolidated grid, can create a combined European energy system that would be sufficient to cater for most of Europe’s energy demand. This system would enable Europe to achieve energy sovereignty and make us mostly independent from imports. We would therefore enjoy one of the cheapest energy cost bases in the world, and thus strengthen Europe’s competitiveness globally. Our ambitious climate change targets would be more realistic with a unified European energy system, as a way to unify Europe socially and politically, and thus strengthen the EU.

This study titled "European Power Sovereignty through Renewables by 2030" has been carried out by a group of well-established independent authors in the field of renewable energy, energy markets and environmental assessment, and led by researchers of the Potsdam Institute for Climate Impact Research (PIK), with the intention to give it the utmost credibility from a research perspective.

For Europe, the current crisis is a once-in-a-lifetime opportunity, and Aquila Group initiated this study with the motivation to analyze the opportunities and prove that Europe already has the resources available to tackle this today. Our aim is to provide research-based recommendations to decision makers going forward.

Having operated in the field for more than 15 years, we are aware of the challenges of such an undertaking. Nevertheless, we would like to formulate this ambitious goal because it takes big goals to achieve big things. And even though much may not be realized, all the measures mentioned in the study are possible. This does not require new technological breakthroughs. We have the technology now, we have the financial resources, and if we can also formulate a common will, there is much to be achieved.

As an investor, we are always guided by the return on investment. With investments of 140 billion euros per year until 2030 in clean energy solutions, we can create an energy system that subsequently produces stable and low prices that are attractive compared to the global market. The realized return of these investments will also be extremely high compared to all alternatives, without even considering the ecological and sovereign safety advantages of clean energy investments. In comparison, just consider that last year in Europe we spent an additional 792 billion euros just to maintain the status quo system to protect consumers from the effects of the energy crisis initiated by Russia's invasion of Ukraine. Therefore, the savings and returns from clean energy investments are compelling.

With this study, Aquila Group wants to provide a full picture of this unique opportunity of "European Power Sovereignty through Renewables by 2030". The intention is to encourage decision makers, politicians, citizens as well as prosumers and other stakeholders, to view renewables as a solution for an integrated and sovereign Europe. Aquila Group would like to initiate critical thinking and the engagement of all stakeholders in these processes, since all are key players in the success of the energy transformation. I am optimistic that with this study and the recommendations therein, we can make a valuable contribution to an objective discussion.

As a market participant, Aquila Group views every suggestion or recommendation towards Europe's power sovereignty also in terms of economic viability and sustainability. Thus, I also would like to point out that Aquila Group entirely distances itself from any dogmatism or radical theories. That is why this study is independent, fact-driven, and research-based.

I would like to thank all the authors and support staff who contributed to the preparation of this study, especially Prof. Jürgen Kropp and Prof. John Schellnhuber for their dedication to this project from the very beginning. In particular, their great expertise and always open minds were extremely important and helpful in placing the study on a solid foundation.

Hamburg, September 2023

Roman Rosslenbroich

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List of Abbreviations

bcm	billion m^3
°C	degree Celsius
BAT	Best Available Technology
BEV	Battery Electric Vehicles
CAES	Compressed air energy storage
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CC	combined cycle
CCTS	Carbon Capture, Transport and Storage
CHP	Combined heat and power
CO_2	Carbon Dioxide
DSM	Demand side management
EEX	European Energy Exchange
EEZ	Exclusive Economic Zone
EJ	Exajoule = 277.8 TWh
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSO-G	European Network of Transmission System Operators for Gas
E/P	Energy to power ratio
ETS	Emission Trading Scheme
EU	European Union
FSS	Flywheel Storage Systems
GHG	Greenhouse gases
HVAC	High Voltage/Alternate Current
HVDC	High Voltage/Directed Current
IPCEI	Important Project of Common European Interest
IRA	Inflation Reduction Act
kWp	Kilo-Watt Peak
kWh/m^2	Kilo-Watt hours per square meter
LCOE	Levelized Costs of Energy
LULUCF	Land Use, Land Use Change & Forestry
m/s^2	Meter per second (speed)
MECEI	Mediterranean Electricity and Climate Change Forum
MENA	Middle East and North Africa
Mt	Mega-Tons (10^6)
MW	Mega-Watt (10^6)
NSCOGI	North Seas Countries Offshore Grid Initiative
OC	Open cycle
PEF	Pentalateral Energy Forum
PtG	Power to Gas (also PtX, if X covers a broader range of options)
PV	Photovoltaics
RES	Renewable Energy Sources
RET	Renewable Energy Technology
TWh	Terra-Watt hours = 0.0036 EJ
xkm	with x=p person; t ton; v vehicle km
ZEV	Zero Emission Vehicle

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Executive Summary

The transformation of energy systems towards sustainability has to happen at all scales, considering aspects as well as seizing opportunities of local, regional and global character, respectively, within a holistic strategy. Such a strategy is necessary for meeting the unprecedented challenge of anthropogenic global warming, but also for establishing affordable energy security in a rapidly changing world. The importance of geopolitical considerations is woefully demonstrated by the current energy markets turbulences as caused by Russia’s assault on the Ukraine.

The focus of our study is on power supply and demand in Europe, led by the cardinal question whether continental electrical self-sufficiency can be achieved in a fully sustainable way by 2030. To be crystal-clear, **European regenerative power sovereignty** means that **(i) no electricity needs to be imported** from outside the continent at no point in time for directly satisfying the ongoing power demand; **(ii) no energy resources for conversion into power need to be imported** from outside Europe; and **(iii) no continental fossil fuels need to be employed**. In other words, the aim is to power Europe entirely from its own renewable energy sources from 2030 on.

What is the present state of play with respect to these three criteria?

- The power sector in the narrow sense is already self-sufficient, as electricity is mainly imported and exported within the European Union (EU27) and between the European and associated countries (cf. Table 4.4).
- Although 38% of the electricity sector in Europe was based on renewable energy sources in 2022, slightly more than 40% of the electricity in Europe is still be produced on the basis of fossil energy and a further 22% is provided by nuclear energy. In this respect, there is an indirect dependency. The fossil energy source is predominantly gas, of which about 50% on average in Europe came from Russia until 2022.
- The dependence of the European power sector on fossil energy has even increased due to the nuclear phase-out after 2022 (cf. Table 8.1).
- The previous growth rates in the RE sector are not sufficient to achieve the defined self-sufficiency targets in the power sector by 2030.

What is the present state of play with respect to the entire energy system?

- The European energy system is characterised by the fact that considerable amounts of primary energy from fossil resources are used for the production of power, heat and to fuel vehicles, which must be substituted for true sustainability (electrification).
- Nearby resources have not yet been used or have been used to a negligible extent, e.g. the provision of thermal energy for building heating from shallow geothermal energy, which is available almost everywhere on a large scale.
- The energy storage capacities to compensate for fluctuations and the necessary network infrastructure are still insufficient.

Intermediate conclusion

- Strategies urgently need to be developed on how to reduce the fossil share of primary energy quickly and efficiently. Waiting for better technological solutions is not an option, as this will undoubtedly cause the necessary energy transition to fall behind.

- Although technological innovations are expected to reduce electricity consumption in the long term, this dampening can also be optimised through consumption changes, e.g. smart mobility concepts, sustainable building materials, etc.
- Consistent use of geothermal resources would also increase the flexibility of the energy sector, as these sources do not fluctuate and thus less energy could be required for electrification.
- Studies show that European integration delivers benefits for all community partners and, in contrast, particular interests lead to further costs. Therefore, an integrated European energy system must be advanced.
- The European energy system must be viewed in an integrated manner, i.e. framework planning is needed at the European level. The reason for this is the manifold interdependencies, which could counteract national/regional activities.

What is the technical potential for regenerative power supply across Europe?

- The technical potential for the provision of renewable energy is enormous and regionally diverse. The potential for wind and solar alone amounts to approx. 200,000 TWh/yr. If competing land uses are taken into account, the available area drops to less than 10%, but it can still generate about 15,000 TWh of electricity, which is equivalent to the European (EU) primary energy demand in 2021 (Table 8.1). If one would install only PV modules on existing rooftops in Europe still approx. 4,000 TWh can be produced, which is equivalent approximately with the EU27 power demand in 2030.
- Geothermal resources, although available almost everywhere, are hardly used at all or only to a small extent (e.g. 4% for final energy demand). Yet it would be possible to provide heat for 25% of all citizens in Europe. The cost of heat supply would be lower as the cost of gas supply. In addition, about 10% of the electricity demand in Europe could be met by geothermal energy, but there are only 3 GW of installed capacity in Europe. Geothermal energy is also interesting from the perspective of supply flexibility. The size of the investment market in Europe in 2050 (supply and demand) could be worth US$ 160-210 billion/year.
- Other energy sources, such as wave power plants or concentrated solar power, do not yet play a role in Europe. The same applies to the use of biomass for electricity generation, which must be viewed very critically, because, e.g. wood as a fuel is too valuable for energy use.

How will the continental power demand develop until 2030 and beyond?

- The European electricity sector can be independent of fossil resources by 2030, although the entire energy system will not achieve this until 2040. In order to make this possible, the resources in the wind and PV sectors in particular must be expanded significantly and quickly, requiring growth rates of 20% in the renewable energy (RE) sector by 2030.
- For Europe as a whole, electricity demand will increase from about 4,000 TWh in 2020 to about 8,000 in 2050. This increase is mainly driven by the electrification of heat production and e-mobility. The scenario models also show that they are subject to considerable uncertainties, because it is still unclear how much synthetic fuels or hydrogen will be required in the future. In the calculated scenario, 1,500 TWh are used for electrolysis alone. Electricity production from wind and solar will be about 2,800 TWh by 2035, which corresponds to the current electricity demand in the EU27. However, given the enormous RE sources, much more massive demand could be met. On the other hand, the right incentives, e.g. for a broad usage of energy saving

appliances at home, or a changing of individual consumption towards a really sustainable life style could reduce energy demands by up to 20%.

Intermediate conclusion

- Flanking policies also have a significant reduction effect on future electricity and energy demand, namely by using sustainable, low-energy building materials, or if the planned energy savings are actually achieved through building upgrades. For the latter, however, this means tripling the current renovation rate.
- In Europe, countries like Spain could become energy exporters in the future based on the model results. For Spain, this would be electricity, hydrogen and synthetic fuels if the necessary measures (PV expansion) were consistently implemented.

At what cost and pace can supply and demand be matched?

- Until 2030, yearly costs of renewable expansion on a European level, not only the European Union, are estimated around 140 billion €/yr, but will drop substantially after 2030 to approx. 100 bn €/yr between 2030-2040. In the model scenario, most investment costs are incurred in the onshore wind sector. In EU27 one third of this amount could be realized by simply diverting the yearly subsidies from fossils to renewable energy sources (RES).
- At the same time, there are significant opportunities for investors to become a relevant player in the energy sector. For example, the underrepresented geothermal/heating sector alone is estimated to require an investment of at least US$ 160 bn/yr by 2050 (supply and demand).
- These figures are considerable, but it is important to remember that the European countries are estimated to have spent additional 792 billion € in the last year just on the status quo system to protect consumers from the effects of the energy crisis introduced by the Russian invasion into Ukraine.
- Levelised costs for power generation in terms of photovoltaic (PV) systems ranges between 15-50 €/MWh, for wind between 25-65 €/MWh. In these terms costs are cheaper than for gas with an actual price of approx 180 €/MWh for household customers (Feb. 2023).

What are the main institutional and infrastructural innovations needed?

- Centralized planning approaches are dominating the European energy system and create a bias toward sites with the highest yield. In contrast, decentralized planning considers both regional supply and demand. As a result, local suppliers can to some extent replace large-scale generators and directly match demand locally. This approach also mitigates the need for grid infrastructure and the corresponding costs.
- Europe and the member states need to accelerate their pathway to a renewable energy system, and phase out fossil fuels and expensive nuclear power. Centralized instruments at the European level need to be combined with national and local initiatives.
- A central element of electricity self-sufficiency is the flexible use of excess energy. This can only be achieved through adequate storage systems and a more flexible demand, e.g. for charging e-mobiles. So far, the infrastructure is insufficient throughout Europe, although the necessary technologies are available. This needs to change.

What are the most important steps between now and 2030?

- The European states should implement an ambitious industrial policy that enables the development and production of components that will be required for the energy transition to be manufactured in Europe. Otherwise, supply bottlenecks for system components in solar, wind and storage could make the energy transition impossible due to dependencies on, for example, China. At the same time, the incentives set by the Inflation Reduction Act should be seen as competition and not as a threat.
- European policy must establish framework legislation that prioritises criteria for the use of land or simplified licensing procedures, which prioritise RE and grid expansion. The change of course in the gas crisis shows that this is possible.
- In the skilled labour sector, too, the foundations for (digital) qualification and recruitment must be laid today, otherwise the required installation capacities cannot be achieved simply because of a labour shortage.
- A regulatory framework must be created that enables the necessary sustainable growth of renewable energies in the EU in all the sectors mentioned, especially in the installation industry, which would have a significant benefit for the development of local labour markets. This would then also eliminate risks of deindustrialisation of Germany as a location.
- In addition, decentralised planning (installation of capacities and grid) should also be established. In the current political framework at national and European level, for example, the advantages of local generation are still insufficiently taken into account. Furthermore, it can promote public acceptance for the energy transition because it can make the exchange with local actors more efficient.

Our top recommendations to stakeholders

- On the demand-side, efficient and sufficient energy demand strategies need to be supported through market-based and administrative instruments to reduce excessive consumption and align it with the supply at a given time. A high level of electrification with renewables supports decarbonization and self-sufficiency. Central and national governments have an important role to play to “lead by example” in their respective administrations.
- On the supply side, the vast potential of renewables needs to be developed efficiently, and with low transaction costs. Policies must maximise the expansion of wind, solar, and other renewable energies at justifiable costs. The future electricity market design must favour capital-intensive investments in renewables, and reduce the transaction costs for all participants, e.g. feed-in tariffs are more effective than auctions. Neither European nor national market designs should cater to attempts by the incumbent fossil and fissile industries to provide capacity payments to fossil or nuclear power plants.
- Sectoral planning processes, e.g. scenario development and network development plans by ENTSO-E and ENTSO-G need to be streamlined and coordinated to facilitate implementation. Regulatory oversight needs to be strengthened to avoid infrastructure lock-ins by the incumbent industries, e.g. current natural gas pipelines re-named potentially “hydrogen-ready” pipelines. Citizen engagement in these processes must be reinforced, too, since these are the key players, as prosumers, to succeed in the transformation process.

1. Introductory Remarks

The transformation of energy systems is a global joint task, not only in the context of combating climate change, ensuring energy security and affordability, but increasingly also in terms of geopolitical considerations. At least since Russia's invasion into Ukraine in 2022, it has become clear that economic and political stability can be fragile if dependence on one energy supplier or source becomes too great. At the same time, almost 40 million Europeans (approx. 7%, cf. WEF 2022) are unable to keep their homes warm, and this number is at risk of increasing caused by a combination of low income, high energy prices, and poor energy efficiency in buildings. This implies that, in addition to combating climate change, the political dimensions of the structure and self-sufficiency of national energy systems become important aspects. Considering these two challenges together is central for several reasons. On the one hand, the question of energy security and political independence has come to the foreground as a result of the energy crisis cause by the war in Ukraine. On the other hand, current global efforts in climate protection are showing at least stagnation, if not a setback. At the same time, European countries have by no means exhausted their capacities with regard to the necessary energy transformation to low-carbon, clean, secure, affordable, and largely-renewable energy sources.

Looking at the commitments already made by states, it is obvious that the limitation of global warming to below 1.5 °C will only be achieved with Herculean efforts. In addition, economic and energy conflicts will continue to limit the possibilities of effective and rapid climate protection. Despite this situation, there remains strong public support for rapid action[1,2,3,4]. For this reason, it is necessary that the potentials and synergies of the states in Europe be identified and leveraged. Thereby, in addition to effective climate protection, autarchy of the European power sector, and further on the energy sector at large, is ensured - and at the same time also political independence. Nevertheless, in the public debate, conflicts of objectives, limitations of any kind or even aspects of impracticability or non-affordability are repeatedly cited. Amongst them, the most prominent ones are that renewable, like solar or wind power are too intermittent, and we do not yet have the ability to efficiently store power surplus. Furthermore, it is often argued that an adequate infrastructure is a key to the transformation, as simply adding renewable energy resources (RES) to the electrical grid would not solve the climate crisis on its own, because transportation, industrial production, heating and cooling make up the largest amount of greenhouse gas emissions. All these arguments are correct from an isolated point of view, but one should also not be so bold as to claim that such limiting factors make the necessary transformation of the energy sector generally impossible. The energy transition is inevitable from the point of view of climate change and in terms of fulfilling a sustainable economy that provides a just and secure livelihood for all inhabitants on the entire earth. Of course, it is necessary to couple or even integrate the above-mentioned – and other – sectors into the electricity sector. Without this, we will certainly not achieve meaningful climate goals. The question this study asks, however, is whether this can be done quickly, i.e. by 2030, at adequate cost and using the technologies already available on the market.

In addition, the efficient and sustainable use of our own resources would also reduce our vulnerability to political blackmailing. Therefore, it is necessary to enrich the political discussion with facts in order to illuminate the European potentials. However, this is not exclusively a question of the naturally available

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[1] e.g. https://fridaysforfuture.org/

[2] https://www.architects4future.de/

[3] https://onepercentfortheplanet.org/

[4] https://climatenetwork.org/

potential, but of the technical potential. In the field of renewable energies, this determines the achievable energy and/or electricity generation, taking into account system performance, topographical conditions, the environment and land use conditions (Figure 1.1).

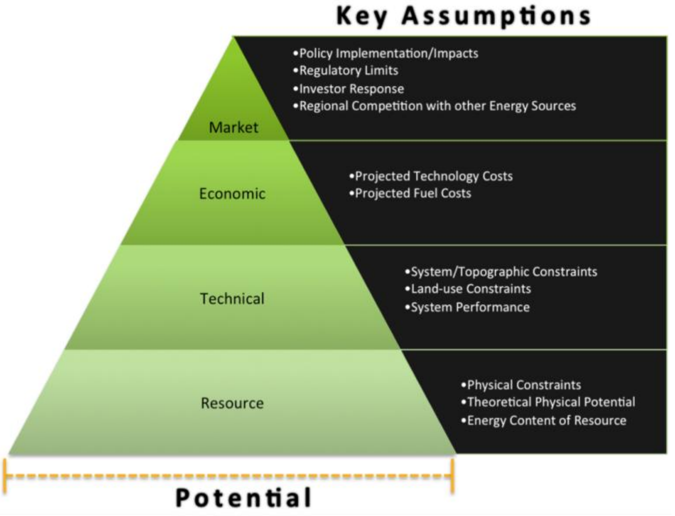
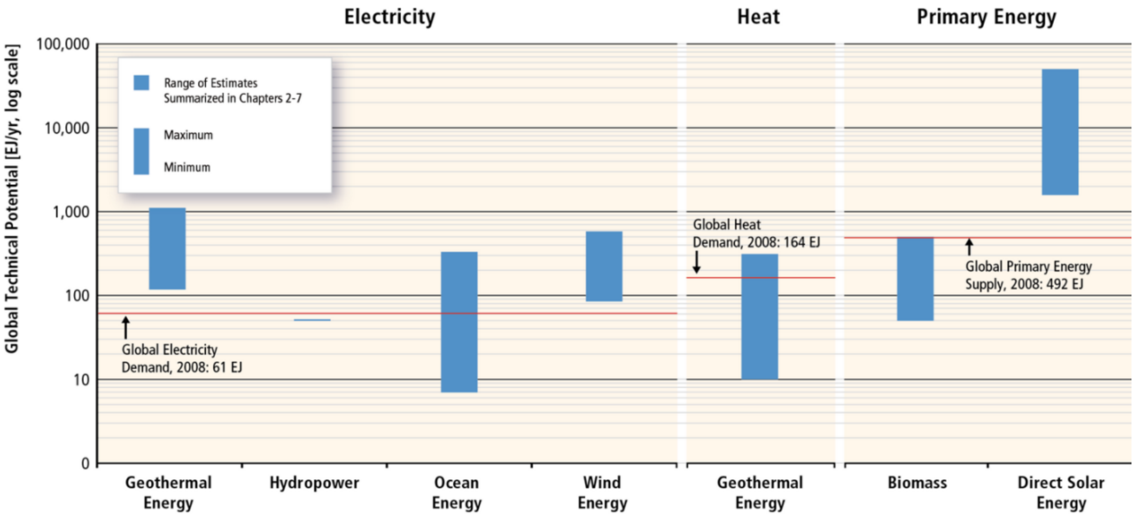


Figure 1.1: Factors defining the potential for the exploitation of RES (Source: Lopez et al. 2012).

The technical potential is an estimate of the upper limit of long-term development potential. There are several types of potential – resource, technical, economic and market – as shown in Fig. 1.1 with the main assumptions. The factors defining the resource potential are the largest, while the others take into account possible constraints, which will be discussed in detail in the subsequent sections. Figure 1.2 shows the IPCC assessment of global technical potentials for renewable energy from the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN 2012). In this context, the argument of further necessary innovations to achieve an energy transition can be achieved at all, is also often mentioned. Following this line of argument, this usually means chasing the new instead of relying on existing technologies and improving them if necessary. This hinders important steps towards the energy transition, because the focus on what is possible with existing technologies is often pushed into the background.



Range of Estimates of Global Technical Potentials

Max (in EJ/yr)	1109	52	331	580	312	500	49837
Min (in EJ/yr)	118	50	7	85	10	50	1575

Figure 1.2: Assessment of global technical RES potentials (Source: SRREN 2012). It indicates that solar power generation is by far in the leading position.

The need to switch from fossil fuels to RES also faces immutable laws of physics and chemistry, but also ecological hurdles (e.g. competition for renewable resources and land, cf. Sect. 6.1) that may be overlooked by political decision-makers. At the same time, the quest to find a clean energy supply while reducing emissions carries important geopolitical implications, as state actors sometimes hold monopolies in certain sectors (cf. Sect. 6.4). However, looking at Fig. 1.2 one can observe that globally RES can provide energy which is far beyond the current demand. The question remains, whether such a solution is also possible for continental Europe and at what costs.

Consequently, this report follows a step-by-step approach, starting with the drivers of energy consumption, the technical potentials of RES and concluding with the system-wide transformations required and unavoidable challenges. On the way, the report highlights the different dimensions of the transformation of the European power sector and briefly summarizes the corresponding conclusions to be drawn from it.

1.1. Point of Departure

The transformation of the electricity and the whole European energy system would bring multiple benefits for just and efficient access to energy services, major reduction of adverse environmental impacts, such as air pollution and waste, fundamentally improved security and lower long-term costs in addition to rendering Europe the first climate-neutral continent. European politics has also recognised this aspect as it aims to make the continent carbon-neutral by 2050 (EC 2019) Consequently, since the middle of the last decade, there have been attempts to further integrate the European energy systems, initially on a sub-European scale. Examples for these various activities are the Pentalateral Energy Forum (PEF), the North Seas Countries' Offshore Grid Initiative (NSCOGI), and the Mediterranean Electricity and Climate Change Forum (MECEI) (cf. Egenhofer & Jong 2014). Here the PEF originally focused on information exchange and cooperation to prevent a power crisis (e.g. blackouts), the NSCOGI aims to maximize the potential of renewable energy sources in the North Sea region, while the MECEI aims to support the transition to a low-carbon economy in the vulnerable Mediterranean region by demonstrating how the integration of energy markets and infrastructure and low-carbon growth can be successfully achieved. To achieve a transformation towards European electricity self-sufficiency, certain options spaces need to be taken into account and gaps filled with investments into a ramp-up of technology production in Europe. The consideration of the right timing and non-exploited capacities across Europe will make clear where further hotspots of action are located, which either may foster order hinder a real power autarchy in Europe. In these regards, a close cooperation with trans-European partners is also desirable (cf. Sect. 6.4).

Thus, it is the aim of this study to assess pathways to achieve self-sufficiency and other co-benefits of the European power sector by 2030 and beyond. For this purpose, more centralized and more decentralized views are taken to understand local potentials and drawbacks and to recommend measures and actions that contribute to achieving electricity self-sufficiency pathways for European countries as soon as possible. Nevertheless, the main purpose of this study is to show that a European self-sufficient electricity sector would be possible even with existing technologies by 2030. Of course, this implies a concerted energy policy that sets the framework to make the right sectoral investment decisions possible in the right places. The latter is already given by the condition of an advancing climate change, which also entails incalculable risks and therefore creating tremendous impacts on the energy sector as well (cf. Box 1.1).

Box 1.1: Option space for hydropower under climate change
The global installed hydropower capacity is currently around 1,360 GW. The maximum estimated global potential is approx. 3,700 GW. If global warming approaches 1.5 °C, this would only amount to approx. 2,600 GW, and with a warming of 2 C° only 2,300 GW, e.g. due to changing rainfall regimes. This implies that climate change could massively limit the options for a transformation of the electricity sector. Although large contributions to electricity generation will come from the wind and photovoltaic sectors in the future (cf. Fig. 1.2), at least 850 GW of additional hydropower capacity will be needed to limit global warming cost-effectively by 2050. To limit global warming to 1.5 °C, almost twice the currently installed capacity would have to be connected to the grid (cf. IHA 2022). This example shows that the options space under climate change can narrow very quickly, and therefore rapid and efficient action is needed.

Therefore, indeed it is necessary to develop alternatives that can provide additional efficiency gains, e.g. by the help of new technologies. However, this should not tempt the political actors to wait until the optimal solution has been found. The slogan of the day must rather be to do one thing, but not to leave the other.

Besides such considerations on the supply-side, assumptions about future electricity demand must also be made for the feasibility of electricity self-sufficiency. This particular refers to the above-mentioned development to electrify other industry sectors and thereby enlarge the power sector. For Germany, for example, it is estimated that electricity demand will increase from 595 TWh in 2018 to approx. 660 TWh in 2030 (approx. 11%). The main drivers of this expected increase are the production of electrolysis hydrogen, the installation of heat pumps, battery production and the provision of charging electricity for e-mobiles. The main contribution of this increase is caused by e-mobility (passenger cars), which alone will demand 44 TWh (considering heavy traffic and buses up to 68 TWh, cf. Fig. 1.3). This assumes a fleet of approx. 16 million e-vehicles in 2030. For comparison, there were approx. 135,000 fully electric vehicles on the roads in 2020 and approx. 618,000 in 2021. To reach the target of 15-16 million vehicles, approx. 1.5 million electric vehicles would have to be registered per year (cf., for comparison, Tab. 2.2). As shown, efficiency gains are also considerably dampening this demand.

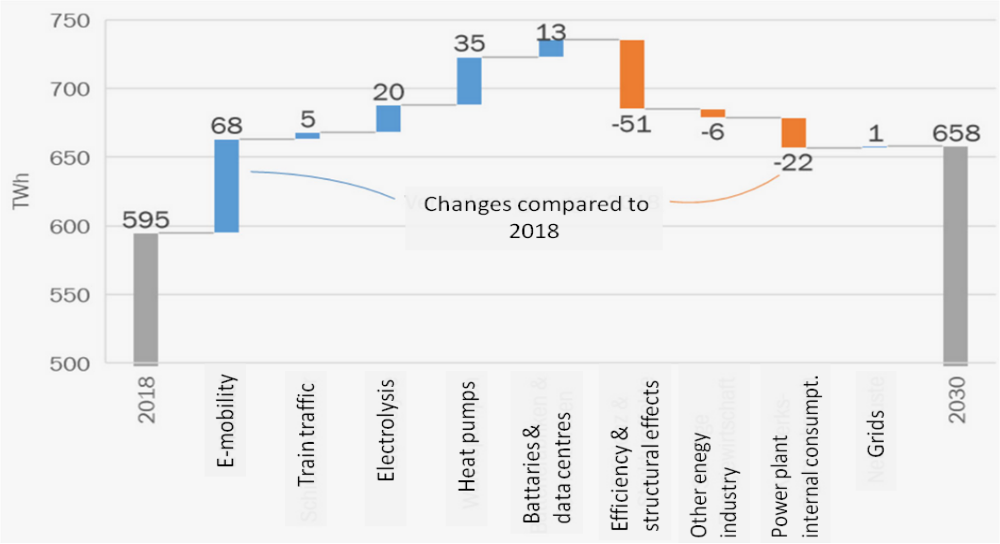


Figure 1.3: Expected development of power demand in Germany between 2018 and 2030. Source: Prognos, Ökoinstitut, Fraunhofer ISE, 2021.

Moreover, while the above example refers to Germany only, a significant share of electricity production across Europe is also provided by the nuclear sector. In 2021, approx. 732 TWh (cf. also Tab. 8.1) of electricity was produced by nuclear power plants in EU27 and although countries like France plan to stick on this technology, which is undoubtedly unsustainable due to its unsolved handling of nuclear waste, this amount would also have to be substituted by RES for a sustainable self-sufficient European electricity sector (cf. also, Tab. 8.2, Chapt. 8).

Consequently, we draw on the existing literature on decarbonized power and energy systems by 2030 and beyond, and describe ideal-typical pathways to achieve autarchy, taking into account existing technology ("supply side"), consumer behavior ("demand side"), and the infrastructure needed to link supply and demand.

In doing so, we start from the following hypotheses:

- While today there is still a linear dependence of the various sectors on dominant fossil and nuclear energy sources, the future lies in energy systems becoming increasingly interconnected, and be based on renewable energy sources. This applies to power plants as well as to energy storage systems in the mobility or building sector.
- A consistently implemented energy transformation requires not many new technologies, but new infrastructures and value chains. This is not creating really a technological change, but a more spatial (organizational) one, because new energy spaces will emerge that are decentralized and also have a certain degree of independence.
- Innovation through digital and other advanced technologies such as circular and shared economy as well as emergence of new consumer behaviors would help achieve the transformative change and make such a sustainable energy future the preferred choice.
- Finally, the reorganization of value creation in the energy sector will lead to a faster decarbonization of energy systems, because a local valorization of energy can more easily take up ecological and climate protection aspects.

In the sense of these four basic considerations, it becomes clear that an aspired energy self-sufficiency for the European electricity sector not only enables political independence, but the innovation pressure described above also leads to a faster European energy transformation in the medium term and thus to a more ambitious climate protection in the long run.

The idea here is to first define a simple starting condition, namely how and whether sustainable electricity self-sufficiency can be ensured in Europe by 2030 if all non-European energy/electricity imports are stopped. Such includes, not only electricity imports, but above all the fossil and fissile energy sources that are used within Europe for electricity production. Finally, the supply side cannot be discussed independently of the demand side.

Preliminary research in the literature and ongoing studies (cf. European TRIPOD project[5], Tröndle et al. 2019) indicate that energy independence at the European level (EU-27, but also Europe as a whole) can be achieved by 2040 if appropriate targets are set to promote the renewable energy potential in all member states and to accelerate the phase-out of fossil fuels and nuclear power. The year 2030 is an important step stone on this pathway. It is also clear from the literature that there is no precedence between a more centralized and a more decentralized approach, but that a combination of both is needed: tapping local renewable resources for rapid decarbonization and local economic development while leveraging pan-European exchange and flexibility through infrastructure. In terms of financing, this

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[5] https://cordis.europa.eu/project/id/715132

requires bold electricity market design reforms, a strong push for adequate infrastructure, and efficient risk-sharing between private and public investment.

1.2. An Integrated European Power System Deepens the Energy and Economic Union

One of the most important components of the “sui-generis” character of the European Union is that it is not only an association of Member States, but that citizens are also recognized as direct members of the Union. The dual character of the Union, uniting both states and citizens, has a direct impact on the nature of the EU and the decision-making process. In the climate and energy debate in particular, civil society has become a fundamental actor that also influences climate and energy policy at the European level. Although the actors in the individual member states (such as Last Generation, Fridays for Future, Scientists for Future, etc. pp.) vary in strength, also actors from the business community have also already made clear statements in terms of European joint efforts in energy use and climate protection. The German Automobile Association, for example, has called for a binding European framework and criticized the fact that parts of the German government want to continue discussing the end of combustion engines. The impact of European integration on climate and energy issues has also been scientifically studied in part. Costa & Moreau (2019) examined trade volumes between the EU and the UK and compared the previously valid domestic trade with a hard Brexit, i.e. the reintroduction of custom regulations and other rules as they applied before the UK joined the EU. Taking into account the respective trade volumes, technologies and energy mixes, this would mean an increase in emissions contained in UK imports of approx. 215 Mt CO_{2eq}. This is in an order of magnitude roughly equivalent to annual Dutch emissions. Replacing EU imports into the UK with imports from the rest of the world (RoW) under the same conditions implies that each dollar of imported activity into the UK causes on average 0.35 kg CO_{2eq}. Conversely, the effects for the EU are not so clear. Closing the gap of imports from the UK by increasing production in the EU would only lead to additional emissions of 12 Mt CO_{2eq}. This shows the benefits of an integrated European market that adheres to common environmental standards and climate policies. It is very likely that this also applies to energy policy, especially since energy is an essential element of all traded goods.

In another approach, Babonneau et al. (2018) used a gaming approach to approximate an architecture that combines an EU ETS market with national obligations. Here, too, it became clear that so-called effort-sharing decision-making leads to the development of affordable and fair burden sharing between Member States, with high-income Member States paying for low-income countries while ensuring overall cost efficiency. This also applies to emissions and also the common energy market. The UK's decision to leave the EU undoubtedly affects European climate policy. The UK played a key role in EU climate policy and is the second-largest European emitter of greenhouse gases (GHG), but was also one of the Member States that pursued an ambitious climate policy. Babonneau et al. (2018) make the point that European countries, for example, could experience some welfare improvements if it is assumed that the UK must implement its emission reduction target through a national price and is not allowed to participate in a European instrument. On the other hand, the UK would suffer costs of around €40 bn by not participating in the EU-CO_2 architecture. It is therefore undeniable that an independent and self-sufficient European energy system also promotes the political integration of the continent. At present, for example, the EU climate diplomacy agreement is on ice, while the dispute over nuclear energy is intensifying. This alone shows through the loss of time that the failure to implement common targets is causing European energy policy to fall behind. The solutions outlined below would send a strong signal.

1.3. Key Starting Points of the Study

1. The starting point of this report is the realization that the transformation of the energy system in Europe should be implemented quickly and consistently in view of the energy crisis caused by the Russian invasion of Ukraine.
2. The considerations in this report are based exclusively on existing renewable energy technologies, with the aim of determining whether a self-sufficient electricity sector can be created in Europe by 2030.
3. Climate protection aspects, energy supply, demand and security, but also affordability for citizens must be at the forefront.
4. Based on recent studies, it can also be stated that European integration, including the integration of energy systems, has undeniable advantages for citizens, the environment and the climate issue.

Sustainability and self-sufficiency in the energy sector, which requires both political independence and ambitious climate protection, must therefore i) be based on a natural territorial potential for electricity generation from renewable energies (24 hours/365 days) that can compensate for internal fluctuations in demand, ii) have the technical capacities to use, store and distribute renewable energies according to demand, and iii) ensure that the conversion takes place at socially acceptable costs.

2. What Drives Power Production and Consumption?

The problem of appropriate sustainable energy planning in relation to the future demand for electricity is essentially based on experience. Since the energy turnaround has gained momentum again with the outbreak of the Ukraine crisis, comprehensive measures must now be taken to ensure that energy self-sufficiency and climate protection can be implemented in parallel. In doing so, it becomes important to recognize that the transformation pace of the European economies is highly diverse (cf. Fig. 2.1). With regard to the use of energy generated by the classical fossil type, it must first be stated that this type of energy use is not only harmful to the climate, but also very inefficient, because about approx. 1/3 of the primary energy is lost, while only 2/3 actually reaches the end consumers. Such efficiency ratio will be maintained, because RES resources, such as PV, are not always available for 24 hours and conversion losses will also occur with the electrification of industrial sectors or power-to–x (PtX) strategies being implemented in the future.

With regard to future demand, any hypothetical scenario analysis must therefore take a number of uncertainties into account. It is still unclear how fast certain branches of European industry can be electrified. The bottleneck for the speed of this electrification is not necessarily a lack of technology, but rather that the demands of the market can be met under the influence of the Ukraine crisis and the political framework for e-mobility or future space heating, the timely and sufficient supply of plant technology for e.g. heat pumps or PV elements, or even the supply of rare earths etc. The aspect of import dependency is particularly important here (cf. also Chap. 6.4) and independence in energy matters has accordingly also long been a security policy aspect. This means that the problem lies less in the natural resources provided than in market organization and control and in the time dimension.

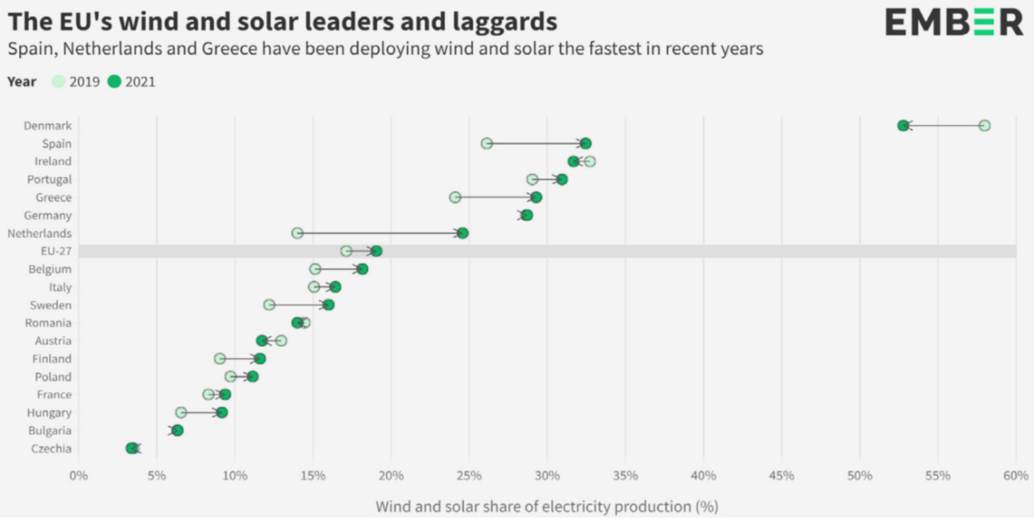
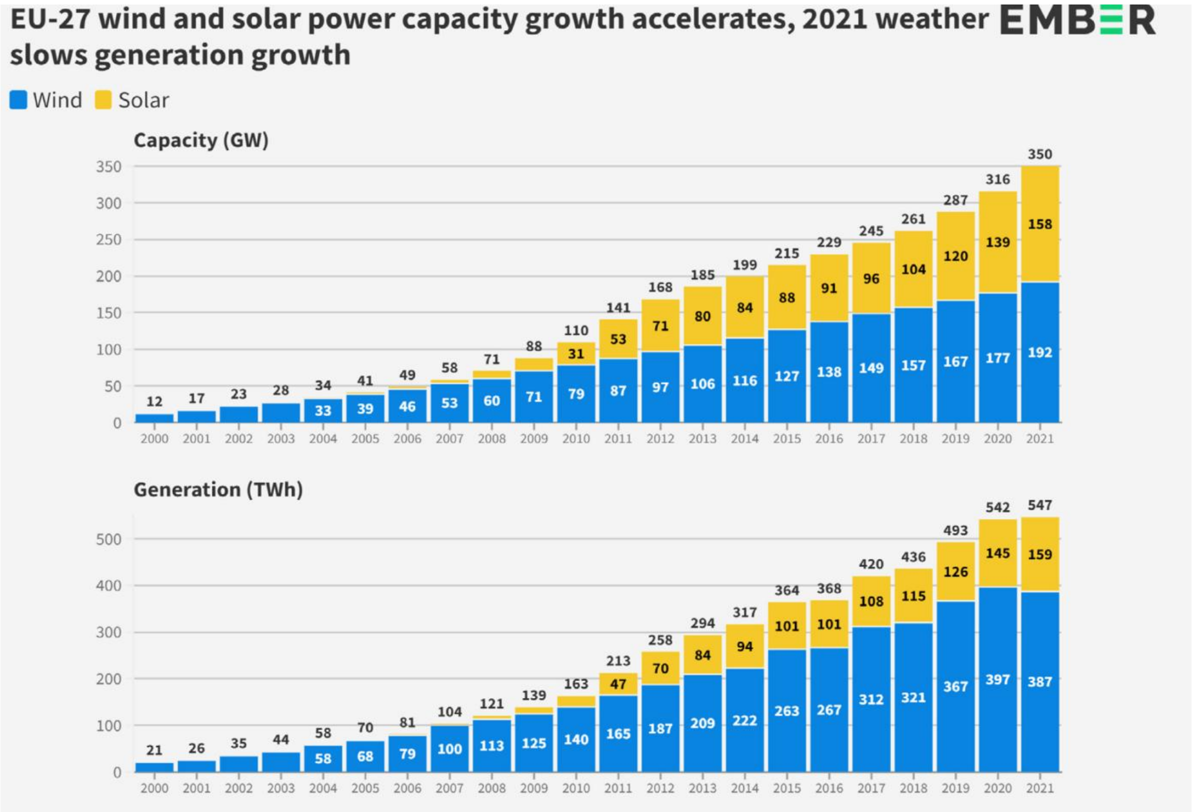


Figure 2.1: First movers and countries lagging behind in terms of RES introduction, note: selected countries make up 97% of emissions and electricity demand in Europe (EMBER 2023).

In terms of the speed of energy transformation, wind and solar energy reached a new record in electricity production in 2021 (547 TWh, cf. Fig. 2.2) and for the first time more electricity was generated from wind and solar than from gas in EU27 (623 vs. 557 TWh, cf. Tab. 8.1) and in the year 2022 (WID 2023). Although electricity demand is back to pre-pandemic levels, fossil fuel consumption remains below previous levels. However, due to nuclear phase-outs fossil fuel use from 2021 until 2022 has been slightly increased in electricity production (cf. Tab. 8.1). Further, in contrast to the increasing installed capacity of RES, electricity production from RES is stagnating (see Fig. 2.2).



Source: Ember's Europe Electricity Review 2022. *2021 capacity estimate taken from IEA Renewables Data Explorer. 2000-2020 capacity data taken from IRENA.

Figure. 2.2: Installed capacity for wind and solar power in the European Union and generated electricity (after EMBER 2022).

Investments cycles, national strategies as well as weather variations and changing consumption patterns play a role in explaining the recent pattern, but also the deficiencies of needed grid infrastructure not yet being in place. For example, the production of solar power is stagnating in Italy due to problems in planning and approval processes, while in countries where relevant framework legislation exists growth has been robust (EMBER 2023). Take the case of Germany, where has committed in the coalition agreement to install 200 GW of PV capacity by 2030.

2.1. The Influence of Consumer Behavior on Power Consumption

Behavioral change favoring the adoption of less material, energy and carbon-intensive lifestyle choices is gaining importance in the decarbonization and energy debate (Creutzig et al. 2018). However, consumers themselves are the drivers of energy consumption. Through their demand for products and their user behavior, they are responsible for the demand. For a real transformation, however, all options must be explored equally, because the transformation could happen much faster in this case. The industry is currently unable to meet the demand for sustainable household appliances with low energy requirements, for example, which customers can purchase at acceptable prices. Therefore, this study will also determine how changes in the use of appliances, changes in the use of materials (e.g. in the construction industry), or changes in mobility behavior would affect energy consumption, knowing that individual decisions can often only be influenced to a very limited extent. Indeed, social theory says that changing an individual's behavior is even hard. Nevertheless, the behavioral change narrative emerges as alternative to growing scientific evidence that the contemporary pace of decoupling between services and energy consumption and emissions is either non-existing or clearly insufficient to achieve globally-agreed climate targets (Vadén et al., 2020, Haberl et al., 2020, Kuhnhenn et al., 2020). Given the stringency of climate targets, EU policymakers are increasingly recognizing that achieving low-carbon pathways requires some degree of societal change in addition to technological measures (EC 2018).

If a significant part of the population would move in this direction, i.e., toward more sustainable energy and consumption options, there would be significant potential for emissions reductions. In this respect, the quantitative analysis of the potential for consumer and technological change in the transport, buildings and agriculture sectors has made it possible to identify the impact of behavioral change – although hypothetical - on final energy demand, emissions and material requirements for a net-zero transition in the European Union (Costa et al. 2021, Ivanova et al. 2020, Vita et al. 2019). However, consumer change always takes place in the context of increasing technological change and innovation. In order to evaluate how far change in consumer behavior is complementary to technological change, both aspects need to be equally considered. Using the EUCalc model[6] (see Costa el al. 2021 for a complete description) can be used to simulate the effects of changes in consumer behavior in parallel with the effect of technological innovations on energy and electricity demand in the European Union. In brief, the EUCalc models energy, resources, production and food systems at the EU level + UK and Switzerland under adjustable levels of ambitions in regard to technological deployment and consumption behavior. It is composed of 15 inter-dependent modules representing the supply and demand sides of activities, materials, energy and emissions; as well as different interfaces of the energy system with society and the environment. At its core, are modules representing the energy-relevant sectors of agriculture, buildings, power/storage, transport and manufacturing (see documentation for sector details[7]).

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[6] https://www.european-calculator.eu/model/

[7] https://www.european-calculator.eu/documentation/

By running the EU-Calculator model under two distinct configurations namely *Tech configuration*[8] and *Tech+behavior* it is possible to distill the effect of the additional benefits of behavioral change to facilitate the transition of the energy system. In the *Tech* configuration, individual behaviors are kept largely unchanged from their 2015 EU-average value. Against the backdrop of advancing technological development, assumptions are thus added about a change in consumer behavior resulting in the *Tech+behavior* configuration (for a more detailed description of the scenarios, see Costa et al. 2021). In both configurations, a carbon budget of 60 Gt CO_2 is set for the EU for the period 2020-2050, aligned with a "fair" per-capita allocation of the remaining global budget[9]. Furthermore, in both configurations the energy system undergoes the required renewable capacity deployment to fill the gap left by fossil fuel phase-out and avoid oversupply due to the considerable gains in efficiency.

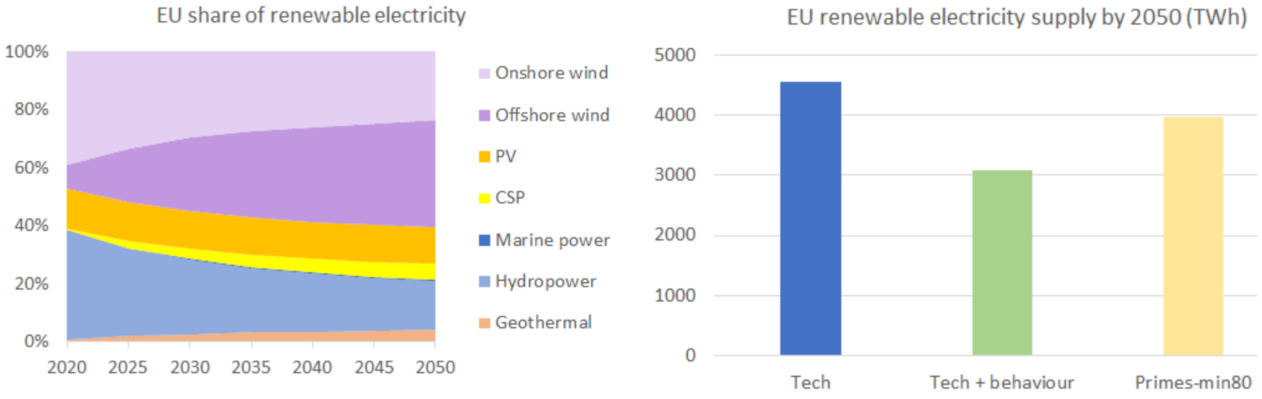

Figure 2.3: Supply of renewable electricity in the EU by 2050 (left), and the respective technology shares (right) under the *Tech* configuration (Costa et al, 2021). Note, that in absolute terms, solar increases from 120 TWh in 2015 to 812 TWh in 2050. In the Primes-min80 scenario (left), the increase in solar amounts from 126 TWh in 2015 to approx. 1,000 TWh in 2050. The levels of the bars show how large the effect of changes in the consumer behavior can be (cf. EUCalc Project[10]).

When evaluated at the aggregate level, supplying carbon- and uranium-free electricity to the EU27 by 2050 would require at least the generation of about 4,500 TWh in the year 2050 under the *Tech* scenario (see Fig. 2.3). This is in line with estimates in other modeling frameworks using a comparable carbon budget (~57 Gt CO_2) - see Figure 2.3 (right) results for the Primes-min80 scenario, a scenario focusing on supply side changes via the deployment of large scale technologies and synfuels tor achieve ~80% reduction in 2050. Further scenario information available in INNOPATHWAYS 2020[11].

Reducing the demand for materials and services would lower the overall demand for renewable electricity generation. In the *Tech+Behaviour* configuration, electricity generation would be capped at about 3,000 TWh in 2050 - a saving of about 33% compared to *Tech*. This highlights the potential of changes in consumer behavior to smooth the total amount of renewable electricity generation capacity that needs to be deployed. In addition, there are cross-sectoral demand alleviations that increase the breathing space for the transition. In the *Tech+behavior* configuration, demand for cement is projected to drop by 40% in 2050 compared to the material production in the *Tech* configuration. This is motivated by the construction of e.g. smaller buildings, the substitution of carbon-intensive construction materials

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[8] For pathways explorer, refer to: http://tool.european-calculator.eu/

[9] EUCalculator deliverable 1.2: Formalizing the relation between EU-level emissions and those from the RoW: perspectives and scenarios for the EUCalc

[10] European Calculator Project: https://www.european-calculator.eu/

[11] Website: https://innopaths.eu/ and Low Carbon Pathways Platform: https://innopaths.eu/lcpp/#/

by wood or fibers, and the lowering need for construction/maintenance of transport infrastructure (as cars in circulation decrease substantially through the combined effect of carsharing/pooling, increases in vehicle occupancy and shifts to public transportation and active travel). With less material production needed, the installed capacity to supply energy-intensive industries like steel, aluminum or chemicals can be reduced. Despite this effect, it should be remembered that the estimated 3,000 TWh of renewable electricity more than doubles the 1,412 TWh of renewable electricity generated in EU27 in 2020 (IEA 2023a). At the current exponential rate of renewable electricity expansion in Europe, this demand would only become feasible after 2030 (see, Fig. 2.4).

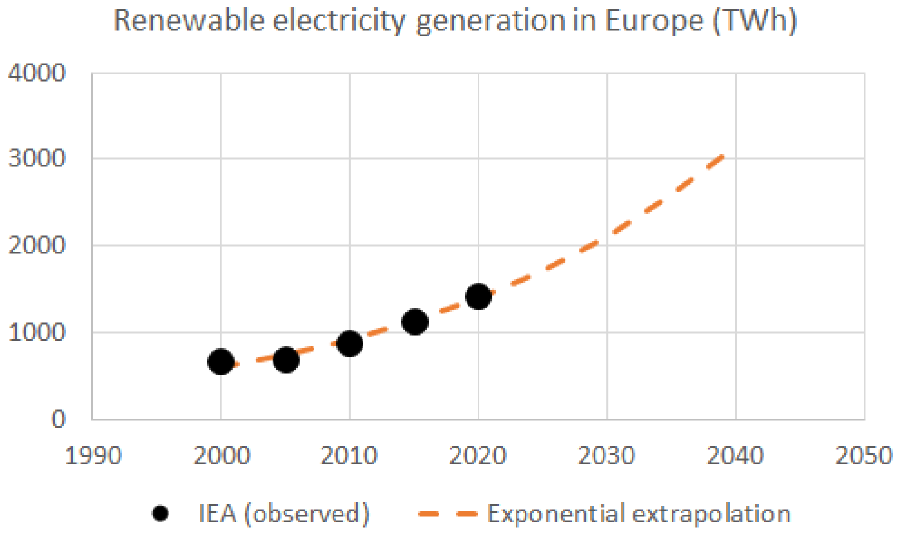

Figure 2.4: Renewable electricity generation in Europe (2000 and 2020) and extrapolation until 2040 (authors' own analysis using reported generation in IEA (2023b)).

It remains to be seen whether the recent political push towards renewable energy (EP 2018) will be put into practice (EEA 2022). Should this be the case, the dynamics of the extrapolation may change. In addition, physical and social factors that influence the viability of renewable energy expansion still apply, but research suggests that these are not insurmountable (cf. Chapt. 3 for European potentials, and Chapt. 6 for industrial aspects). For wind, these include environmental impacts like bird collisions, human attitudes, and energy performance. If such constraints are taken into account in Germany, Eichhorn et al. (2019) estimate that an area equivalent to 7.3% (for comparison, cf. Sect. 6.1) of Germany would be available for wind generation, with an equivalent capacity to deliver twice the net power consumption of Germany in 2016.

In terms of fossil fuel phaseout, the *Tech+behavior* configuration implies a fast decommissioning of power production from carbon-intensive sources in order to stay below 1.5 °C. Differences in country-specific legacy energy infrastructure result in different time frames for coal decommissioning (see Fig. 2.5, top), but the window for action is nevertheless narrow across the EU. Total coal phase-out must occur - at the latest - by 2035 for countries that still rely significantly on coal (e.g., Poland and Germany with a share of electricity generated by coal of 70% and 30% in 2021) and as soon as 2025 for less reliant countries such as France and Austria (less than 5% of the electricity production based on coal in 2021)[12]. The country-specific yearly reduction target (in terms of TWh) to achieve this ambitious timing is shown

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[12] IEA energy statistics
https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=POLAND&fuel=Electricity%20and%20heat&indicator=ElecGenByFuel

in the bottom panel of Fig. 2.5. In EU aggregate, approx. 580 TWh of power production from coal in 2019 (EU27+CH+UK) needs to be replaced by renewable sources by 2030 and an additional 60 TWh by 2035.

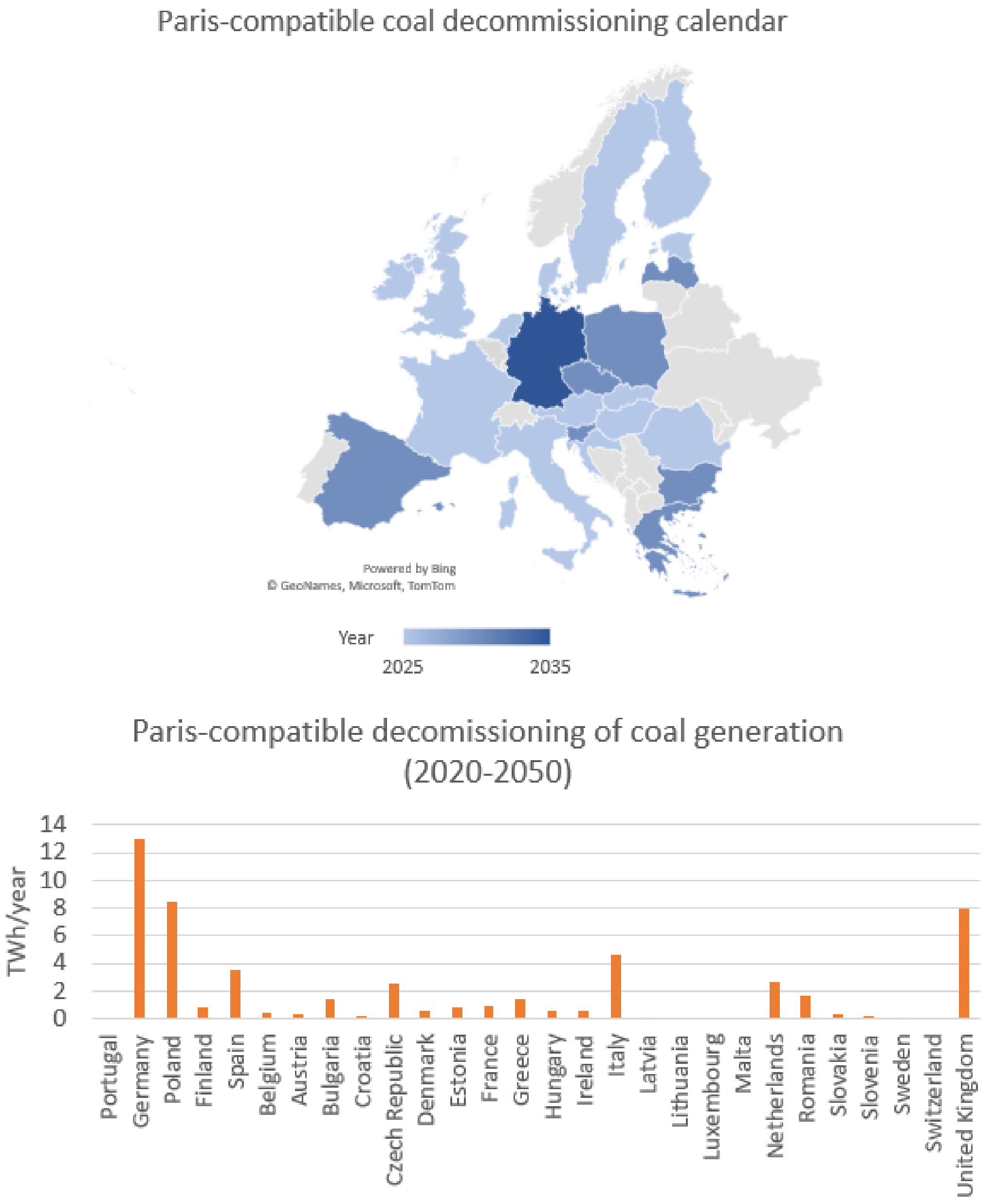

Figure 2.5: Paris-compatible coal decommissioning calendar (top) and effort (bottom).

2.2. Material Shifts - Building and Construction Emissions

Globally, 40% of the global carbon footprint of materials stems from the construction sector (Hertwich 2021) and therefore far off the track to reach the goals of the Paris Agreement (UNEP 2022). As 80% of today’s buildings will still exist in 2050, the renovation rate would need to be increased from 0.4-1.2% today to at least 3% per year (cf. Tab 2.1) combined with an average energy demand reduction of 75% to reach climate neutrality by 2050 (Eurocities 2020). This need highlights the urgency for massively accelerating the transformation of the construction sector to be able to meet the climate targets and be ready to apply to upcoming national laws which will translate European directives on the national level. This is feasible, as the construction sector has a gigantic value creation potential of approx. US$ 1.6 trillion/year if efficiency gains in construction were realised similarly as the rest of the economy evolved over the past 20 years (McKinsey 2017). However, when paving the way towards a sustainable building sector one has also to consider that in the EU alone the construction sector accounts for 9% of the gross domestic product (GDP) and 18 million direct jobs (in 2018) (EC 2018a).

Greenhouse gas emissions from the EU buildings sector have shown a sustained decline since 2005. In the period up to 2019, combined emissions of fossil fuels and electricity from buildings have decreased by 29 % (EEA 2021). Long-term strategies and projections from several Member States point to a further decrease by 2030 and full decarbonization by 2050, but according to the actual renovation quota (cf. above) it is rather unlikely to achieve this without any further economic/political pressure, i.e. the definition of clear targets. Indeed, the progress observed is due to stricter energy standards for new buildings, as well as increases in energy efficiency in existing buildings (e.g. renewed heating systems, thermal insulation). The renovation waves in the Member States aim for 35 million renovated building units by 2030 (EC 2020d) and will further strengthen the trend towards energy efficiency. Crucially, cumulative renewable energy capacity in Europe between 2022 and 2027 is expected to grow twice as fast as in the previous five-year period, i.e. a total of 425 GW of new capacity will be required (IEA 2023a). While the political will and trends in the generation of electricity from renewable energy sources in the building sector seem to be on the right track, it is clear that a significant part of the GHG reduction achieved in the past has been overcompensated by the increasing the number of dwellings and by a larger average building area across world regions (Lamb et al., 2021).

In line with the previous background, energy demand by 2050 in the building sector is expected to fall to about 2,500 TWh (see Figure 2.7) in the *Tech* configuration (see Section 2.1 and Tab 2.1 for details). This represents a 44% reduction compared to the year 2020 and reflects improvements in overall technology efficiency and a strong annual renovation rate of 3% from 2020 onwards. Energy demand reductions of 40% for the same time frame and comparable carbon budget constraints are found in other energy models, albeit some difference in absolute numbers (see Remind-min80 in Fig. 2.7). Adding the effect of a change of consumer behavior (which lowers energy demand by 20% compared to the *Tech* configuration - Figure 2.6), energy reductions in 2050 can be further boosted to 54% lower than those in 2020.

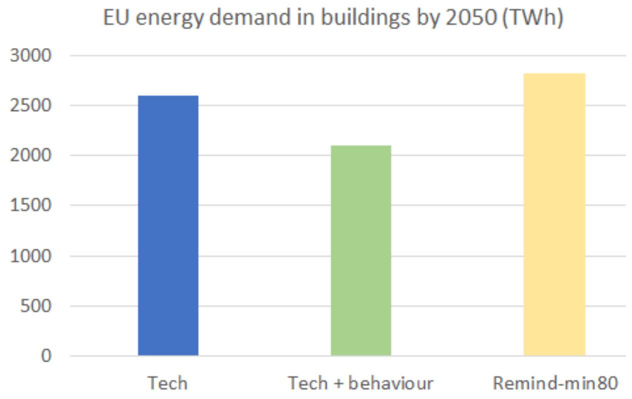

Figure 2.6: Projected energy demand in the EU building sector in 2050 following *Tech* and *Tech+behavior* configurations (Costa et al, 2021). Again the comparison makes clear how on the basis of changed consumer behavior, e.g. material shifts, energy demand could decrease.

The savings in energy consumption of the building sector due to behavioral change derive primarily from reductions in the demand for space floor heating in multi- and single-family homes by circa 30% in the year 2050. There are also important savings in the demand for district heating by circa 12% comparing *Tech* to the *Tech+behavior* configurations. On the other hand, electricity demand is expected to increase in both scenarios compared with the current (that is, 2015) situation. Demand for electricity is expected to increase by 23% in the *Tech* configuration to a total of approx. 1,870 TWh driven mostly by a marked increase of demand related to heat-pumps (approx. 550 TWh in 2050). In the *Tech+behavior* configuration, the overall increase in electricity demand in buildings is far lower and projected to be only 2% higher in 2050 than in 2015. Although savings from changing consumer behavior significantly reduce electricity demand in the *Tech+behavior* configuration, this excludes heat pumps, whose increase in demand in 2050 may also increase electricity demand by about 570 TWh..

While the effect of behavioral change is important, it needs to be coupled with significant investment in building renovation and a technology shift. For a climate-oriented development in the building sector, the use of more renewable energy and accompanying energy efficiency must be significantly intensified. The European Commission proposes with its “Fit for 55 Package” to renovate at least 3% of the total floor space of all public buildings annually (as in 2021: 0.2%) and in addition to achieve an increase in the use of renewable energy in buildings to 49% by 2030 (EC 2021a). Studies show that to achieve these goals by 2030, deep energy renovations need to be promoted and at least a quarter of fossil heating systems need to be replaced (Tsiropoulos et al., 2020). The scale of change is remarkable, as 90% of building stock will be renovated or demolished by 2050 (Boza-Kiss et al., 2021). In Figure 2.7 a regional perspective is provided based on the outputs of the *Tech+behavior* configuration - building stock necessary to undergo deep renovation (right) and that to be newly constructed with a very high efficiency standard of less than 50 kWh/m²/yr of energy consumption (left).

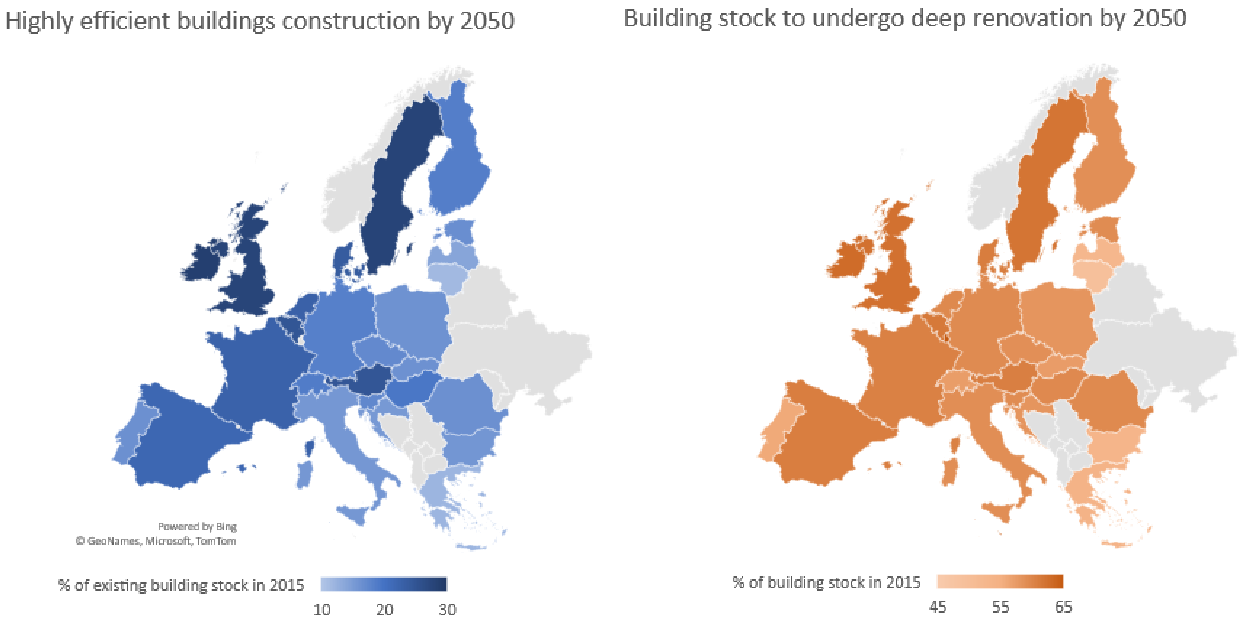

Figure 2.7: Efforts in renovation (right panel) and construction of highly efficient buildings by 2050 in the *Tech+behavior* configuration (Costa et al, 2021). The scenario is compatible with a generalized annual renovation rate of 3%, where 30% of renovations are medium, 70% are deep, 70% of new constructions are highly efficient, and a demolition rate is 1%/yr.

The potential for energy and emission savings from new construction and renovation is further enhanced by the construction sector shifting away from carbon-intensive to bio-based construction materials (cf. also Sect. 3.5, Tab. 2.1). Via the substitutions such as conventional wall insulation with cellulose or the substitution of concrete and steel with timber in buildings, important energy savings are expected in the EU. Under the *Tech+behavioral* configuration, cumulative energy savings of cement and steel production that are not required in the EU building sector due to material shifts are about 230 and 20 TWh respectively for the time frame 2020-2050. These savings in energy come associated with CO_2 savings across member states, as shown in Figure 2.8.

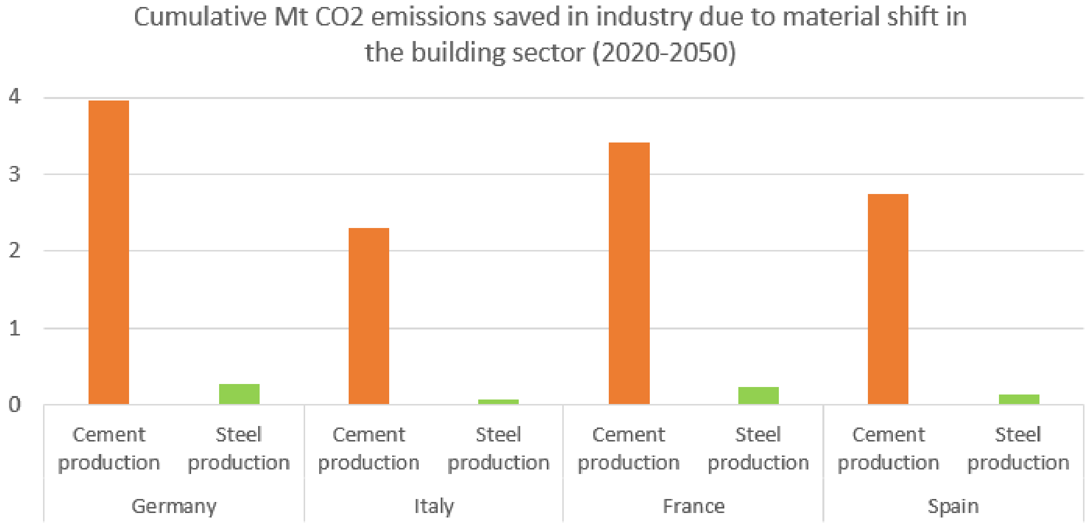

Figure 2.8: Cumulative 2020-2050 CO_2 savings in industry due to material switches in the building sector in the *Tech+behavior* configuration (Costa et al. 2021).

The transformation in the building sector, through material shifts, enhanced renovation and energy source substitution, is expected to have a positive effect on the economy via the creation of jobs, savings in fuel costs and reduced exposure to fossil fuel prices. In terms of the labor market, studies indicate that more jobs are created in demand-side activities, particularly in heating services and building retrofit activities, than in renewable energy generation (Füllemann et al. 2020). The Building Performance Institute (BPIE) concluded in 2020 that for each € 1 million invested in energy renovation of buildings, an average of 18 jobs are created in the EU (cf. also above)[13]. Of particular interest are the nature of the jobs, which tend to be local and long-term, further stimulating the regional economic activity across the EU.

2.3. The Effect of e-Mobility on Electricity Demand

Currently, about 94% of the emissions of the transport sector originate from road vehicles. Thus, the electrification of the vehicle fleet is the most important technological innovation to decarbonise the transport sector (Peiseler & Serrenho, 2022). The *Fit-for-55* package includes a proposal by the European Commission to introduce more ambitious CO_2 emission standards. It would result in a reduction in fleet emissions standards (from 2021) of 55% for cars and 50% for vans by 2030 and 100% for both by 2035, which would in effect impose a ban on the sale of internal combustion engine vehicles from 2035 (Peiseler & Serrenho, 2022). This strengthens the call for a significant increase in the electrification of transport. At least 30 million electric vehicles (as of 2021: 5.5 million, IEA 2022) must be on the roads of the EU by 2030 in order to achieve the committed climate protection targets. For comparison, the German plan is to have at least 15 million electric vehicles on the roads by this time (cf.

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[13] Building Renovation: A kick-starter for the EU recovery (BPIE)

Sect. 1.1). Thus, investments in charging infrastructure must continue and accelerate, as it is crucial for the acceptance of electric cars by consumers. Apart from these aspects, however, it is important to bear in mind that the expansion of e-mobility is not the only sector requiring more electricity. While in Germany, for example, the net electricity supply is expected to increase from approx. 500 TWh in 2021 (compare with Fig. 1.3, which mention a lower estimate, as at this time the new government was not yet in office and until then less ambitious goals applied), the increasing e-mobility and the installation of modern heating systems (heat pumps) is expected to increase it to approx. 700/750 TWh in 2030 and 2045 up to 1,000 TWh (German Minister for Economics Habeck on the inaugural session "Plattform Klimaneutrales Stromsystem", PKNS). Although, the highest penetration rate can occur with a strong expansion of charging infrastructure, low battery costs and in combination with strict CO_2 emission standards (Statharas et al., 2019), one has to consider that charging infrastructure and drive technology also require more rare earths and lithium for battery production. Here, trade dependencies must be taken into account (see Sect. 6.4).

Overall, the foreseen surge in electric vehicle deployment brings about a substantial rise in electricity generation demand across the EU. This effect is well visible in the *Tech* configuration (see Figure 2.9) with demand for the transport sector increasing nearly tenfold from approx. 64 TWh in 2020 to approx. 608 TWh in 2050 (approx. 250 TWh in 2030). Independent of the scenario chosen, a significant rise in electricity demand from the transport sector over the current decade seems unavoidable.

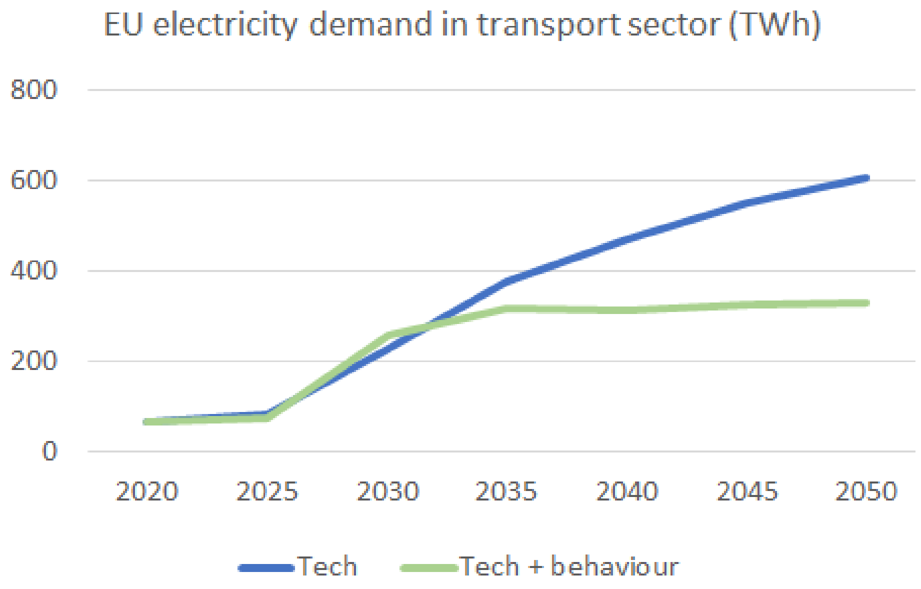

Figure 2.9: The effect of changes in consumer behavior on the demand for electricity in the EU transport sector (both passenger and freight).

2.4. Conclusions and Key Messages

Summing up, although behavioral changes can contribute to energy savings, there is still a need for widespread adoption of electrification technologies such as electric heat-pumps and battery electric vehicles at the consumer level - which will require to tap into large amounts of renewable energy potential as explored in section 3. However, the speed of this transformation is constrained by the current stock of heating technologies and vehicles. Europe needs to develop new economic sectors in these areas as it currently relies too heavily on imports. Additionally, the expansion of new heating systems and vehicles is limited by the retirement of existing systems. This requires a socially acceptable approach to change.

Policymakers in the EU are increasingly recognizing the importance of behavioral change to achieve climate targets as a complement to the deployment of low-carbon technologies.

1. Changes in consumer behavior alone do not lead to the necessary emission reductions compatible with stringent climate protection goals, nor can they cover the increasing demand for electricity through the necessary transformation of the energy sector.
2. However, the dampening of electricity demand (sufficiency) is quite considerable and can add up to 20% in the building sector alone, e.g. through the intelligent use of more efficient appliances, or new building materials.
3. In the transport sector, electrification of the vehicle fleet is a key technological innovation for decarbonization, but it also carries the risk of a sharp increase in electricity demand and market pressure on rare earths, cobalt, nickel and lithium for battery production.
4. Incentive schemes to promote alternative mobility concepts can help stabilize electricity demand from this sector at around 260 TWh/yr between 2035 and 2050 and would almost halve the demand compared to unchanged usage profiles.

3. European Renewable Energy Potentials

The transformation of the European electricity sector towards European autarky requires the assessment of the theoretically possible generation potential but also the possible provision of the necessary technology and engineering services. As indicated in Chapt. 1, due to the short time horizon until 2030, this study starts with a scenario in which electricity generation is based on existing technologies - risks of creating new dependencies via this approach are discussed in Sect. 6.4.

The REPowerEU Plan assumes that renewable energies are the cheapest and cleanest energy available and can be generated domestically, thus reducing our need for energy imports (EC 2022b). So far, the EU targets are quite compatible with the approach of this study. The European Commission proposes to increase the renewable energy target for 2030 from the current 40% to 45% (final energy). The REPowerEU plan would increase total renewable energy generation capacity to 1,236 GW by 2030, compared to the 1,067 GW envisaged under Fit for 55 for 2030. In this plan, the expansion of photovoltaics plays a pivotal role, as more than 320 GW of newly installed photovoltaics are to be connected to the grid by 2025, i.e. about twice the current level, and almost 600 GW by 2030.

Based on these policy goals, one can therefore also state that, according to the European Commission, 2022 was a record year for the European photovoltaic market, with annual growth of 17-26 % in the largest EU member states. The industry group SolarPower Europe shows that solar energy is growing rapidly across the continent (SolarPower Europe, 2022). According to the report, 41.4 GW of solar energy was installed in the EU in 2022, 47% more than in 2021, when 28.1 GW was installed.

In terms of wind energy, about 17 GW of new wind capacity was created in Europe in 2021 (EU27, about 11 GW) (cf. Wind Europe 2021). About 80 % of the new wind turbines installed in Europe in 2021 were onshore wind turbines. Sweden, Germany and Turkey added the most. Most of the new offshore wind turbines were installed in the United Kingdom. In total, Europe now has 236 GW of wind power capacity. Looking ahead, Windpower Europe (2021) expects another 116 GW of new capacity to be added between 2022-2026, of which around 75% will be onshore turbines. For the EU27, the average is about 18 GW per year, but 32 GW would be needed to reach the new EU target of 40% renewables.

Since the 40% target has since been increased to 45%, it is clear that the expansion targets are far from being achieved. After two COVID19 years, wind turbine suppliers have had a record year for deliveries, despite pressure on the supply chain and the market. In 2021, for example, approximately 30,000 wind turbines were installed globally by about 30 manufacturers. Of these, 18 are based in the Asia-Pacific region and 9 in Europe (see Sect. 6.4 regarding market dependencies).

Although this study refers to the leviable potential in Europe's entire renewable energy sector, it will also make clear how large the deficits still are with regard to a green power sector actually implemented by 2030. Nevertheless, the European Green Deal presented by the President of the European Commission, Ursula von der Leyen, explicitly calls for the current fossil fuel-based energy model in the EU to be replaced by renewable technologies by 2030, the current pace of expansion is far from sufficient to achieve these goals. Therefore, there is a need to explore in parallel which energy technologies can become an important pillar of energy supply in the EU by exploiting the abundant natural resources in the region, such as solar and wind energy, wave and tidal energy, hydropower and geothermal capacities. In the following, we will therefore first outline which technical potentials are generally available for renewable-based electricity generation.

3.1. Wind and Solar Potential in Europe

3.1.1. Wind Potential

Theoretically, the earth's winds could provide enough energy to meet the global demand for electricity with almost no emissions, even if the demand for electricity continues to grow (Marvel et al. 2013). However, the energy density of the winds in the atmosphere is highly uneven. It would be more profitable to exploit kinetic wind energy at high altitudes, but conflicts with air traffic have to be taken into account. From a global perspective, there is a potential of about 400 TW of kinetic energy at the earth's surface - which, in conjunction with the efficiency of 40-45% for modern wind turbines - implies that about 180 TW of electrical energy from wind is available worldwide.

The global annual average wind speed at the average wind turbine height (100 m) in Europe is shown in Fig. 3.1. Strong winds (>9 m/s) are mostly evident along the coastal areas of Europe and more specifically at the Atlantic Ocean, the North Sea and the Baltic Sea coastlines. Moreover, the wind potential at certain regions in the Mediterranean, such as the Aegean Sea and the Gulf of Lion is also comparable to that of the North European coastlines, with an average wind speed exceeding 8 m/s. Local wind patterns in the Mediterranean, like the Mistral in southern France and the Etesians winds in Greece, last for several consecutive days per year providing a stable energy source for direct consumption or for storage (i.e. hybrid wind-hydroelectric plants, hydrogen storage etc.).

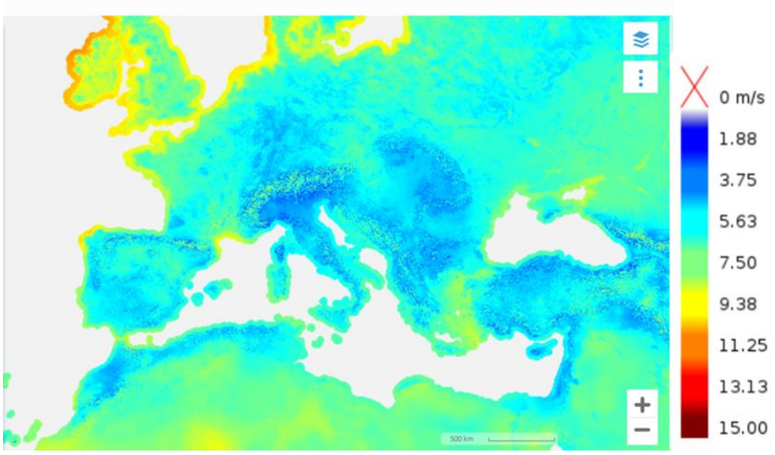

Figure 3.1: Annual average wind speed (m/s) from the Technical University of Denmark via the Global Wind Atlas. It takes into account small-scale spatial variability of winds speeds and surface roughness change effects.
(Source: https://globalatlas.irena.org).

In 2021, about 15% of the total electricity consumption in Europe is covered by onshore and offshore wind energy production (Tab. 3.1). This share is projected to increase in the following years, according to the plans for new installations of up to 20-27 GW per year until 2026 (Fig. 3.2).

Table 3.1: Electricity production from wind power in 2021 in the EU27+UK (TWh) (Wind Europe 2021).

EU + UK electricity consumption (TWh)	Onshore wind energy production (TWh)	Offshore wind energy production (TWh)	Total wind energy production (TWh)	Share of consumption met by wind energy
2,921	357	80	437	15%

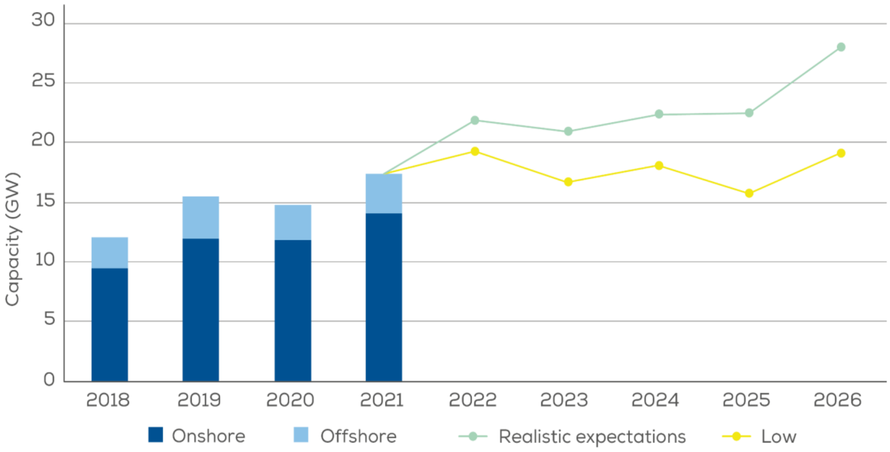

Figure 3.2: Projection of new onshore and offshore wind installations in Europe 2022-2026 (Wind Europe 2021).

Increasing the reliance on weather-dependent resources for electricity production makes it imperative that the planning of electricity systems considers the temporal variability of wind resources at inter-annual, seasonal and hourly scales (cf. also Chapt. 5). For example, the inter-annual variability of combined onshore and offshore generation for 2021 that is shown in Fig. 3.3 indicates a limited energy production from wind power in the EU during the summer months. This is related to the location of most wind power installations in the northern parts of the continent, where strong weather systems are commonly prevailing during the winter months (Fig. 3.4A). The lack of wind energy during summer could be compensated by the installation of more offshore plants in the Mediterranean that is characterized by several strong wind patterns during the summer, such as the Etesians in the Aegean Sea. At local scale, the wind potential for specific areas in the Aegean can reach up to 20 m/s as seen in Fig. 3.4B.

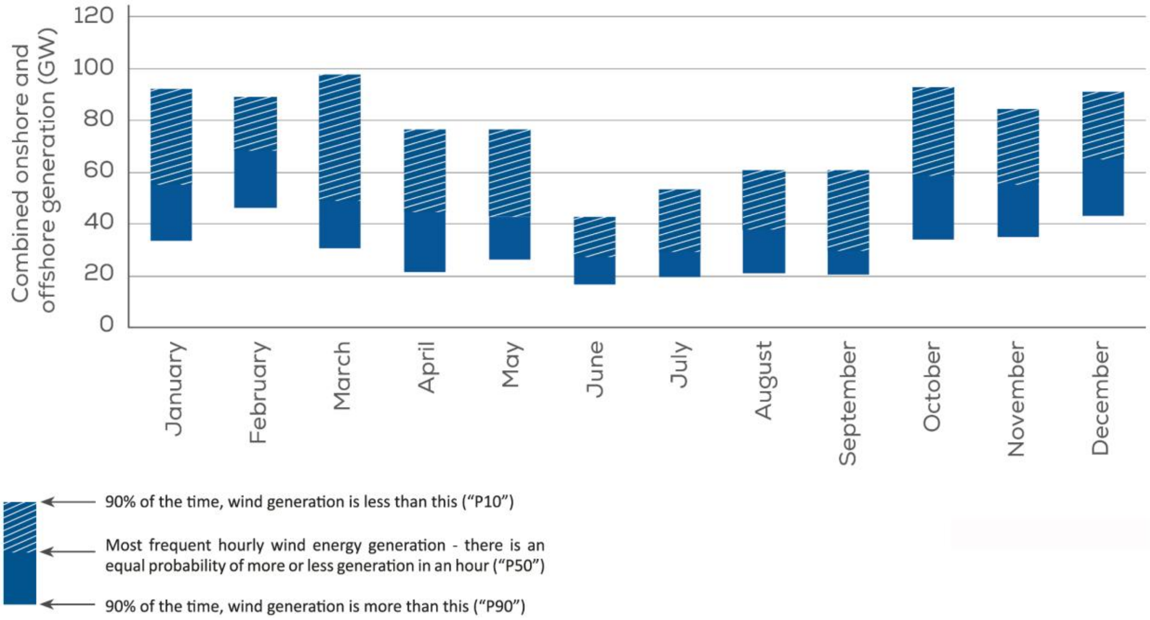

Figure 3.3: Spread of hourly wind energy generation in Europe in 2021 (after: Wind Europe 2021)

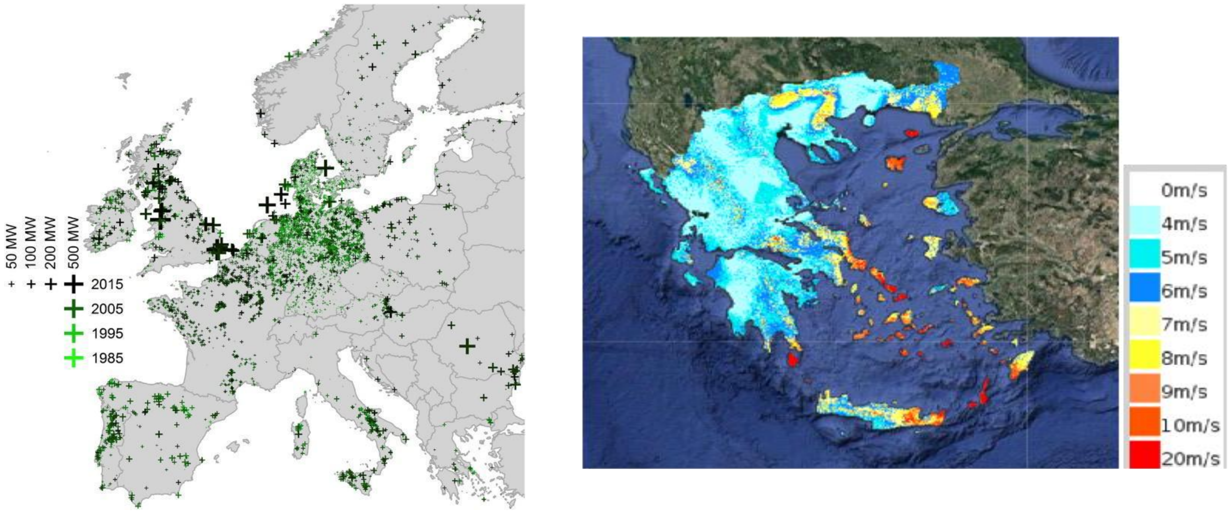

Figure 3.4: A - left: Europe's wind farms as of 2015. Darker colors signify newer farms, and marker size is proportional to farm capacity (after: Collins et al. 2018). B - right: Wind potential (m/s) at 120 m over Greece. (Source: Regulatory Authority for Energy (RAE), Greece).

3.1.2. Solar Potential

The World Bank in collaboration with SolarGIS conducted a global survey of the electricity generation potential of Solar PV technologies. From their results, the solar power potential is adequate for economic exploitation in Europe, especially in South Europe. As seen in Fig. 3.5**,** the yearly total potential for photovoltaic electricity production in the southern parts of Spain, Italy, Greece and Cyprus exceeds 1,700 kWh/kWp per annum and is comparable to the values obtained over North Africa and the

Middle East (in regard to the explanation of kWp refer to Box 3.1). The solar potential at country level is also shown in Fig. 3.6 for selected countries.

As documented in these maps, the average yearly total solar electricity generation potential exceeds 2,000 kWh/kWp/year for Spain, 1,600 for France, 1,700 for Italy, 1,750 for Greece and 1,700 for Cyprus. Significant solar potential is also available for northern European countries with 1,250 kWh/kWp/year for Germany, 1,150 for Sweden, 1,000 for the Netherlands and 1,400 for Romania.

Box: 3.1: Definition of Kilowatt Peak (kWp) performance

kWp is the maximum electrical power that a PV system can produce under standard conditions. The electrical power produced by a solar panel depends on the time of day and the season, the atmospheric layer, the geographical position, orientation and the tilt angle of the solar panel. The watt-peak (Wp) is therefore the maximum electrical power that can be supplied by a photovoltaic panel under standard temperature and sunlight conditions, defined as:

Solar irradiation power = 1,000 Watts/m^2.
Ambient temperature = 25 °C (temperature affects the efficiency of the photovoltaic panels)
Air density = 1.5 kg/m^3 (clear sky)
Incidence angle = 90° (perpendicular to the plane of the panel)

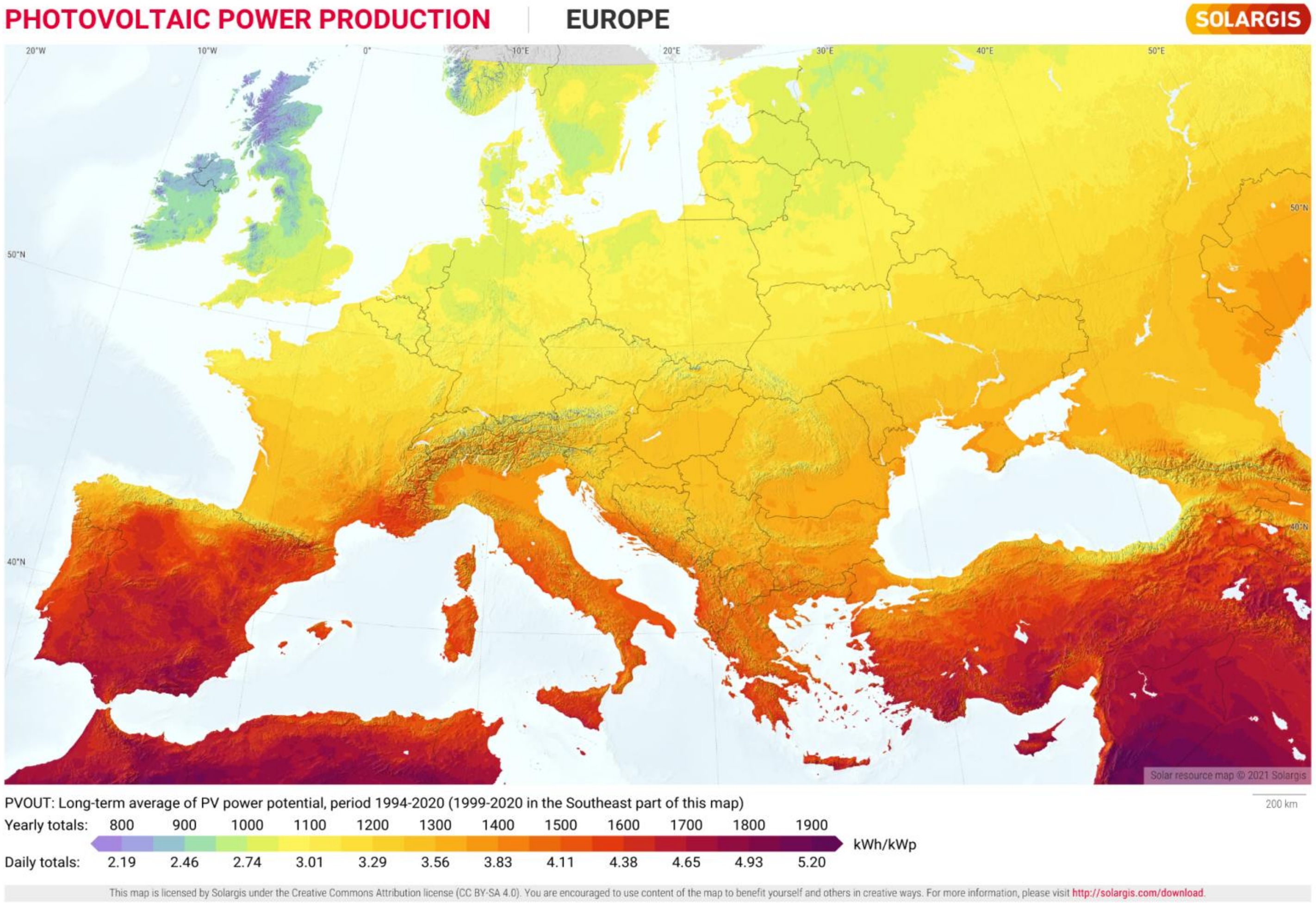

Figure 3.5: Potential photovoltaic electricity production (Source: Global Solar Atlas 2.0: 2023).

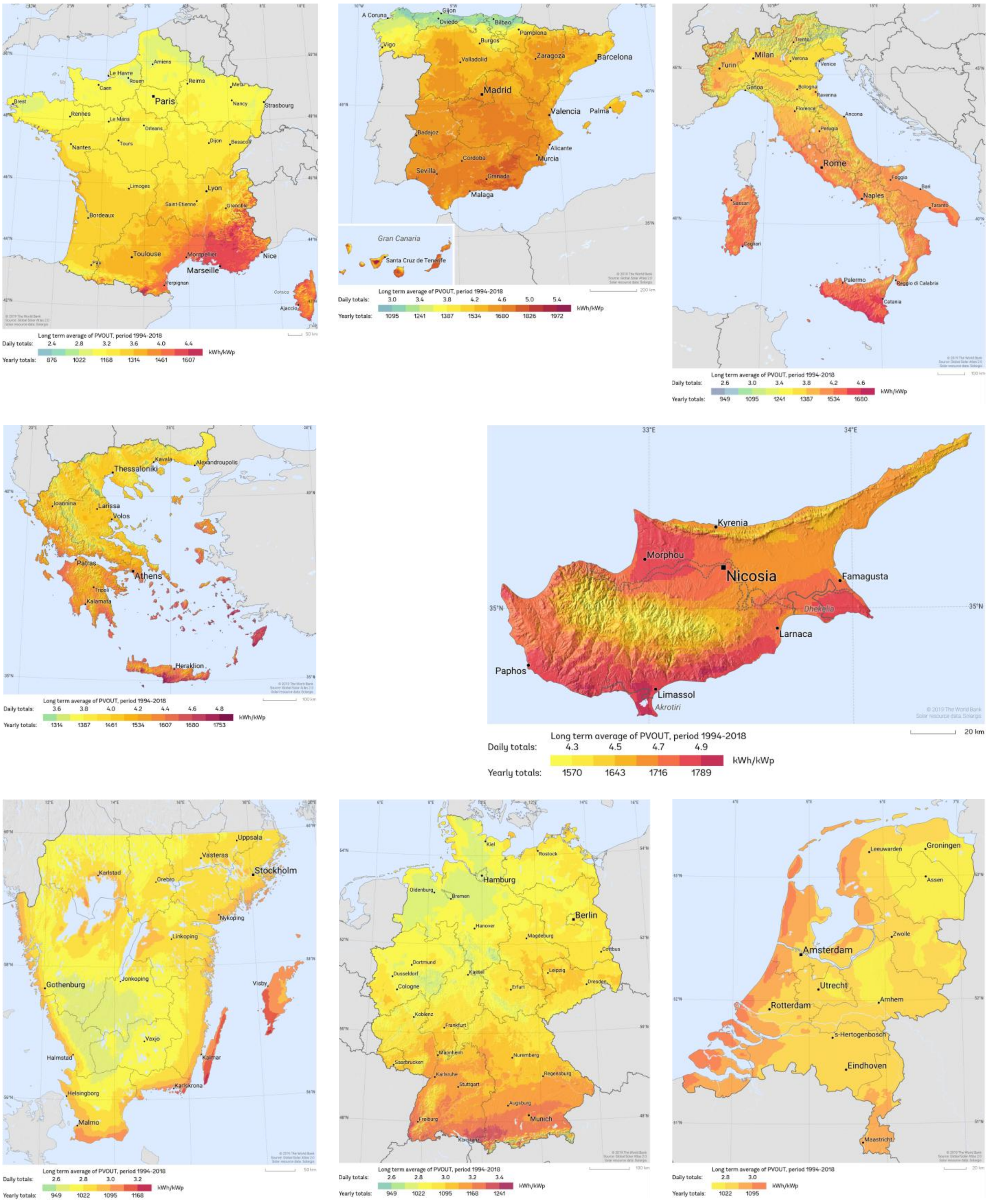

Figure 3.6: Photovoltaic Power Potential for France, Spain, Italy, Greece, Cyprus, Southern-Sweden, Germany, and the Netherlands (Source: Global Solar Atlas 2.0, 2023).

Although large electricity generation potential from Solar PV exists in Europe, the seasonality of the generation is the prime impediment in terms of rapid uptake of Solar PV technology. Figure 3.7 visualises the geospatial spread of the Seasonality Index within Europe. As can be observed from the figure, low seasonality (cf. Box 3.2) in power generation (Seasonality Index ≦2) exists in Southern parts of Europe, with high seasonality (Seasonality Index > 2) existing in the Scandinavian parts of Europe. This variation in seasonality of the power generation renders some countries in Europe more suitable for a reliable yearly power generation from Solar PV. In Germany, the average value of the seasonality index is around 4.4, meaning that there is less than a quarter of electricity generation in the lowest winter month compared to the best-performing summer month.

Box 3.2: Definition of a seasonality index for solar exploitation potentials

Although the annual solar yield is often the most indicative value for project evaluation, its seasonal distribution is also quite important. The 'seasonality index', is calculated as a ratio between the highest and the lowest average monthly potential values in an average year:

$$PVOUTSEASON = MAX[m_{01}, m_{02}\ldots, m_{12}] / MIN[m_{01}, m_{02}\ldots, m_{12}]$$

Where:

$MAX[m_{01}, m_{02}\ldots, m_{12}]$ = Highest monthly average yield of PV_{OUT} for a country/region

$MIN[m_{01}, m_{02}\ldots, m_{12}]$ = Lowest monthly average yield of PV_{OUT} for a country/region.

*PVOUT*SEASON = Seasonality index

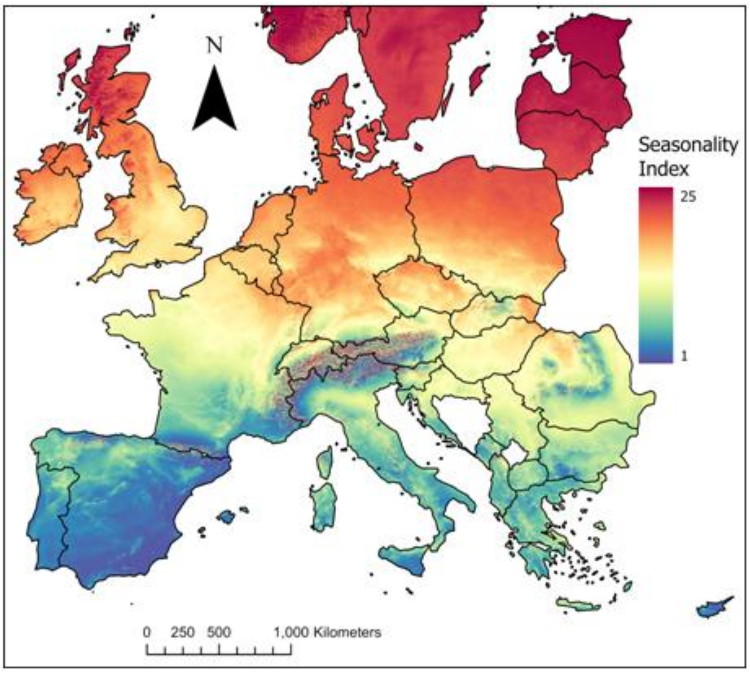

Figure 3.7: Seasonality Index for European Countries (source: Suri et al. 2007).

Another important aspect when understanding the potential for Solar PV in Europe is to analyse the investment cost trends for installing 1 kWp capacity for utility, commercial and residential Solar PV. Figure 3.8 charts out the installation cost – disaggregated by various cost components for Utility Solar PV (Panel A) for the year 2020. Although the average costs across Europe are clustered together below 1,000 USD/kWp installed capacity, Cyprus and Germany can be considered as two outliers. Cyprus with its beneficial Seasonality Index and high Solar PV power generation potentials can benefit from lower costs due to a higher generation level, while Germany with its medium Seasonality Index and medium

Solar PV power generation potentials is benefiting from lower installation costs from the local manufacturing companies. Panels B and C chart the rapid decline in installation costs for Residential and Commercial Solar PV over the better half of the past decade. From the trends, it can be observed that Commercial Solar PV is cheaper in Europe than Residential Solar PV. Upon comparison, Utility Solar PV is the cheapest installation topology, followed by Commercial and Residential Solar PV.

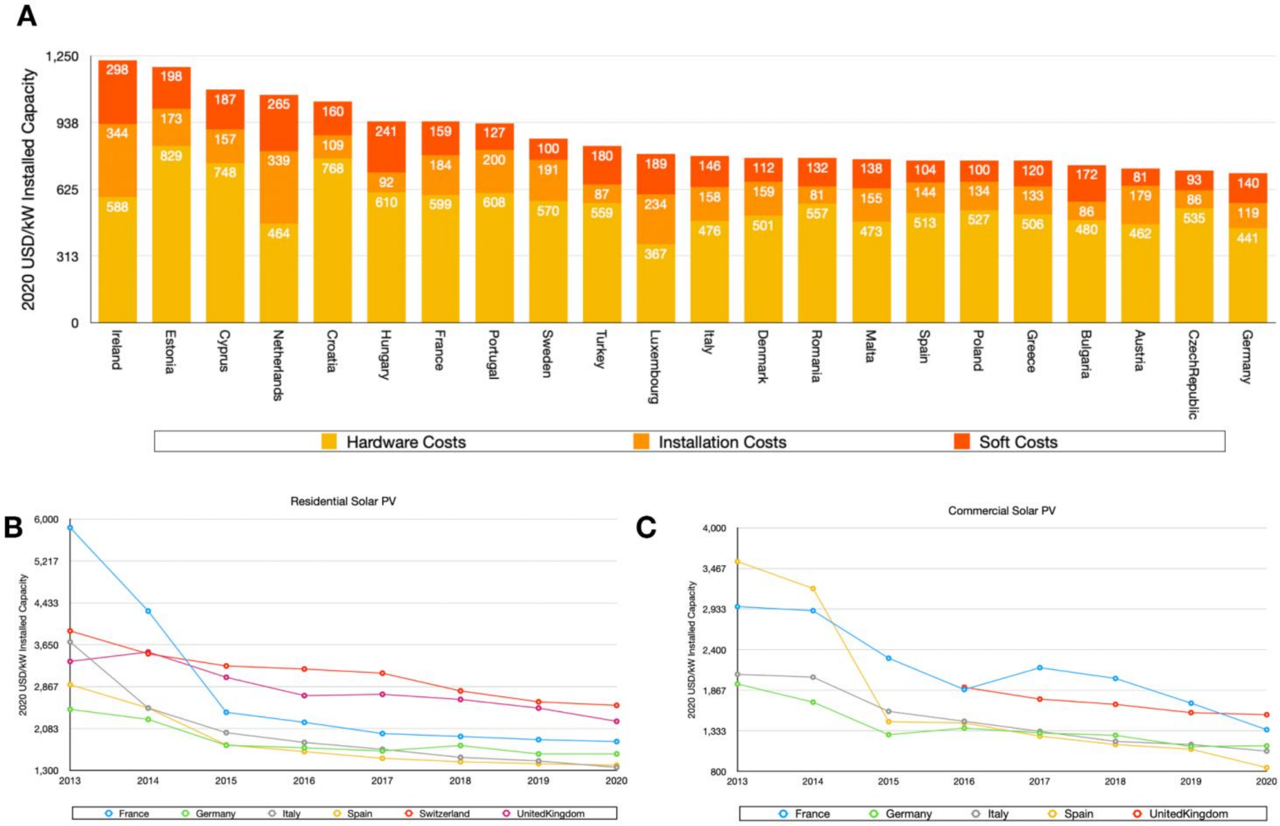

Figure 3.8: Installation Cost trends for Utility (Panel A), Commercial (Panel B), and Residential Solar PV (Panel C), topologies in Europe (source: IRENA (2022)

To summarize the results from Fig. 3.8, besides the stock take of current installed capacity of Solar PV in Europe, the different shares of PV systems are also relevant for a mid-term energy planning. Figure 3.9 visualizes the trends in total installed capacity for different topologies of Solar PV in Europe. In total, by the end of 2021, Solar PV in Europe had a net installed capacity of 198 GWp. Amongst these, Commercial Solar PV formed the largest chunk with 82 GWp installed capacity followed by Utility Solar PV with 68 GWp installed capacity and finally Residential Solar PV with 43 GWp installed capacity in 2021. This would imply that in Europe, the major focus until now has been on roof mounted Solar PV in both Commercial and Residential sectors.

Figure 3.10A maps the results of the assessment of the spatial spread of gross rooftop area in Europe for 2015 based on a study by Joshi et al. (2021). A zoomed-in view for Germany is provided in the same figure as a panel. Each pixel in the image corresponds to 100 km^2 of spatial area, with maximum gross rooftop area per pixel is estimated between about 12 km^2 and 0.01 km^2. The hotspots for gross rooftop area are contained within 50 km of major cities of Europe (Fig. 3.10B). Nevertheless, more than 50% of the rooftop area exists outside of it (cf., e.g. also Tab. 6.1). This implies that a large part of geolocation for deployment of future rooftop Solar PV Potentials in Europe lies outside the major cities.

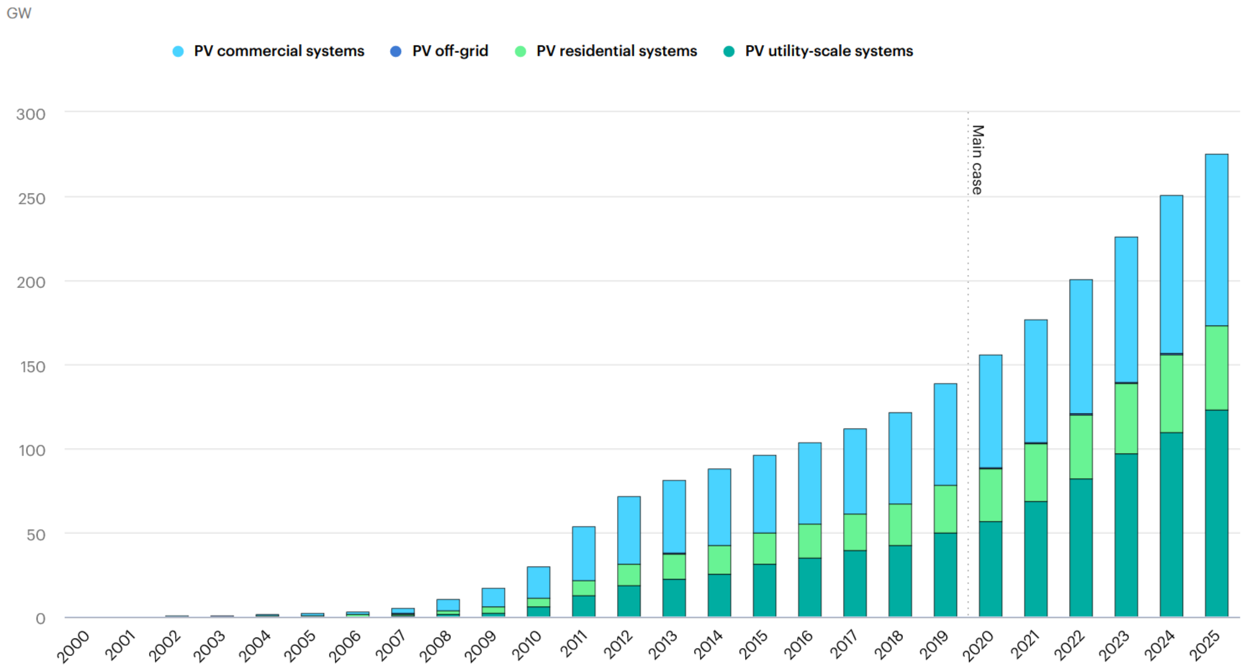

Figure 3.9: Net installed segment capacities and future trajectories for Solar PV by sector in Europe (source: IEA Renewables Report 2023)[14].

The study by Joshi et al. (2021) applied a hybrid method that leveraged the top-down information from remote-sensed imagery and bottom-up geo-mapped metrics like population count, road length and open-source building footprint area. The original results of the study were documented for global landmass, with an assumption of 10% Panel Efficiency and 100% Gross Rooftop Area being used for placing roof-mounted Solar PV (Fig. 3.11). In this report, the results were recalculated for 16% panel efficiency and 56% of gross rooftop area being available for installing roof-mounted Solar PV, based on Tröndle et al. (2019). These advanced assumptions were made to incorporate the loss in gross rooftop area due to shading, orientation and slope of the rooftops. On comparing the results of technical potential for rooftop Solar PV in Europe based on studies by Tröndle et al. (2019) and Joshi et al. (2021), a large range of uncertainty exists, e.g. for France and Germany. This uncertainty can be attributed to the methods used in the assessment of the potential, where Tröndle et al. (2019) focussed on using European Settlement Maps for the calculation of rooftop area and Joshi et al. (2021) used a hybrid method for it. European Settlement Maps have a general tendency to overestimate rooftop area (Bodis et. al. 2019), but are valuable for mapping and quantifying geospatial spread of rooftop area at a high resolution in the EU. Other sources of uncertainty correspond to the assumption of how much of the gross rooftop area is actually usable for the installation of rooftop Solar PV. Global data ranges around 30% of gross rooftop area, whereas studies used in Tröndle et al. (2019) infer an average value of 56% (cf. Sect. 6.1 for further details). Tröndle et al. (2019) also conducted a Europe-level assessment of Utility Scale Solar PV by generating exclusion masks for land areas that are unsuitable for installation of ground mounted (Open Field) Solar PV (cf. Sect. 6.1).

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[14] https://www.iea.org/fuels-and-technologies/renewables

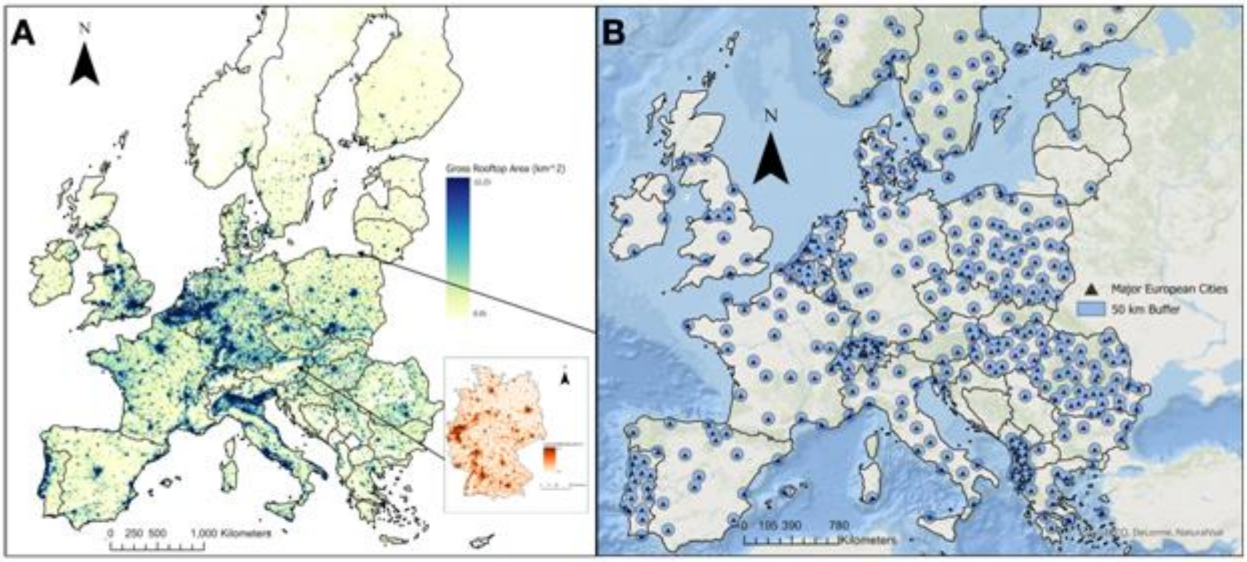

Figure 3.10: A) Spatial spread of gross rooftop area in 2015 for Europe. B) Major cities of Europe with 50 km buffer around them (source: Joshi et al. (2021), ESRI).

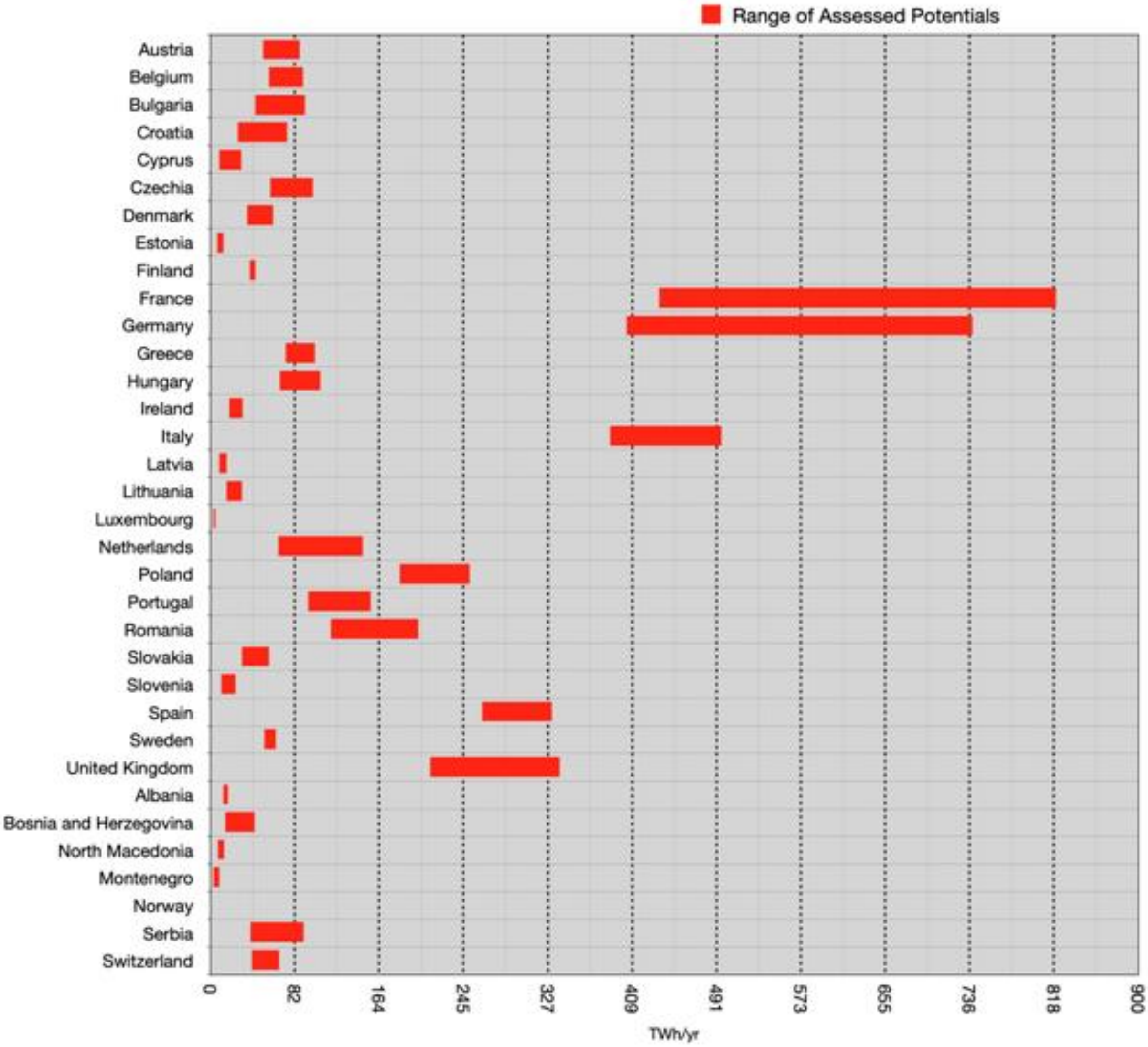

Figure 3.11: Range of assessed average yearly rooftop solar PV potentials for European countries (source: Joshi et al. (2021), Tröndle et al. (2019).

3.2. Offshore Renewable Energy Potential in EU

Offshore sites are characterized by stronger and more consistent winds; therefore, the deployment of floating offshore wind turbines is a major task in Europe in the frame of the Green Deal. Exploiting the potential for both offshore wind and ocean energy in all 5 sea basins of the EU (North Sea, Baltic Sea, Mediterranean Sea, Black Sea, Atlantic Ocean) in the following decades would provide up to 300 GW from offshore wind energy and up to 40 GW from wave and tidal energy until 2050 (EC 2020c)[15].

3.2.1. Offshore Wind Energy

As seen in Fig. 3.12, the offshore wind potential is available in all European Seas, with bottom fixed or floating turbine technologies depending on the water depth and exclusive economic zones. These technologies are more mature in the North Sea due to the shallow waters and due to the potential for wave and tidal energy. The North Sea is the most exploited region in terms of offshore wind park installations (Fig. 3.13), and it is expected to provide up to 117 GW of renewable offshore power until 2030 (Tab. 3.2).

The Baltic Sea also offers a high natural potential for offshore wind energy and some localized potential for wave energy (EC 2019). The EU's Atlantic Ocean also has a high natural potential for both bottom-fixed and floating offshore wind energy and a good natural potential for wave and tidal energy (EC 2020a). Member States in these regions have established strong regional cooperation and networks for the exploitation of marine renewable energy.

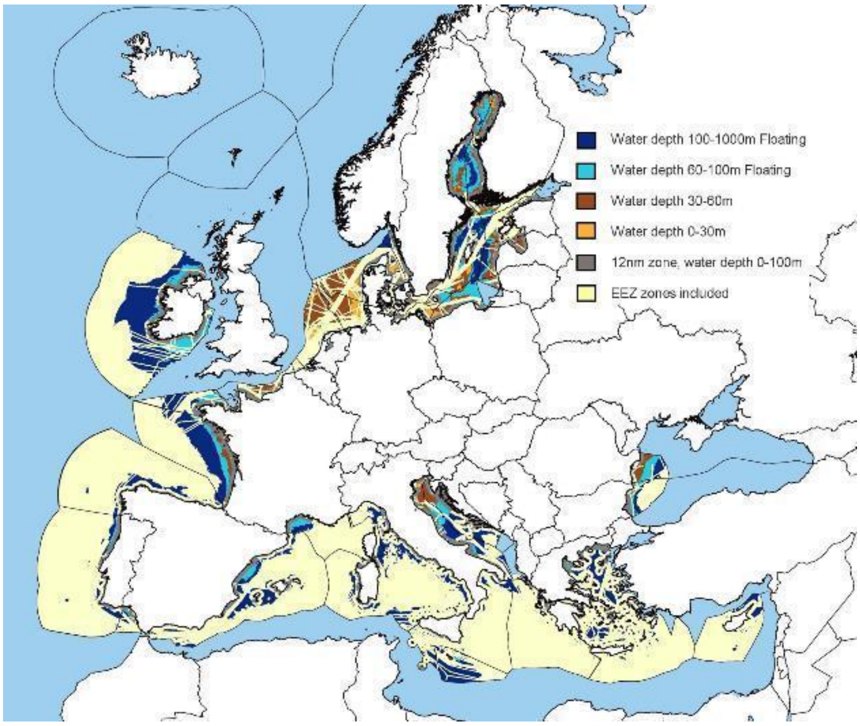

Figure 3.12: Offshore wind technical potential in sea basins accessible to EU27 countries (JRC 2019).

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[15] https://ec.europa.eu/commission/presscorner/detail/en/fs_20_2099

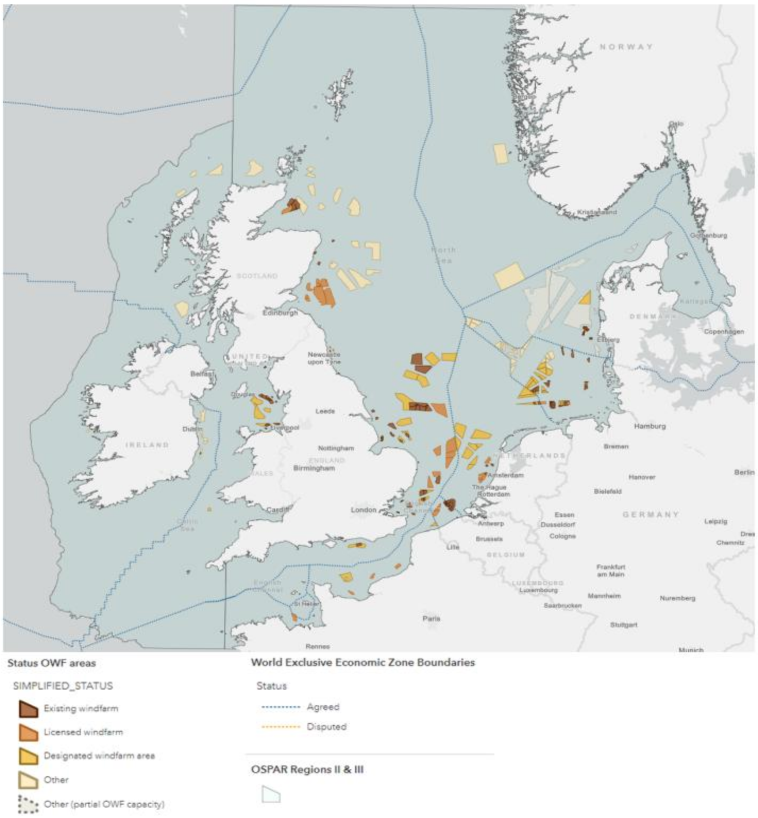

Figure 3.13: Overview of existing offshore wind farms in the North Sea and planned developments up to 2030 (Haskoning DHV 2022).

Table 3.2: Existing offshore energy capacity and ambition for 2030 at the North Seas (after Haskoning DHV, 2020).

Country	Existing Capacity (GW)	Planned Capacity (GW) until 2030	Ambition for 2030 (GW)
Ireland	0.025	4.6	7
France	0	5.3	5
Belgium	2.3	3.5	5.4-5.8
Netherlands	2.5	18.5	21
Germany	7.7	18.9*	30*
Denmark	2.3	10.5*	12.8*
Norway	0	unknown	4.5
UK	11	unknown	50
Total	**25.8**	**61.3**	**124.8**
*not limited to North Sea			

The Mediterranean Sea has a high potential for offshore energy production (mostly from floating wind turbines), good potential for wave energy and localized potential for tidal energy (EC 2020), but the technological developments are not yet mature in this area. The extended marine Exclusive Economic Zones (EEZ) of the Mediterranean countries (Fig. 3.14) determine the need to investigate additional opportunities for offshore renewable energy production. An analysis has been recently conducted by the Directorate-General for Energy of the EU (EC 2020), to describe the off-shore wind, solar and wave energy potentials in the Mediterranean. Based on this study, the most promising technology appears to be the installation of floating wind turbines (Tab. 3.3). The technology of floating wind turbines is not yet in a fully mature state but is expected to evolve quickly in the forthcoming years. Floating wind potential presents the most suitable solution for the Mediterranean due to the large areas with high wind speeds in the open sea and due to the deep bathymetry of the Mediterranean Sea that permits bottom-fixed installations. As seen in Tab. 3.3, the expected annual production from floating wind parks is about 4,600 TWh/yr by 2030 and 4,700 TWh/yr by 2050. The second more promising technology in the Mediterranean is the wave potential, reaching about 4,500 TWh/yr (Tab. 3.3), with minor contributions from bottom-fixed and tidal potentials. As a comparison, the more mature technologies of onshore wind and solar PV farm installations on the islands, have a technical potential of 60 and 207 TWh/yr respectively. A practical limitation for offshore wind farms is that they must be installed at least 12 nautical miles away from shore.

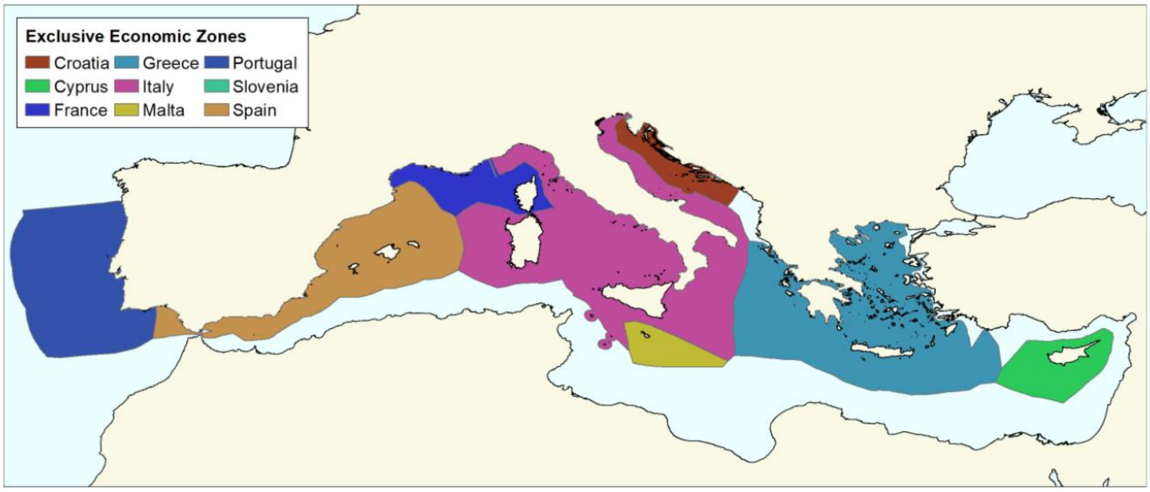

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Figure 3.14: Exclusive Economic Zones of EU countries in the Mediterranean Sea (EC 2020).

Table 3.3: Annual technical resource potential for offshore technologies.

Country	Bottom-fixed wind potential 2030 (TWh/yr)	Bottom-fixed wind potential 2030 (TWh/yr)	Floating wind potential 2030 (TWh/yr)	Floating wind potential 2050 (TWh/yr)	Wave potential 2030 and 2050 (TWh/yr)	Tidal potential 2030 and 2050 (TWh/yr)
Croatia	17.9	22.9	313.2	325.3	0.0	0.0
Cyprus	0.0	0.0	109.7	128.1	0.0	0.0
France	0.0	0.0	271.0	276.5	174.6	0.0
Greece	0.0	0.0	840.3	858.4	1,810.3	0.0
Italy	24.2	31.9	1,610.2	1,622.9	623.6	0.1
Malta	1.4	1.4	430.5.	440.4	341.0	0.0
Portugal	1.9	1.9	427.3	436.3	887.9	0.0
Slovenia	0.0	0.0	0.0	0.0	0.0	0.0
Spain	1.0	1.1	580.5	594.0	660.8	22.0
Total	**46.3**	**59.2**	**4,582.6**	**4,722.0**	**4,498.3**	**22.1**

An example for the offshore wind potential in the Mediterranean Sea is shown in Fig. 3.15, indicating that the Aegean, South Ionian, Gulf of Lion and the Sicily – Tunis straits are the most promising areas for offshore wind production installations in this region. Unlike the North Seas, the fixed bottom wind potential is limited in the Mediterranean Sea due to the relatively deep waters. The areas available for floating wind turbines are much larger and could provide a maximum potential of 38 GWh/km^2/yr in particular in the Aegean Sea and along the Atlantic cost of Portugal (Fig. 3.16).

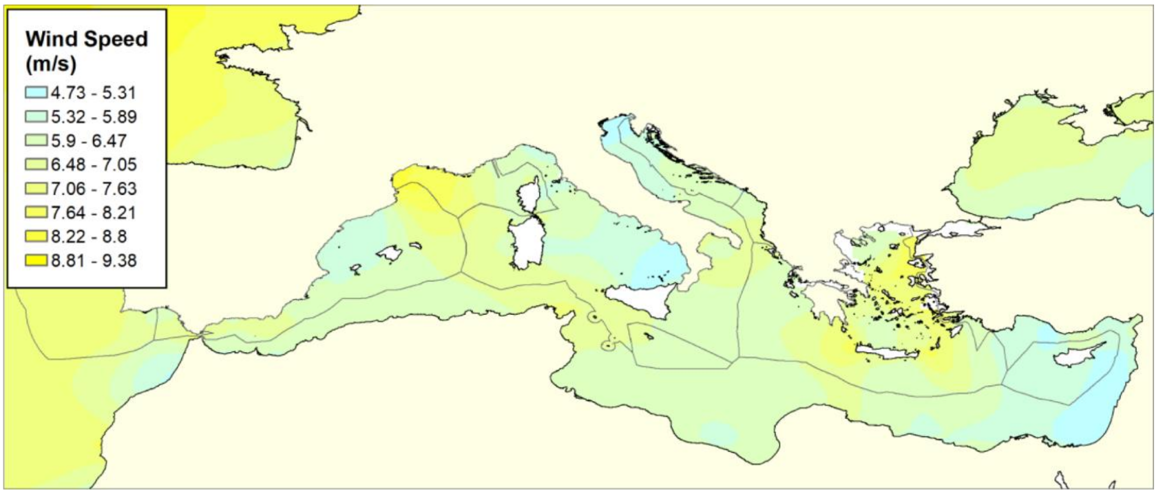

Figure 3.15: Annual average wind speed at 10 m above sea level in the Mediterranean Sea (Source: EC 2020).

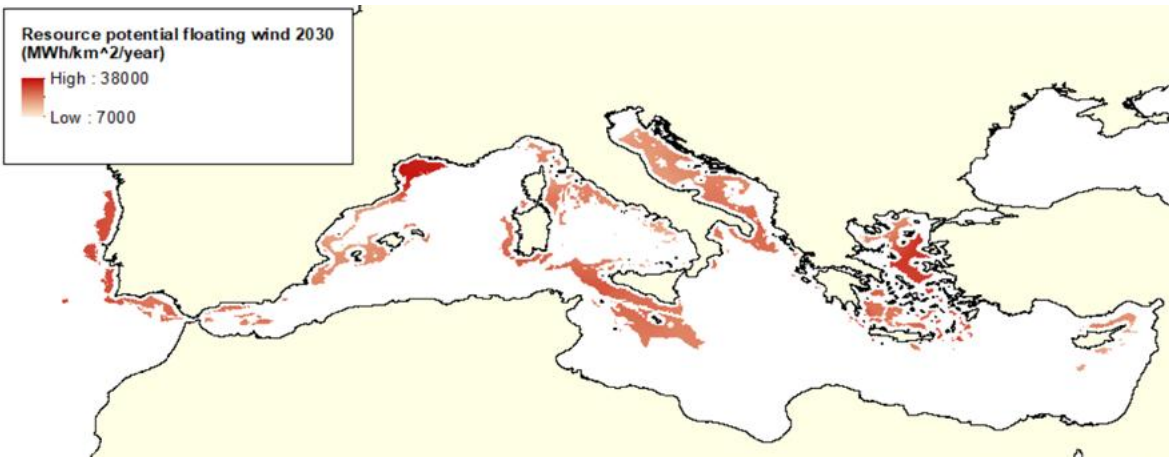

Figure 3.16: Resource potential for floating wind turbines in 2030 in MWh/m^2/yr (Source: EC 2020).

3.2.2. Offshore Solar Energy

Solar energy in marine areas is also prominent and as seen in Figure 3.17 it is exceeding 5 kWh/m^2/d in most southern regions in Europe. This potential could be exploited on several Mediterranean islands like for example Mallorca, Corsica, Sardinia, Sicily, Malta, Crete, Rhodes, Cyprus. The financial feasibility for both on-shore and off-shore power plants needs to be considered along with the connectivity options (cf. Sect. 5.4 and 7.2) to the nearest power grid at European level, but also with African and Asian countries. The latter option is particularly relevant in South Europe, as seen for example in Fig. 3.18. The islands of the Mediterranean Sea can rely on solar energy and become almost autonomous for their own needs, especially during the tourist peak period in the summer. Additionally, they can contribute to the energy needs in continental Europe but also provide the interconnections between Europe – Africa and Middle East power grids, to maximize the network stability and energy security.

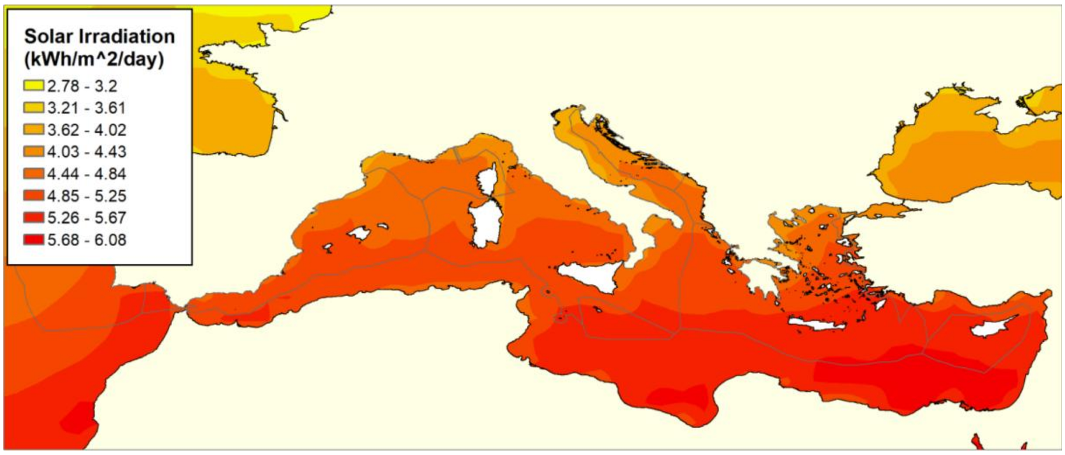

Figure 3.17: Solar radiation (kWh/m^2/day) in the Mediterranean Sea (Source: EC 2020).

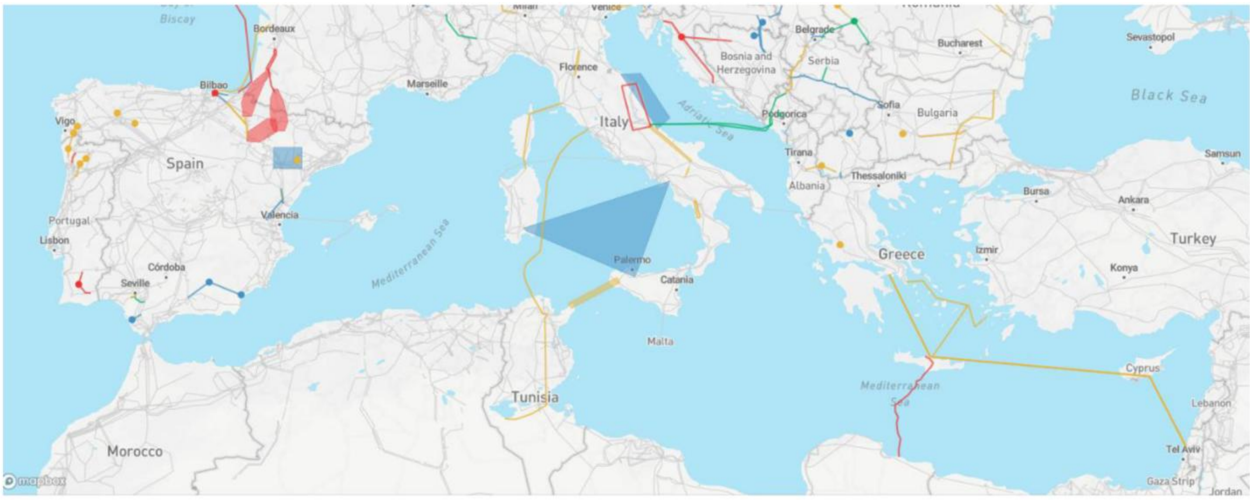

Figure 3.18: Transmission projects in or around the Mediterranean Sea (Source: EC 2020).

3.2.3. Wave Energy

Wave energy is related to both the amplitude and the period of the motion. Long period (≃7-10 s), large amplitude (approx. 2 m) waves have energy fluxes commonly exceeding 40-50 kW per meter width of oncoming wave (kW/m). As a result, the western coast of Europe is the area with the highest wave energy potential. This area is located at the end of the long fetch of the Atlantic Ocean and at the 30°N - 60°N latitude zone, which is affected by increased wave activity due to the prevailing western winds (Westerlies). As seen in Fig. 3.19, the wave power at the Atlantic coasts of Portugal, Spain and France ranges between 33 - 55 kW/m. At the west coasts of the British Isles and the north parts of the North Sea, the wave power is even higher, reaching up to 76 kW/m. On the other hand, the wave climate in such open oceans is very aggressive and may cause technological difficulties for the installation and operation of conversion systems. In the most sheltered and closed seas, such as the Mediterranean, the annual power level varies between 8 and 13 kW/m.

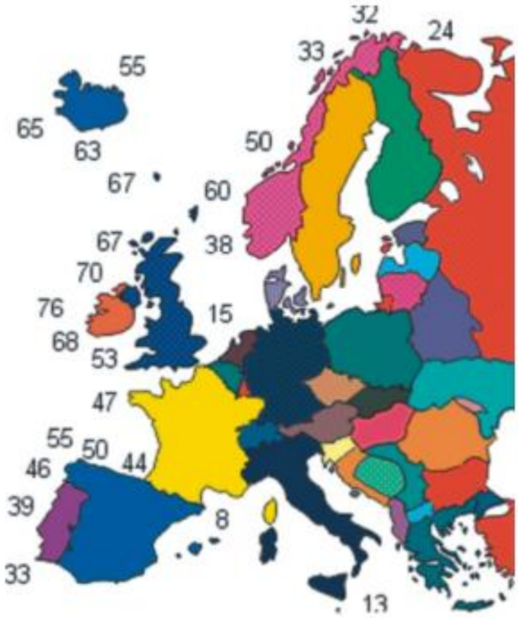

Figure 3.19: Wave power (in kW/m of wave crest length) in European waters (from CRES 2002).

A more detailed analysis of the production of electric power from sea waves in the Mediterranean is shown in Fig. 3.20. The most prominent regions in this area are shown in Fig. 3.22 - after the consideration of certain technological criteria, nature conservation aspects, shipping limitations etc. These areas include almost the entire Greek marine territory, the Italy-Tunis Strait and the Italian and France islands and coastlines.

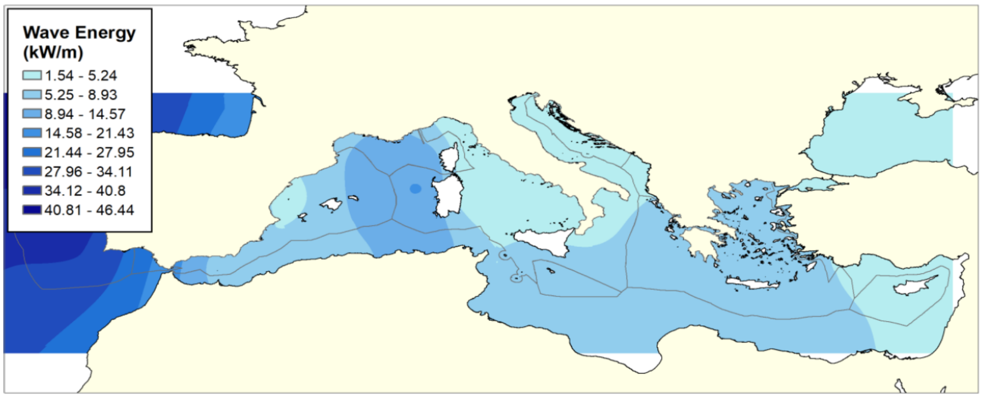

Figure 3.20: Wave energy resource level (source: EC 2020).

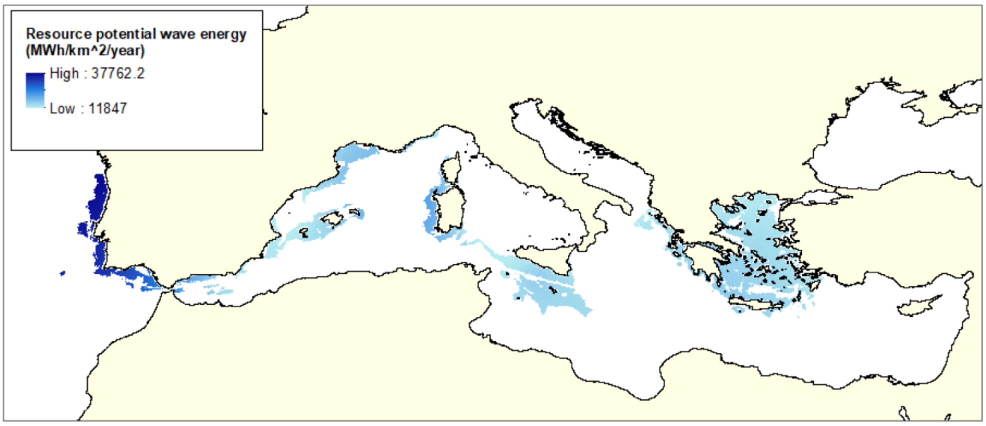

Figure 3.21: Resource potential for wave energy installations in 2030 and 2050 in MWh/km^2/yr (source: EC 2020).

3.3. Geothermal Energy

3.3.1. Deep Geothermal Energy

Exploitation of geothermal potential is also a renewable form of energy that needs to be considered in the frame of the EU targets for energy and climate. Reservoirs of very high temperature (>375°C) can be considered for Geothermal Systems with enhanced energy output per well, thus decreasing the number of required drills. The typical depths for such critical temperatures are at 12-15 km, however, certain geological formations imply their presence at shallower depths, as has been found for example in Larderello and Phlegraean Fields in Italy, Reykjanes in Iceland and the Geysers in California. In a recent study, Manzella et al. (2019) present the potential super-critical resources for geothermal energy in Europe based on temperature-depth potential, crust thickness and earthquake density.

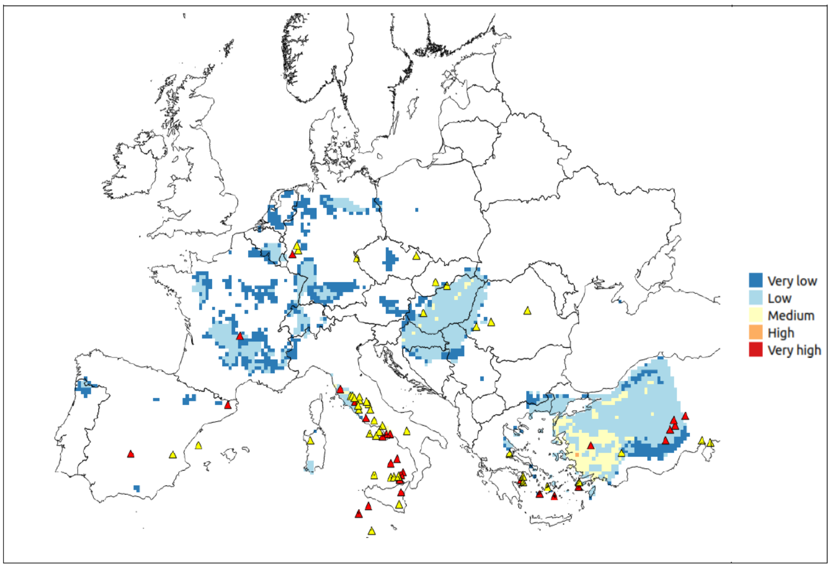

Figure 3.22: Map of favorability for supercritical geothermal resources, including the locations of Holocene volcanoes (red triangles) and Pleistocene volcanoes (yellow triangles) (from Manzella et al., 2019).

A combined map of favorability for supercritical geothermal resources, also including the location of recent (Pleistocene-Holocene) volcanism, is shown in Fig. 3.22. Certain areas in Europe and especially in the Mediterranean, i.e., in France, Italy and Greece, can be exploited for geothermal potential, due to the existence of active volcanoes. The spatial distribution of heat-flow potential in Europe is shown in Figure 3.23, based on an updated database of heat-flow values, to which paleo-climatic correction is applied across the continent (Majorowicz & Wybraniec, 2011). As shown in the map, the potential for geothermal energy is very significant, especially in Southern Europe. In Italy and Greece, the onshore heat flow density exceeds 200 MW/m^2 in certain areas. Extended areas of increased heat flow (> 100 MW/m^2) are also evident in central France. In general, the geothermal potential is higher in the southern European countries compared to North Europe. Statistics of the observed heat flow values in different countries for land and marine regions in Europe can be reviewed in different studies (e.g. Cermak et al. 1979). As shown significant observed heat flows over land have been identified in many European countries, such as in Iceland (146 MW/m^2), France (99), Switzerland (83) Germany (83) and Spain (82). The observed heat flow in marine areas with an overall highest observed value for Europe is found in the Tyrrhenian Sea (113 MW/m^2).

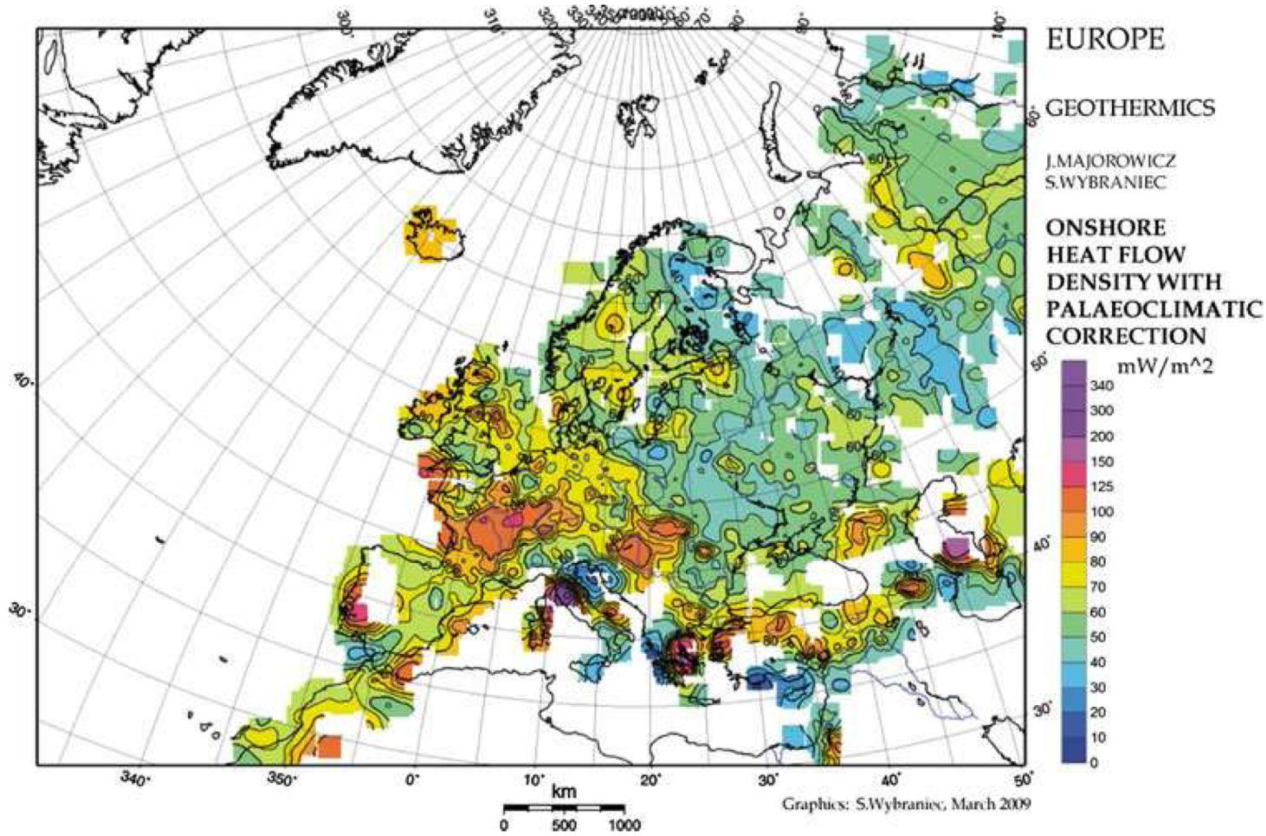

Figure 3.23: Heat flow (MW/m^2) map including paleoclimatic correction (from Majorowicz & Wybraniec, 2011)

Overall, the use of deep geothermal energy for electricity production accounts for an installed capacity of around 3 GW and therefore hardly plays a role in Europe. For example, there are only 39 deep geothermal plants (an example is "Geothermie Unterhaching[16]" which is in use since 20 years) in Germany. However, examples show that efficiencies of up to 90% can be achieved in the provision of heat via district heating[17]. Despite these facts, expansion would be possible in certain areas of Europe, as Figs. 3.22, 3.23 show. Recent studies estimate, based on model results, that up to 33 GW of geothermal power generation capacity can be installed in 2050, providing up to 210 TWh/yr. This would cover a maximum of 7% of total power generation in 2022 (Dalla Landa et al. 2020). However, the authors also foresee a European geothermal energy investment market (supply plus demand side) possibly worth about 160–210 billion US$/yr by 2050. For Germany, it is estimated that 70 GW installed capacity based on deep hydrothermal geothermal resources could cover one quarter of heat energy demand. With 1.7 TWh thermal energy, the sector plays only a minor role in Germany. To boost the capacities it is estimated that until 2030 investments of 33 bn € would be needed (Fraunhofer 2022a).

3.3.2. Shallow Geothermal Energy

Irrespective of the exploitation of deep geothermal energy, which is preferred for district heating systems shallow geothermal energy (low-enthalpy) will play a significant role in the future, because it will also be increasingly used in a decentralized manner. An example of this is e.g. Greece, where low-enthalpy geothermal energy is only used for direct use and not for electricity generation, despite the large geothermal potential in Europe (Figure 3.24).

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[16] https://geothermie-unterhaching.de/

[17] cf. e.g., https://www.geothermie.de/aktuelles/nachrichten.html

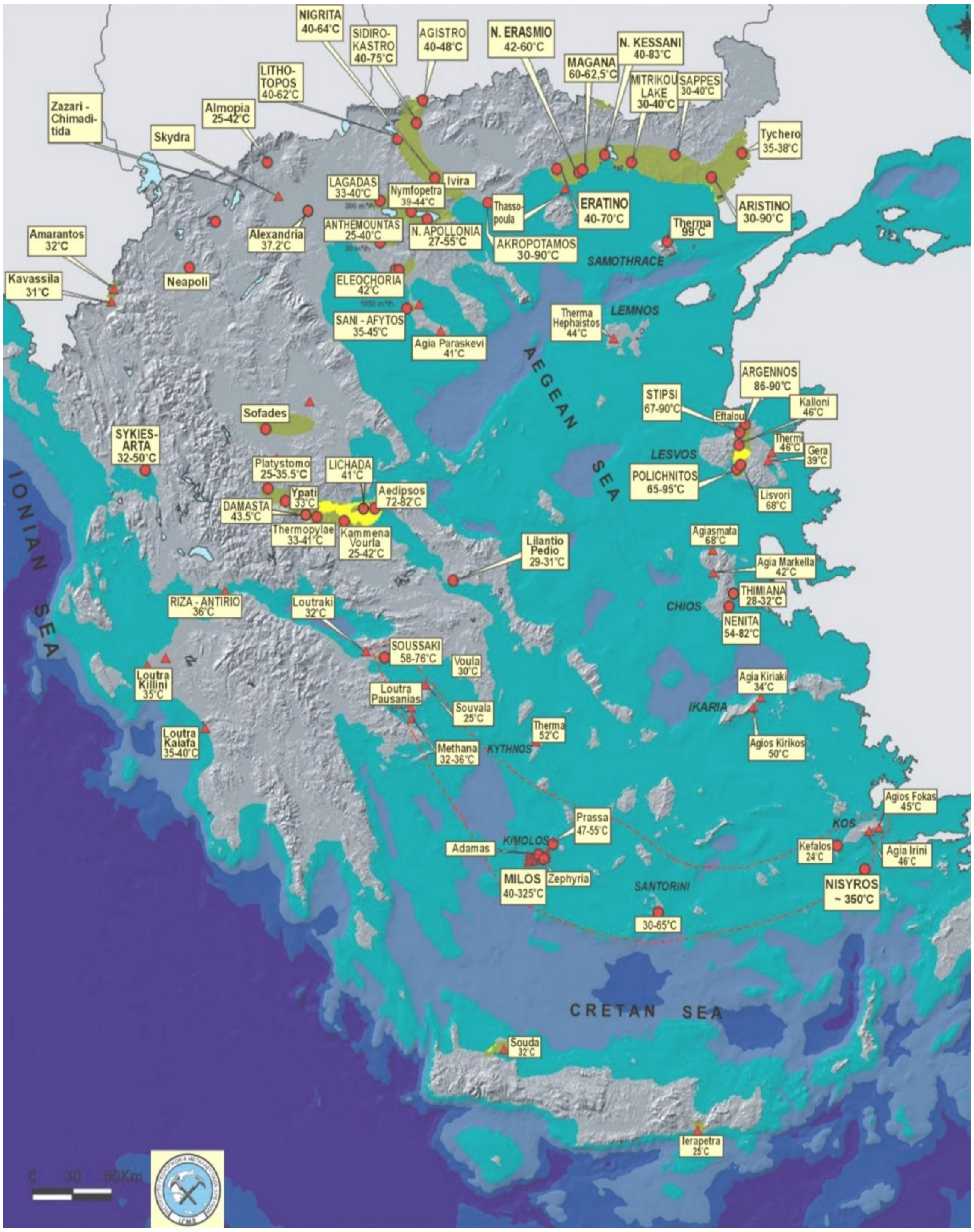

Figure 3.24*:* Shallow geothermal fields and areas of geothermal interest in Greece. (This map has been compiled by I.G.M.E. – Division of Geothermal Energy and Thermal Mineral Waters, with recent modifications and additions by Arvanitis A. The officially characterized as proven and probable geothermal fields are written with capital letters into the frames and the other areas of geothermal interest with no classification are written in lower case letters), (from Andritsos et al., 2010).

A further technology are shallow ground-source heat pumps, which are a promising application to drive the decarbonization of the building sector (cf. also Sect. 2.2). These heat pumps use the ground heat directly and converts it for heating and cooling purposes.

Overall, shallow geothermal energy (geothermal collectors - vertical, or heating probes - through boreholes) is seen as an important component for the implementation of climate protection goals as direct use for heat would significantly reduce the European gas bill and the electricity demand (cf. Box 3.3 on energy dependency). This indeed will open further maneouverial space for the implementation of energy autarchy (cf. below). In general, two approaches are conceivable here and are implemented to varying degrees in Europe. On the one hand, geothermal heat pumps tailored to individual buildings can use the thermal energy of the subsoil from a depth of less than 500 m (in most cases even less than 100 m) for heating the building. On the other hand, deeper aquifers or the energy stored in the rock can be exploited by thermal power plants and made available for entire districts as part of district heating. Individual studies also suggest storing heat generated in summer in the ground in order to be able to cover the cooling requirement (bidirectional heat exchange, see Walch et al. 2022).

In 2022, all EU27 countries were heavily dependent on fossil fuels - especially gas - for the necessary heating energy and hot water requirements of buildings (EU-wide approx. 50%) (EC 2022c). Even if the dependency is different (Netherlands >90%, Germany approx. 50%, Sweden 5%, Finland 10%, Malta, Slovakia, Italy and Hungary approx. 60 percent, technologies such as heat pumps or solar thermal energy have so far played a minor role in terms of space heating and hot water demand of buildings (approx. 4%) (EC 2022c). Overall, it is expected that geothermal heat use will represent a cheaper alternative to air heat pumps in the long term, as they are more efficient in heat use. The geological risks of near-surface heat use are now also well manageable.

Box 3.3: What does dependence mean in terms of energy sources?

The focus of the study is on European self-sufficiency in the electricity sector. As shown in Sect. 4.4, the European electricity sector is already self-sufficient, i.e. almost 100% of electricity is imported and exported between EU and associated countries. However, the question remains whether this is really true? To assess this, one has to look at energy sectors from an integrated perspective (cf. also Chapt. 4). For Germany, in example, this implies that in 2020 174 TWh of thermal energy (gas) was used for electricity generation whereby 89 TWh were converted into electrical energy. As Germany was by 50% dependent on Russian gas imports at that time, Russia would have been responsible for about 45 TWh of German electricity production (Leopoldina 2022). In addition, in Germany, 50% of the demand for space heating and hot water provision is also covered by gas. This demand amounted to approx. 600 TWh for private households in 2021 (approx. 800 TWh in total) (UBA 2023). This means that Russia was again responsible for at least providing approx. 300 TWh of thermal energy in Germany.

In terms of total installed geothermal heat pump capacity, the market is dominated by Germany and Sweden, which account for half of the installed geothermal heat pumps in Europe. The heat pumps sold in these two countries are mainly used in private households as well as service companies. However, there is still considerable potential for the exploitation of geothermal energy to provide heating energy and hot water, even if not to the same extent in all regions of Europe (see Fig. 3.25), because the potential can also change quickly on very small scales. The Thermomap project[18] has provided Europe-wide maps for estimating the shallow geothermal potential (up to a depth of 10 m). For more industrial uses (e.g. district heating systems) the Heatmap project[19] provides detailed information about the deeper hydrothermal resources. With regard to heat energy requirements, the latter project also dealt extensively with the synergistic use of heat, i.e. waste heat from industrial processes or from process water, which can also be displayed using the map tool (Möller et al. 2018).

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[18] https://www.thermomap.eu/

[19] https://heatroadmap.eu/peta4/ or https://map.mbfsz.gov.hu/geo_DH/

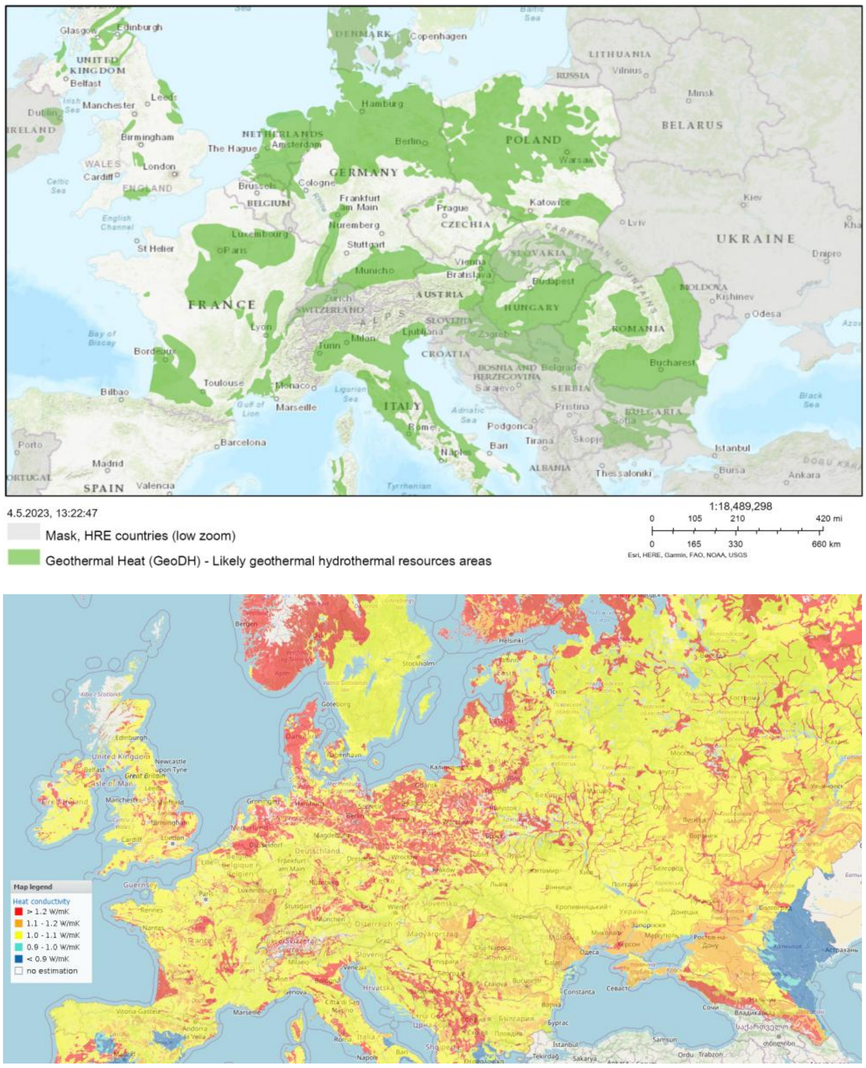

Figure 3.25: Deep and shallow geothermal resources in Central Europe. A) top: Deep geothermal resources in Europe, which are likely hydrothermal RES (source: cf. footnote #19).
B) bottom: near-surface (low-enthalpy) geothermal energy represented by the thermal conductivity of the subsoil at a depth of up to 10 meters (source cf. footnote #20).

However, the market for the necessary systems as a whole is still very distributed, e.g. on the one hand in drilling companies such as ROTOTEC or DRILLHEAT and heat pump manufacturers such as VIESSMANN or NIBE. Overall, small and medium-sized players are predominantly active in the European market. Nevertheless, the amendment to the Building Energy Act in Germany also shows that there is considerable future potential for these systems. In summary, it is clear that geothermal energy is a niche market in terms of power generation in Europe. Although there is potential for capacity expansion, but the European energy sector must also be viewed as an integrated system. And then it becomes obvious that energy self-sufficiency can be achieved faster the more sustainable the substitution of fossil fuels would be possible. And this is where the building sector plays a significant role, because it is heavily dependent on gas for heat energy needs. Electrification of heating systems or even using hydrogen as substitute for gas are certainly not good options, because i) that would take the electricity away from other sectors that need it more urgently for a sustainability transformation (e.g. e-mobility) and ii) heating with hydrogen is far less efficient and more expensive than alternatives such as heat pumps, district heating or solar thermal energy (Rosenow 2022). Nevertheless, the stipulation in the planned German Building Energy Act that gas heating systems can continue to operate if they can be easily converted to hydrogen could cement a dangerous path dependency that is ultimately detrimental to a true energy transition. In addition, the expansion speed of the RES is not sufficient for such a strategy, especially if owners of family houses and dwelling units will soon have to convert their heating systems.

In summary, technologies such as heat pumps or solar thermal have so far played a minor role (about 4%) in the final energy demand for space heating and hot water (EC 2022), i.e. the transformation of the space heating sector is still to come. Consequently, the European SET Plan emphasise that with today's technology, 25 % of the European population can cost-effectively deploy geothermal heating, while geothermal power could provide up to 10 % of Europe's power demand[20]. Underground thermal energy storage will be therefore crucial for the energy transition to bridge the seasonal gap, i.e. creates flexibility for the energy system.

3.4. Hydroelectric Energy and Hybrid Stations

Hydropower is one of the oldest sources of renewable energy, as it has been already used in pre-industrial watermills. Hydroelectric power is abundant in Europe due to the existence of numerous rivers and lakes. The combination of these water reservoirs with a steep topography provide a natural and renewable resource of clean energy to produce electricity. The hydroelectric technology is mature, and examples of hydroelectric stations are already operational in most European countries (Tab. 3.5). According to Eurostat, in 2020, hydropower accounted for 33% of the EU's renewable electricity production and provided 17% of EU's electricity[21].

Besides generating significant amounts of renewable electricity, hydroelectric power provides an excellent solution for the storage of renewable energy and for the stabilization of the electricity distribution network. The water reservoirs can be used to maintain the stability of the electricity system and facilitate the integration of the ever-growing share of renewable energy sources, such as solar and wind power, into the European energy grid (cf. also, Chapt. 5).

In total, Europe (incl. Russia) currently has an installed hydropower capacity of 254 GW (globally 1,360 GW), a further 23 GW (globally 548 GW) are projected and an estimated 73 GW (globally 500+ GW) are still exploitable. The top ten countries in Europe cover approx. 79 % of the total installed European capacity (Table 3.4, IHA 2022). Overall, the magnitudes for the further addition of hydropower capacity in Europe are at the lower end of all continents in a global comparison. By far the greatest development potential is in Asia and Africa.

Table 3.4: Top Ten Countries with the highest hydropower capacity in Europe in GW (Source: IHA 2022).

Norway	Turkey	France	Italy	Spain	Switzerland	Sweden	Austria	Germany	Portugal
33.4	31.5	25.5	22.6	20.4	16.8	16.5	14.7	10.9	7.2

In terms of pumped storage hydropower, Italy is the leader in the European Union with 7.7 GW of installed capacity (followed by Germany 6.2 GW, Spain 6.1 GW, France 5.8 GW, Austria 5.6 GW) (IHA 2022). Also, the size of plants varies between countries: In Norway there are several hundred mainly small plants, while in Germany there are about 33 plants, the largest of which has a capacity of about 1,000 MW. In Europe as a whole, pumped storage capacity is around 55 GW (IHA 2020), with further additions at a low level, e.g. only a further 4 MW was added in 2019. The reason for this is certainly also

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[20] https://setis.ec.europa.eu/implementing-actions/geothermal_en

[21] https://energy.ec.europa.eu

due to the fact that the additional capacity for onshore hydropower is relatively small. However, with an efficiency of 75-80 %, pumped storage accounts for 97 % of the current energy storage facilities in the EU. It is a proven and efficient way of storing energy at a competitive cost - although the development potential in Europe is limited (cf. also the discussion in Chapt. 5).

Further, new generation hybrid hydroelectric and wind/solar energy stations are natural accumulators for storing and managing electricity. Such "combined pump-storage" stations consist of two reservoirs at different elevations. The water that is used for the production of electricity is falling from the upper reservoir to the lower. Afterward, it can be pumped back to the upper reservoir with the help of turbines using wind, solar or other forms of energy that the system does not need at that time. This technology is the most economically and technically mature solution for storing electricity, and such installations are a priority for energy security in Europe.

3.5. Biomass to Energy

Biomass is derived from organic material such as trees, plants, agricultural and municipal waste. It can be used for heating, electricity generation and as a fuel. Increased use of biomass in the EU can help diversify Europe's energy supply, create growth and jobs and reduce greenhouse gas emissions. It is also needed for electricity generation to balance variable renewables. Biomass for energy production (bioenergy) is the most important source of renewable energy in the EU, accounting for almost 60%. The largest end-user is the heating and cooling sector, which consumes about 75 % of total bioenergy (Scarlat et al. 2019). The Biodiversity Strategy for 2030 (EC 2020b), published in 2020, made clear that the use of forest biomass for energy production should be an essential element of European climate and energy policy. Although this is to be done under strict sustainability criteria, forest resources are also subject to conflicting interests. The revised Renewable Energy Directive (EP 2018, also known as REDII), which must be implemented by the member states by June 2021, clarifies that sustainability criteria must be strictly adhered to. These have also been extended to solid biomass and biogas used in large-scale heating/cooling and electricity installations. In addition, REDII introduces risk-based sustainability criteria for forest biomass to ensure compliance with forest management laws and principles (e.g. regeneration, protection of sensitive areas, minimizing impacts on biodiversity and maintaining long-term forest productivity) and that the carbon impacts of bioenergy in the LULUCF sector are properly addressed. In particular, it should be noted that new biofuel plants must emit at least 65% less direct greenhouse gas (GHG) emissions than the fossil fuel alternative. New biomass-based combined heat and power (CHP) plants must produce at least 70% (80% in 2026) less GHG emissions than the fossil fuel alternative and large-scale biopower plants (above 50 MW) must use high-efficiency CHP technologies or apply the best available techniques (BAT) or achieve 36% efficiency (for plants above 100 MW) or use carbon capture and storage technologies.

Biomass is increasingly also being considered as a basis for the production of e.g. bio-methane. Forestry is the main source of biomass for energy (logging residues, wood-processing residues, fuelwood, etc.). Wood pellets, mainly for heating and electricity production, have become an important energy carrier (Scarlat et al. 2019). This is also manifested in the EU's REPower Plan (EC 2022b), in which the European Commission sets the target of increasing intra-European production of bio-methane from 3 bn m^3 today to 35 bn m^3 by 2030. Today, the greatest biomass potential is available in Northern Europe and the Baltic States, regions where forest products are already marketed on a large scale (Verkerk et al. 2019).

In terms of energy production, however, biomass is negligible compared to PV and wind energy potential. But, as already indicated above, the use of biomass for energy production (electricity or biofuels) must be viewed critically. Although it is a renewable resource, numerous conflicts have been identified, e.g. limiting food production or water resources (see Sect. 6.1 for further details). In addition, there may also be increasing competing uses in the future. For example, it makes more sense to use wood resources for sustainable timber construction (Churkina et al. 2020) instead of burning them or converting them into biofuels. As the building sector itself is responsible for a significant energy and carbon burden, this valuable resource should be used for longer-term carbon storage (withdrawal) rather than substitution. Clear political goals must therefore be defined here so that market mechanisms are not established that lead in the wrong direction. Consequently, forest experts warn that Europe's Renewable Energy Directive may harm forests worldwide (Searchinger et al. 2018). Even the European Commission's DG Research & Innovation itself says that according to recent studies, a gap between the potential demand for biomass and its sustainable supply could be 40-70% by 2050, depending on the scenario (cf. John Bell, 'Healthy Planet' director at the EC's DG Research & Innovation). For this reason, forest-based biomass should not play a role in a large-scale and profound transformation of the power sector, especially as other RES are disproportionately more available.

3.6. Conclusion and Key Messages

As conclusion, it is obvious that the variety of natural landscapes in Europe provides excellent opportunities and a rich diversity for the exploitation of several renewable sources of energy, depending on the local characteristics of each region. In principle, even much more than Europe/the European Union itself would consume, even under consideration of the most ambitious scenarios (cf. Chapts. 4, 8). While some resources are almost fully exploited, others are not. Already existing technologies such as solar panels, wind farms and hydroelectric plants need to be expanded and modernized. At the same time, it is imperative to invest in emerging technologies for the offshore production of energy by floating wind and wave turbines and in technologies for geothermal systems. Summing up, the following statements can be made:

1. **Wind Potential** - About 15% of the total consumption needs in Europe are covered by wind energy production. This share is projected to increase in the following years, according to the plans for new installations of up to 20-27 GW per year until 2026.
2. **Solar Potential** - Solar power potential is very high in Europe (cf. Sect. 3.1.2) and photovoltaic (PV) installation costs are rapidly declining (Figs. 3.8, 3.9). Almost 600 GW of PV are to be connected to the grid by 2030. PV installations in South Europe are more efficient due to the sharp North – South gradient in solar potential seasonality.
3. **Offshore energy potential** – High potential for offshore floating wind and wave energy farms is available in all sea basins of the EU (North Sea, Baltic Sea, Mediterranean Sea, Black Sea, Atlantic Ocean). The technologies for offshore energy exploitation from wind and waves are rapidly emerging.
4. **Geothermal potential -** Low-enthalpy geothermal energy is available throughout Europe and can be directly used for heating/cooling purposes at domestic and industrial level, but insufficiently used. Similar holds for the deep geothermal potential. A consequent exploitation of these resources could add flexibility to the European energy system, as it can provide large amounts of heating energy.
5. **Hydroelectric potential –** Hydropower accounts for about 17% of the EU's electricity production. The magnitude for further addition of hydropower capacity in Europe is rather low. Hybrid hydroelectric and wind / solar energy stations provide an excellent solution for the storage of renewable energy and for the stabilization of the electricity distribution network.

6. **Biomass potential -** Biomass from organic material such as trees, plants, agricultural and municipal waste is the most important source of renewable energy in the EU, accounting for almost 60%. The greatest biomass potential is available in Northern Europe and the Baltic States based on the abundance of forest products. Biomass should be used only in certain limits for power production in order not incur negative social and environmental consequences. Moreover, lignite from wood is a valuable raw material for a real bioeconomy. Wood is also a building material that removes carbon dioxide from the atmosphere and can be stored in buildings, i.e. contributes to the solution of the climate crisis.

4. Energy Transformation in the European Context

For Europe, becoming independent of energy imports of fossil fuels and fissile material aligns with the existing goals of climate policy and coincides with a shift towards renewable energy sources (Hainsch et al. 2020). In order to establish an independent and exclusively RES-based power system by 2030, it is necessary to take into account necessary transformations in the other sectors of the European economy. This means that significant amounts of fossil and nuclear energy have to be substituted by electricity (cf. Tab. 8.1 and 8.2 for a summaries).

Several academic studies describe a renewable European energy system and the path towards it. Although the exact results vary by study, all share common points, creating a joint vision for decarbonized energy systems. The following Sect. 4.1 provides an overview of the studies and how they envision the future energy system. This report then contrasts these visions with the status quo of European energy supply and its dependence on the imports of fossil fuels in Sect. 4.2. To connect both, a detailed examination of the European energy system that achieves climate goals and independence from fossil fuel and fissil material imports into the power sector by 2030 is presented. The focus is on sketching out the required investments into renewable generation, like wind and photovoltaic, end-user technologies, like heat pumps or battery-electric vehicles (BEVs), and other enabling technologies, such as energy storage or power grids.

4.1. Long-term Visions for the European Energy System

European energy independence by 2030 must be placed in the broader context of long-term decarbonisation. Investments in renewables are urgent today, but even more beneficial in the long-term beyond 2030. In addition, full independence of fossil fuels and fissil materials is unlikely to be fully achieved by 2030, so that we need a vision on the longer-term steps towards a climate- and uranium-neutral energy system.

Alternative visions of a truly renewable future exists, though: A modeling exercise between the European network operators and NGOs depicted a future without fossil fuels and fissil materials for Europe by the 2040s (CAN Europe 2020). Lappeenranta-Lahti University of Technology in cooperation with Solar Power Europe provides a vision of a 100% renewable energy supply for Europe (SolarPower Europe and LUT University 2020). Growing number of academic publications analyzes the topic show that accelerated decarbonization is beneficial in the long term and that there are a multitude of economically and technically viable options to achieve full decarbonization (Victoria et al. 2020, Neumann & Brown 2021, Pickering et al. 2022).

All these studies differ regarding details like exact shares of wind and photovoltaic power, the importance of power grids and batteries; and on the extent and use of synthetic fuels. Furthermore, the study results also differ with regard to the underlying assumptions about future electrification in the various sectors - as we discuss it in Sect. 4.4, or even the development of the final demand for energy services. Nevertheless, there are crucial points of consensus. First, the massive expansion of wind and solar is key for the energy transition, through which renewable energy sources can entirely substitute fossil fuels and fissile materials. Second, substituting fossil fuels in the heating, transport, and industry sector requires direct electrification. Synthetic fuels produced from biomass or electricity, like hydrogen, are limited to specific applications due to costs and limits to their sustainable potential.

In the following, we will exemplarily discuss these characteristics in greater detail based on a specific study. This joint study by DIW Berlin, the CoalExit group and TU Berlin in the wake of the Corona crisis showed that combining climate- and uranium-neutrality was compatible with economic recovery, in an attempt to make the European Deal really “green” (Hainsch et al. 2020, 2021). Like the studies cited above, the vision for Europe (not just the European Union, but the entire continent plus Turkey) includes a renewable energy system by 2050, with a high share of electrification, technical and behavioral changes as well as energy efficiency.

In this joint study, primary energy demand drops significantly due to an increase in energy efficiency and high electrification rates in all sectors of the energy system, as shown in Fig. 4.1[22]. The path to climate neutrality with regard to coal use requires short-term reductions in CO_2 emissions that go beyond the target of 40 % by 2030. The focus of the study was a compliance check with the Paris Agreement. As a result, emissions drop significantly after 2020 and climate neutrality is already achieved by 2040 reducing the need for carbon capture technologies. In contrast, a business-as-usual scenario exceeds the Paris compliant level of emissions by 15 billion tons in 2030 and 60 billion tons in 2050.

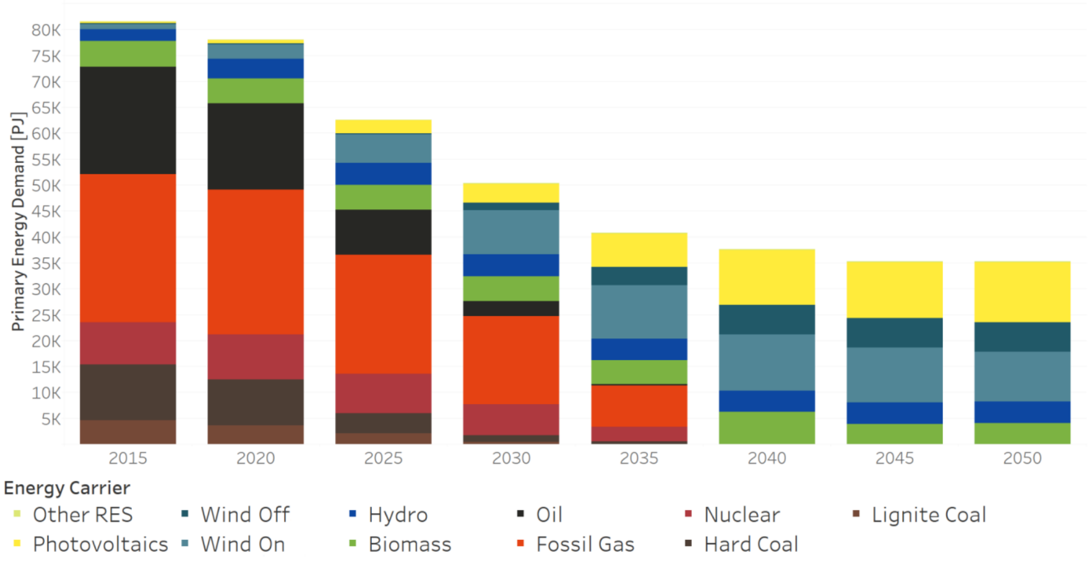

Figure 4.1: Primary energy demand in representative decarbonization scenario for Europe including Balkans and Turkey (Hainsch et al. 2020).

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[22] In the report, the corresponding scenario is termed “Paris” and builds on the "Societal Commitment" scenario developed in the current H2020 project "Open Entrance", but results do not directly match specific project outputs (Auer at al. 2020).

Although energy efficiency increases and primary energy demand drops, electrification substantially increases the final demand for electricity that doubles from approximately 4,000 TWh in 2020 to above 8,000 TWh in 2050 (Note these numbers relate to the whole European continent, for comparison of Europe and EU27, refer to Tab. 8.1). This steep increase in electricity demand is characteristic for decarbonization scenarios. Over the next ten years, it is predominantly driven by electrification of the heating and transport sector. In the presented scenario, residential heating accounts for 750 TWh of electricity demand in 2035; heating in industrial processes for 1,300 TWh and battery electric vehicles for 600 TWh. Until 2050, remaining fossil fuels in these applications keep on being replaced by electricity, but in addition electricity is to some extent also deployed for the production of synthetic fuels. These fuels are needed for applications that, at least under present technology assumptions, cannot be easily electrified, for instance aviation. In the presented scenario, this results in 1,500 TWh being used for electrolysis. At the same time, the generation shares of fossil (coal, gas and oil) and fissile (nuclear) successively decrease and these energy sources are replaced by renewable sources, mainly onshore wind and photovoltaics, as displayed in Fig. 4.2.

Due to its extensive energy potential and sharply declining costs (cf. Fig. 6.6), capacity and generation of photovoltaic will increase throughout Europe (cf. also Sect. 3.1.2, 3.2.2), especially from 2030 onwards. Onshore wind is a competitive option for electricity generation as well, producing a third of the total electricity generation by 2050 (cf. also Sect. 3.1.1). Offshore wind is mostly focused on coastal regions in the North Sea (cf. Sect. 3.2.1), but its competitiveness in terms of costs greatly depends on future cost developments.

On the demand side for electricity, direct electrification is crucial to achieve the climate targets. The heat sector is converted to renewables by 2040, with electric heat pumps being used for the low-temperature heat demand of residential buildings and industrial processes. Such scenario assumptions are, however, subject to a high degree of uncertainty, as the political dynamics are currently very high. For example, German Minister for Economics Habeck plans to fundamentally ban heating systems based on fossil energy from 2024 onwards. Further, at higher temperature levels, exclusively electrifying energy demand is not possible and a certain amount of bioenergy and synthetic fuels are required. These synthetic fuels can also be considered as indirect electrification because they originate from green hydrogen produced with renewable electricity. However, shallow and deep geothermal energy represents a resource for the provision of heat that has so far received little attention. The consistent use of these sources may significantly reduce the need of synthetic fuels and electricity for heating systems (cf. Sect. 3.3.1, 3.3.2).

Electrification in the transport sector involves a switch from internal combustion engine to battery electric vehicles, especially in private passenger transport (cf. Sect. 2.3). For the transportation of goods, either road transport is electrified with battery electric vehicles as well or transportation shifts to electric rail transport.

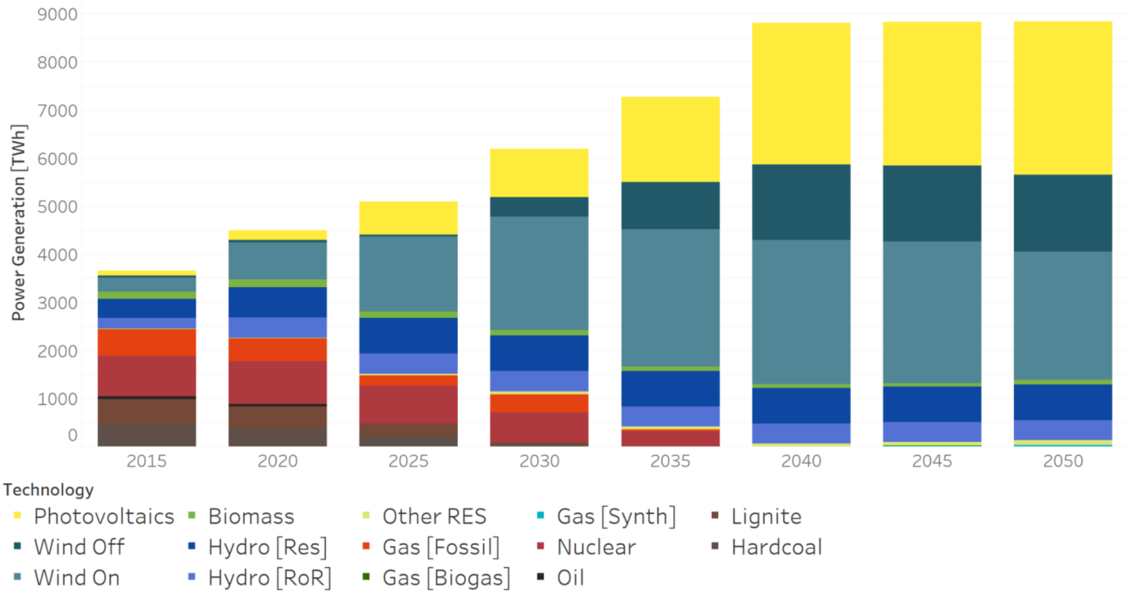

Figure 4.2: Electricity generation in a representative decarbonization scenario including Balkans and Turkey (Hainsch et al. 2020).

4.2. Today, Europe Heavily Depends on Fossil and Fissile Imports

Independence from fossil and fissile imports in 2030 implies that the remaining European demand for fossil fuels (natural gas, oil, and coal) can be produced within Europe, and be as far as possible substituted by renewable energies. Uranium imports, too, need to be phased out, as a lot of imports are coming from Russia. In the following, we will compare the current demand and production for each of these carriers in detail and discuss the challenges when reducing demand to the current level of domestic production until 2030. For demand, we show both 2019 and 2020 data to capture the unusual effects the pandemic had on consumption in some sectors. For domestic production, we use the last 12 months of data available because data availability varies substantially by country and commodity.

4.2.1. Natural Gas

Figure 4.3 compares demand and domestic production of European countries for natural gas. Process heating in the industry accounted for 964 TWh in 2019 and 985 TWh in 2020; generation of electricity and district heat for about 1,500 TWh in both years.[23] Space heating made up the largest share of demand, amounting to 1,763 TWh in 2019 and 1,731 TWh in 2020. Energy losses from refinery processes and the non-energy use of gas as a feedstock are small positions of around 260 and 190 TWh, respectively. Overall, the pandemic did not have a significant effect and demand remained rather constant in both years.

The most important domestic producer of natural gas in Europe is Norway, supplying a total of 1,400 TWh. The United Kingdom is second with 450 TWh. The domestic demand from other countries, like the Netherlands, totals 460 TWh.[24] For reference, European countries imported 1,600 TWh of gas from Russia in 2021 before the invasion. Overall, domestic demand before the current energy crisis is almost

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[23] To facilitate comparison, we consistently use Watt-hours as an energy unit in this chapter. As a reference, for gas 1,000 TWh corresponds to 95,000 million cubic meters.

[24] The data covers October 2021 to 2022, the latest data available when writing this study.

exactly twice as high as domestic production. Correspondingly, independence from gas imports at constant production requires halving gas consumption, for instance by replacing gas boilers with heat-pumps for space heating.

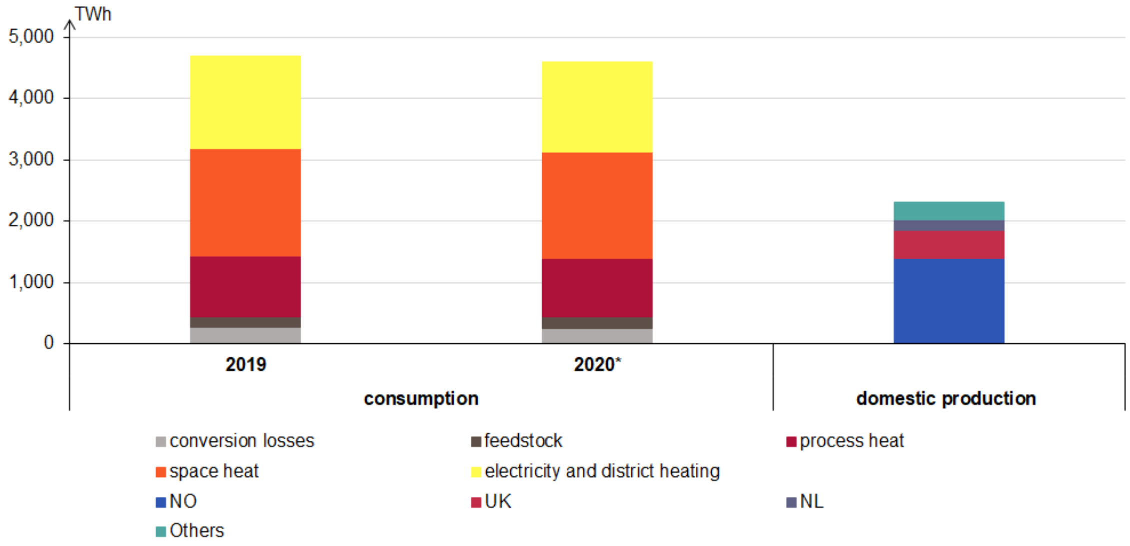

Figure 4.3: European demand and production of natural gas, Source: eurostat.

4.2.2. Oil

Figure 4.4 shows demand and domestic production of oil within Europe. The major share of oil is consumed for road transport, amounting to 3,700 TWh in 2019 and 3,300 TWh in 2020. This clearly demonstrates the impact of the pandemic on road transport. How the electrification of transport would impact power demand is discussed in particular in Sect. 2.3. The same effect can be observed for oil demand in aviation and navigation which amounted to 791 TWh in 2019, but only 463 TWh in 2020. Space heating accounts for about 770 TWh of oil demand in both years. Oil demand for process heating and the generation of electricity and district heat is significantly below gas demand of these sectors and roughly totals to 320 TWh and 160 TWh in both years, respectively. The conversion losses from refineries amount to about 330 TWh; non-energy use of oil for feedstock to 970 TWh, both substantially above the numbers for natural gas.

Similar to natural gas, Norway and the United Kingdom are the biggest European producers of oil providing 1,000 TWh and 570 TWh, respectively. The supply of other countries only amounts to 220 TWh in total[25]. For reference, Europe imported about 2,300 TW of oil from Russia before the invasion. Overall, the relative gap between domestic demand and production is much greater for oil than for gas. Demand is more than three times greater than production, exceed it by 4,500 to 5,200 TWh.

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[25] The data covers October 2021 to 2022, the latest data available when writing this study.

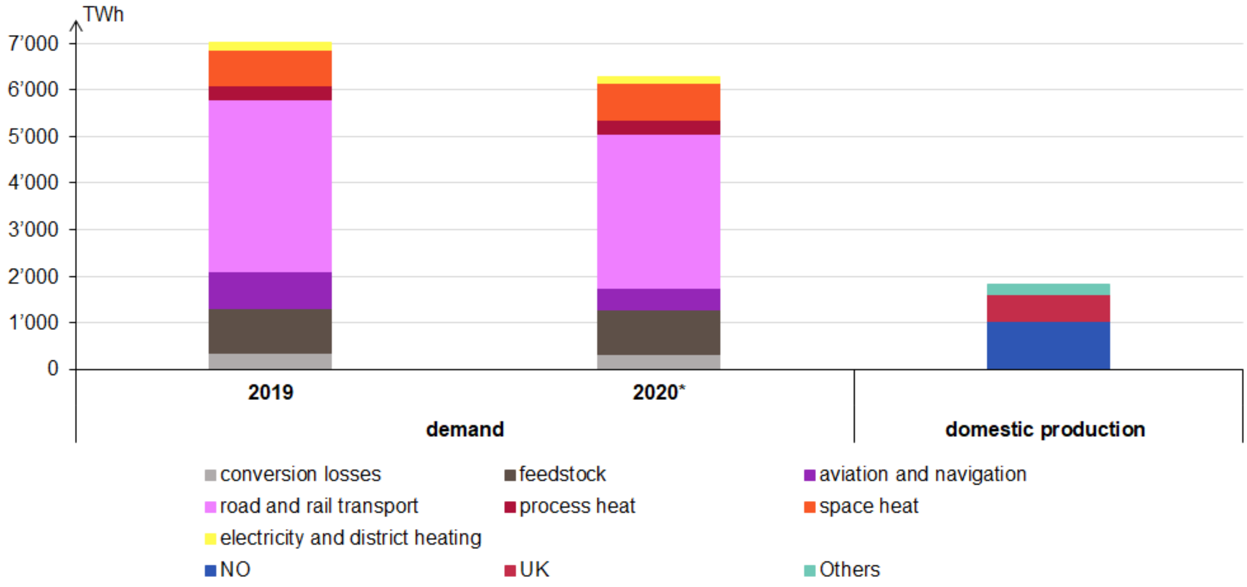

Figure 4.4: European demand and production of crude oil, Source: Eurostat, converted into energy units assuming 44.5 MJ/kg.

4.2.3. Hard coal

Figure 4.5 compares demand and domestic production for hard coal. Hard coal is mostly used for the generation of electric and district heating, accounting for 640 TWh in 2019 and 500 TWh in 2020 showing a clear impact of the pandemic. About 500 TWh are consumed for process heating in the industry and 100 TWh for space heating. The non-energy use demand for feedstock is negligible, totalling to 20 TWh. For lignite, a comparison of demand and domestic production is not necessary because production already is exclusively domestic.

The only European country that produces significant quantities of hard coal is Poland supplying about 500 TWh. The next biggest producer is the Czech Republic, with only 16 TWh. Overall, demand is more than two times higher than domestic production, but the absolute gap is small compared to natural gas and oil and amounts to 560 TWh in 2019 and 760 TWh in 2020.

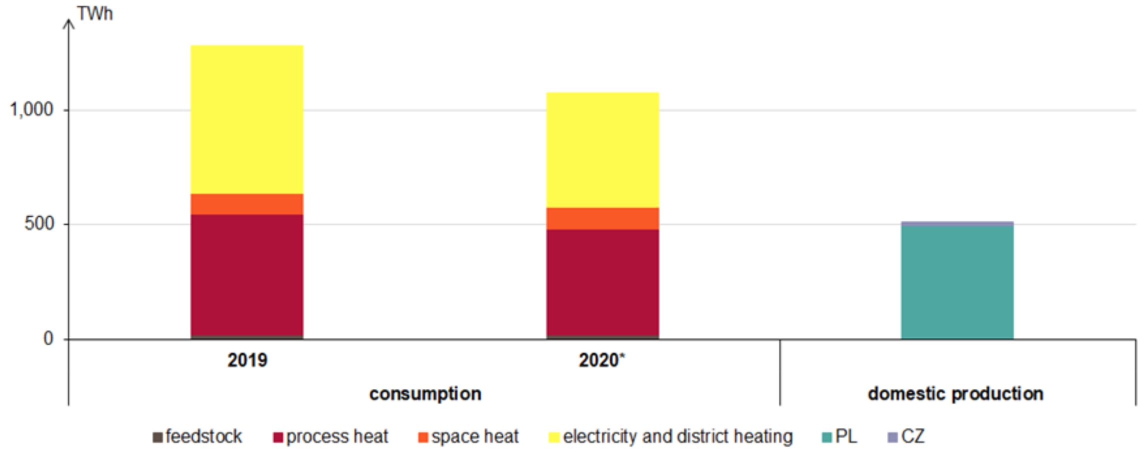

Figure 4.5: European demand and production of hard coal, Source: Eurostat, converted into energy units assuming 32.9 MJ/kg.

4.2.4. Uranium

Nuclear energy is repeatedly regarded as indispensable in European electricity production, as these power plants can ensure the base load. In addition to the already depreciated costs for the construction of the power plants, it is often stated that this form of energy is also carbon-neutral. Uranium is used for conversion into yellow cake, which is the basis of producing uranium fuel for nuclear power plants, accounting for about 612 TWh (cf. also Tab 8.1) of electricity production in 2022 (22% of total EU net electricity production). A few nuclear power plants also produce some heat, but this is negligible at the European level.

In 2020, Europe's natural uranium demand for reactor-related requirements amounted to 17.63 kt U. Uranium production in Europe is quite insignificant compared to demand – some 21 t U (ESA 2022) and almost exclusively a by-product of legacy uranium mine remediation in the form of uranium concentrate. In 2021, the countries of the European Union imported 12 kt U of Uranium. The most important importer was Niger with 24%, followed by Kazakhstan with 23% and Russia with 20%. Domestic supply only accounted for 0.001%. Inventories held by utilities currently amount to approximately 3 years of demand, but since 2015 "European utilities have been loading more material into reactors than they have been buying it, which has resulted in a steady decrease in inventory levels" (ESA 2021). The only European country that produced marginal quantities of uranium ore until recently was Romania. In November 2021, the Crucea mine in Romania became the last working uranium mine in the EU, with a production of 3,200 metric tons of uranium. Now it has been closed because the national uranium company operating the mine filed for insolvency.

In 2020, the largest supplying countries to the EU were Russia, Namibia, Canada, Kazakhstan and Australia, accounting for over 90% of total supply. During that time, Russia's share of EU supply was about 20%; together with Kazakhstan (approx. 20%) and Uzbekistan (approx. 2-3%), the countries of the former Soviet Union supplied about 42% of uranium. Overall, therefore, import dependence in uranium ore is close to 100%.

The import dependence of Europe in the field of nuclear power also stretches to other segments of the production chain. Thus, Europe is also dependent on imports of yellow cake and enriched uranium.[26] Actually, 21 nuclear reactors in the EU rely on fuel elements and technical support from Russia: This corresponds to about one third of the reactors in Finland and almost 100% in the Eastern European countries that belonged to the former Eastern Bloc and imported the technology either from the Soviet Union and/or Russia (e.g. Bulgaria, Hungary, Czech Republic and Slovakia).

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[26] This section largely draws on two publications: Gufler, Klaus, and Franz Meister. 2022. "Analyse der Rosatom-Aktivitäten bzw. Rosatom-Verflechtungen mit der EU." Erstellt im Auftrag des Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie. https://www.umweltbundesamt.at/fileadmin/site/publikationen/rep0814.pdf.; and Bowen, Matt, and Paul Dabbar. 2022. "Reducing Russian Involvement in Western Nuclear Power Markets." Columbia: Sipa. Https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/RussiaNuclearMarkets_CGEP_Commentary_051822-2.pdf.

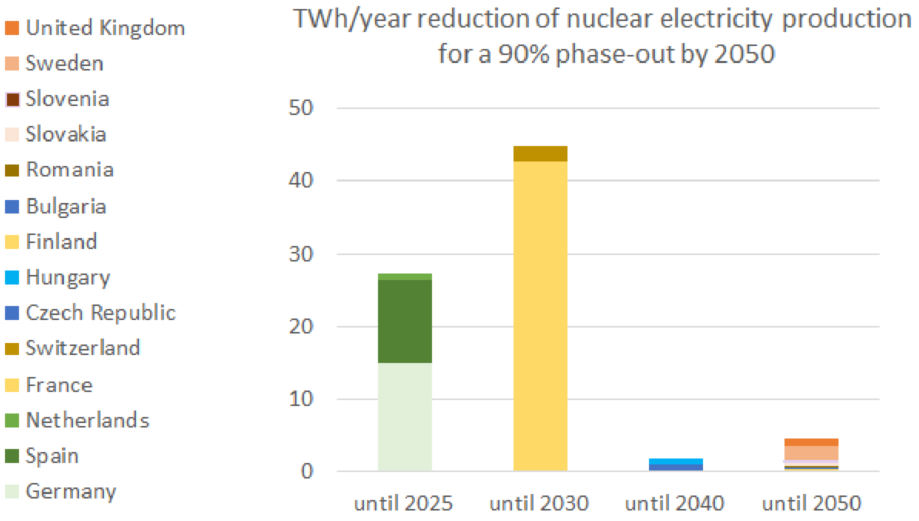

Figure 4.6: Decommissioning calendar of nuclear electricity for a 90% phase-out (source: EUCalculator).

Because of this dependence, cost reviews and safety reasons, it is suggested not to pursue the nuclear-uranium-plutonium route as this energy form overall is not sustainable. Figure 4.6 details a nuclear decommissioning calendar that takes into consideration the current installed capacities of countries power plant life-time. At least 90% of the nuclear generation could be decommissioned by 2050 by stopping new capacity and not extending the existing capacity beyond the normal operational life-time, these are the largest efforts required by 2030 in Germany, Spain and France. Although not a complete phase out, the proposed decommissioning would go a long way to mitigate the unsolved disposal and storage of residual waste. The dismantling of nuclear plants as well as this storage will, however, cause eternal costs that are hardly calculable. In total, the nuclear phase-out, i.e. dismantling and disposal, will cost about €50 billion in Germany according to the report of the Atomic Energy Commission. A co-author of this study (C. Kemfert), however, estimates that this is far too low and assumes at least €175 billion. Jarvis (2022) estimate social costs of nuclear phase out up to € 8 bn/yr, mainly due to additional health costs because of the use of more coal and gas. Nevertheless, they also showed that risk reduction will outweigh these costs. The war in Ukraine and the phase-out of nuclear power even resulted in more coal and gas being used (at least on a temporal time-scale) to generate electricity (see Table 8.1). The costs for these resources literally exploded in the course of 2022, which also had an impact on electricity costs (cf. Fig. 6.4). Although costs are now falling again, a comparison between coal-fired power generation and wind and solar can definitely be used as a comparison. In 2021, the electricity production costs for coal-fired electricity, including climate costs, were around 50ct/KWh. In contrast, the electricity from wind and solar was in the range between 4-8 ct/KWh (Fraunhofer/ISE 2021, 2021a, cf. Fig 4.7, also Fig. 6.6). This shows that from an economic and ecological perspective, a quick phase-out is unbeatable.

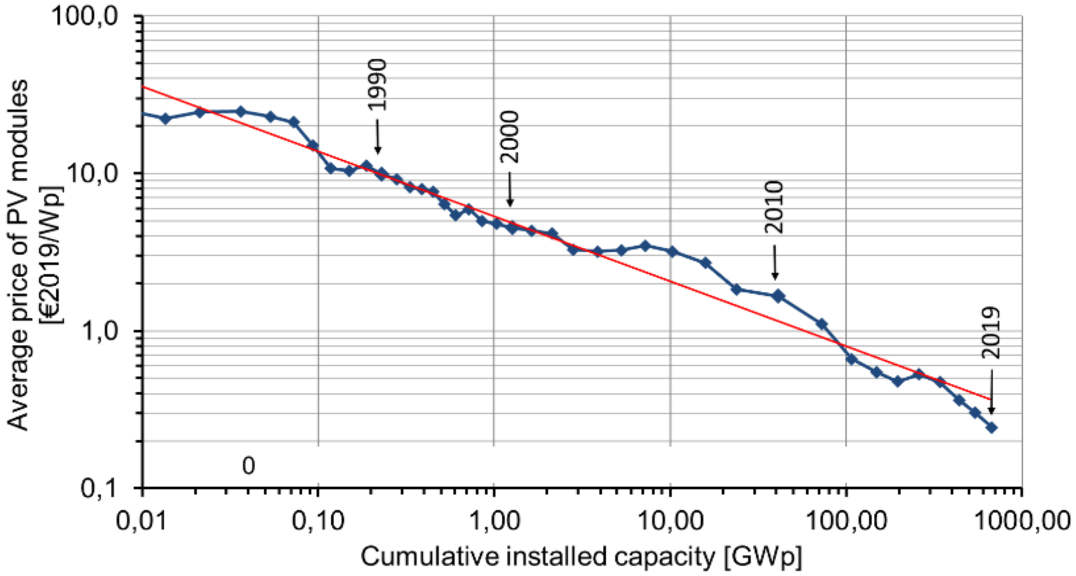

Figure 4.7: Historical price development of PV modules (PSE AG/Fraunhofer ISE, data from: Strategies Unlimited/Navigant Consulting/EuPD). Note, scales are logarithmic! Source: Fraunhofer/ISE 2021.

Especially with regard to the latter, this means that even if a society had decided to follow a sustainability path, considerable burdens will have to be carried into the future, which will significantly limit the room for manoeuvre. From this point of view alone, it is astonishing that even in Europe, countries like France continue to focus on a long-term perspective for nuclear energy. This is even more incomprehensible considering that this study shows that substitution by PV would be possible, even in France, with an adequate level of investments and implemented regulatory frameworks.

4.3. Paths to Energy Independence and System Interdependence

Closing the gap between domestic production and demand can be achieved in two ways: First, reducing the final demand of energy services, like space heating and electricity. Most of the reductions achieved in the current energy crisis fall into this category. Second, imports of fossil fuels can be replaced with domestic renewable energy, although some industrial applications cannot use renewable electricity directly but require renewable synthetic fuels.[27]

The options to replace fossil fuels with renewable sources greatly depend on the purpose natural gas, oil, or hard coal are deployed for. In the electricity sector, these options are already thoroughly discussed in Chapt. 3 of this report: mainly photovoltaic, wind, hydro, and geothermal. Also, renewable options for other sectors often rely on this renewable electricity to substitute fossil fuels.

For space heating and low-temperature process heat, heat pumps using ambient energy (for geothermal resources, refer to e.g. Sect. 3.3.2) and electricity are the most efficient option to replace fossil fuels (Altermatt 2023). Obviously, they are ideally operated with fully renewable electricity, but thanks to their high efficiency, they can already substitute fossil fuels, if they are transitionally operated with electricity from fossil fuels as well. For example, in Germany aero-thermal heat-pumps on average reached an efficiency of 2.9 in 2020 meaning they require 34 kWh of electricity to produce 100 kWh of space heat (Eurostat 2023). Geothermal or hydrothermal heat pumps are even more efficient and capable of

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[27] Since our analysis aims to show pathways for energy independence that are consistent with decarbonization targets, we do not consider the option of expanding domestic production of natural gas, oil, and hard coal.

producing the same amount of heat with just 27 kWh (Eurostat 2023). In contrast, the most efficient gas boiler require at least 98 kWh of gas to produce the same amount of space heat. If instead this gas is used for electricity generation in gas power plants, it produces between 40 and 60 kWh of electricity, depending on the technology[28]. Even if exclusively fueled by electricity from gas power plants, the least efficient type of heat pumps still provide at least 117 kWh of space heat – 19 kWh more than the most efficient gas boiler. This back of the envelope calculation demonstrates that even today with low renewable shares in electricity generation, heat pumps can already contribute to the substitution of fossil fuels.

Non-electric options for renewable heating include geothermal energy, biomass, and feeding excess heat from industrial processes into district heating systems. (cf. Möller et al. 2018). In some industrial processes, synthetic fuels from biomass and hydrogen produced from renewable electricity are the only option to substitute fossil fuels. In certain cases, electric boilers instead of heat pumps can provide high-temperature process heat as well. Furthermore, there are many specific technologies for certain industrial processes, for instance the production of steel or cement.

In road transport, the greatest consumer of oil, direct electrification with battery electric vehicles is the most efficient option to substitute fossil generation, similar to heat pumps in the heating sector. Again, thanks to the high efficiency of electric vehicles compared to internal combustion engines, the electrification of transport can already reduce the dependence on fossil fuels if power generation is not fully renewable yet. In other parts of the transport sector, like aviation or navigation, options for electrification are not as advanced yet and again synthetic fuels from biomass or hydrogen might remain the only renewable option to substitute fossil fuels. The same applies to the non-energy use of fossil fuels as feedstock in the chemical industry.

Electrification is crucial for reducing reliance on fossil fuels outside of the power sector. However, the amount of fossil fuels replaced by heat-pumps or electric vehicles depends on the power generation mix at the specific time they are used. To properly analyze the substitution of fossil fuels, it's necessary to consider the power, heating, and transport sectors as an integrated system. This is complicated by competition for renewable biomass and the use of hydrogen as a substitute for fossil fuels in heating, transport, and energy storage.

The spatial dimension of energy supply further increases the complexity of the problem. While renewable energy systems can be a lot more decentralized, regions with the greatest energy demand will not directly match regions with the greatest potential for supply, as we will show in Sect. 4.4. The transport of renewable energy using grid infrastructure is possible, but the costs of additional lines must be weighted against the costs of other infrastructures. Alternatively, also other energy carriers, like hydrogen or biomass, can be transported between regions to match supply and demand in each region.

To address this complexity, our analysis uses a comprehensive planning model of the European energy system based on the AnyMOD framework to investigate how imports of fossil fuels can be substituted by renewable energy sources until 2030 (Göke et al. 2021a, 2021b). At the same time, the modeled system is set on a path to full decarbonization beyond 2030 and achieves all climate goals. The analysis re-iterates work discussed in the previous section to provide the updated results on European self-sufficiency in the coming sections (Auer et al. 2020, Hainsch et al. 2020). In addition, results for the fully

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[28] Open cycle gas turbines typically have an efficiency around 40% while combine cycle plants achieve 60%. (Deutscher Bundestag 2022)

self-sufficient energy system in 2040, not just the power sector, build on a recently published working paper (Göke et al. 2023).

The techno-economic planning model decides on the expansion and operation of energy technologies, like photovoltaic solar wind plants, end-consumers technologies, like heat pumps or battery electric vehicles, and other relevant infrastructure, like power grids, battery storage, or electrolyzers. Decisions on capacity and operation seek to minimize the total costs of the system under the condition that Europe is independent of imports all long-term decarbonization targets are achieved, and the final energy demand of all sectors is met. To capture the pathway of the resulting energy transformation, the temporal scope of the model starts in 2020 and goes forward in 5 year steps until 2040 under perfect foresight (Göke et al. 2021a, 2021b). Tables 4.1A and 4.1B show technology assumptions, like investment costs and efficiency, used in the model in 2040 for the power sector, building on comprehensive data sets by the Danish Energy Agency (DEA, 2022). For renewable generators, Figure 4.8 compares the range of levelized costs for power generation (LCOE) resulting from these cost assumptions and the range of full load hours in Europe.

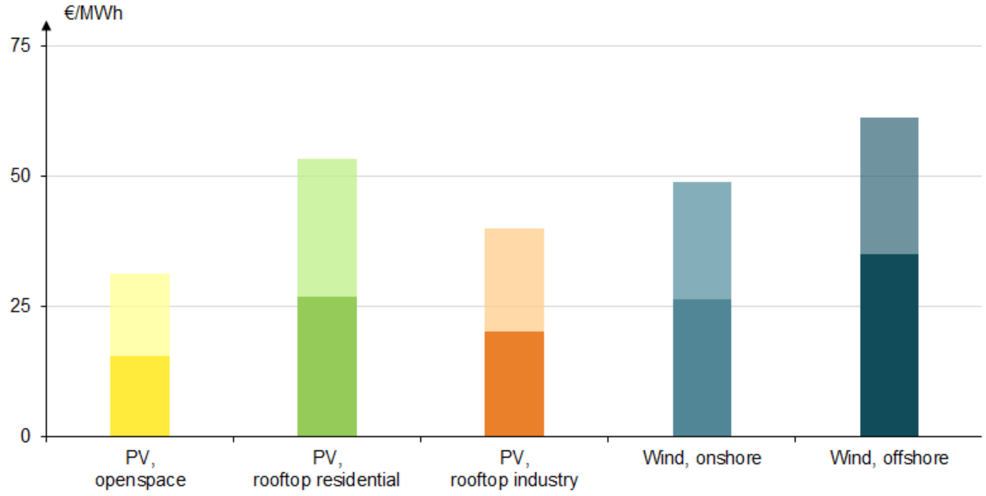

Figure 4.8: Range of LCOEs for renewable generation in Europe based on DEA (2022).

Table 4.1A: Technology assumptions for the power generation in 2040 (from Göke et al., 2023 and based on DEA, 2022).

technology	investment costs [10^6 €/GW_in]	operational costs [10^6 €/GW_in/yr]	lifetime [yrs]	electrical efficiency	availability
CC gas turbine, back pressure turbine	586.0	13.7	25	50.3%	93.0%
CC gas turbine, extraction turbine	480.7	15.9	25	58.3%	93.0%
CC H_2 turbine, back pressure turbine	673.9	13.7	25	50.3%	93.0%
CC H_2 turbine, extraction turbine	552.8	15.9	25	58.3%	93.0%
OC gas turbine	177.8	3.2	25	41.5%	97.2%
OC gas turbine CHP	226.6	7.7	25	41.5%	93.0%
OC H_2 turbine	204.4	3.2	25	41.5%	97.2%

OC H_2 turbine CHP	260.6	7.7	25	41.5%	93.0%
engine, biogas	384.8	3.9	25	43.3%	95.1%
engine, diesel	118.8	2.9	25	35.0%	96.8%
engine, gas	221.5	2.9	25	47.6%	98.7%
engine CHP, gas	415.5	4.2	25	46.9%	95.5%
non-solid biomass plant CHP	272.4	9.7	25	28.1%	91.2%
solid biomass plant CHP	870.5	24.9	25	26.8%	91.2%
polymer electrolyte fuel cell	475.0	23.8	10	50.0%	99.7%
solid oxide fuel cell	840.0	42.0	20	59.6%	100.0%
PV, open space	271.2	5.4	18		

Table 4.1B: Technology assumptions for the power storage in 2040 (from Göke et al., 2023 and based on DEA, 2022).

technology	**cycle efficiency**	**Lifetime [yrs]**	**investment costs**		**operational costs**	
			power capacity [10^6 €/GW]	**energy capacity [10^6 €/GWh]**	**power capacity [10^6 €/GW/yr]**	**energy capacity [10^6 €/GWh/yr]**
Lithium battery	0.89	18	80.9	199.6	1.21	2.99
redox battery	0.52	18	614	174.5	9.21	2.62
pumped storage	0.81	-	-	-	-	-

Figure 4.9 shows the spatial scope of the model that covers the European Union, the United Kingdom, Norway, Switzerland and the remaining Balkan countries (blue lines symbolize where the model would invest in hydrogen lines between regions). The spatial resolution disaggregates these countries into 96 sub-regions. Representation of the electricity grid aggregates these sub-regions according to existing zones of the European power market. The grid will be expanded under cost considerations. If it is cheaper, for example, to cover demand by expanding a line than to invest in more battery storage or generation plants, for example, then the expansion will take place. Yellow and orange arrows represent existing high-voltage alternating current (HVAC) and direct current (HVDC) connections. This figure shows, in particular, that the connectivity between Spain/Portugal and the rest of Europe could be improved. Similar holds for Eastern and parts of Southern Germany.

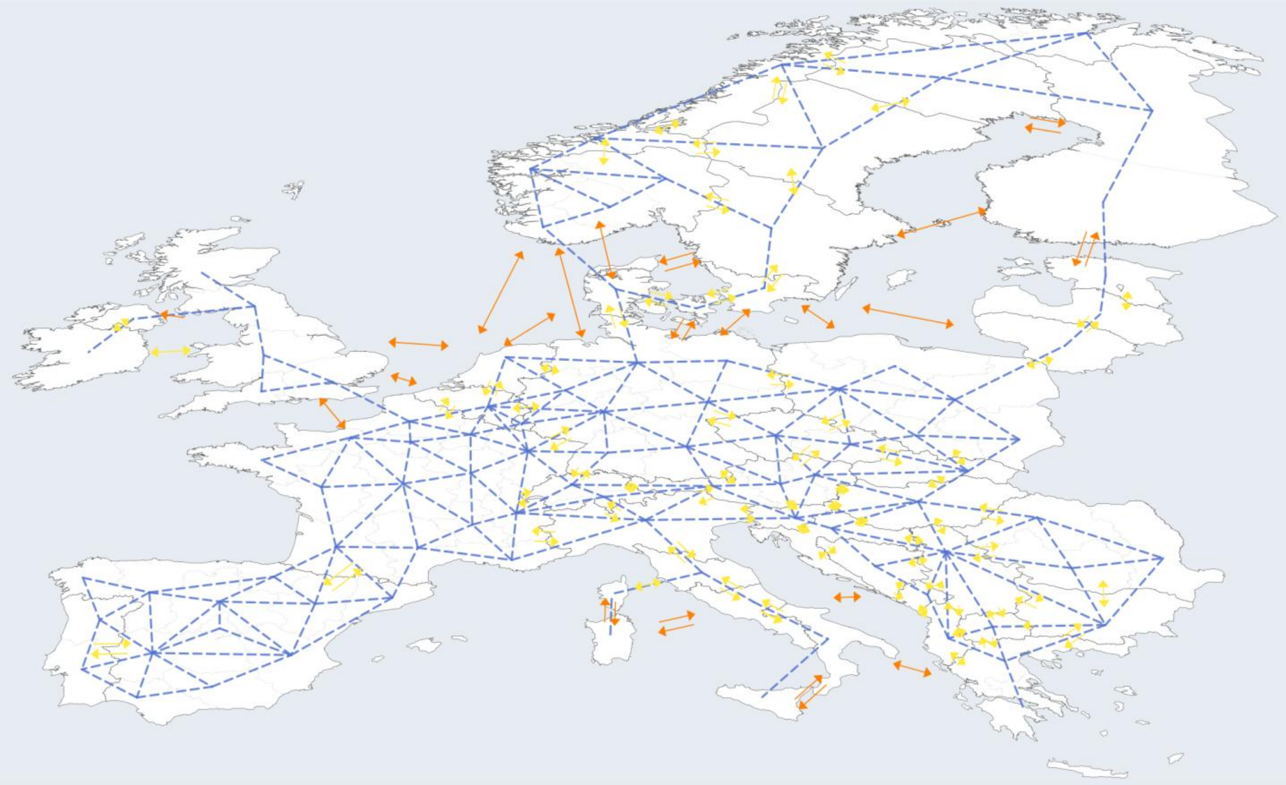

Figure 4.9: Scope of the analysis and representation of current and potential grid infrastructure.

Tables 4.2A and 4.2B show the assumed demand for final energy and transport services that the model must meet. The general assumption is that these demands remain constant at the current level until 2040 except for space heating where improved building insulation reduces demand. Accordingly, demand assumptions build on recently reported demand data and for space heating on building stock projections.

Table 4.2A. Assumed final energy demand by country (from Göke et al., 2023 based on Heat Roadmap Europe, 2015, Heat Roadmap Europe, 2017 and eurostat, 2020).

country	Electricity [TWh]	space heat [TWh]	process heat [TWh]		
			low (until 100°C)	medium (100 to 500°C)	high (above 500°C)
Albania	4.6	4.2	2.7	3.8	4.9
Austria	62.8	45.2	17.0	26.2	20.7
Bosnia and Herzegovina	9.6	4.9	3.2	4.5	5.7
Belgium	73.6	62.5	17.1	22.6	28.8
Bulgaria	29.2	11.0	9.1	4.7	4.8
Switzerland	51.8	43.7	7.4	30.8	6.6
Czech Republic	57.8	38.9	17.5	16.7	19.0
Germany	480.7	470.9	112.1	119.0	153.0
Denmark	29.5	30.3	5.6	7.0	2.6
Estonia	7.2	5.3	1.0	1.9	0.6
Spain	241.9	62.8	25.5	57.2	54.1
Finland	65.8	30.4	27.7	42.4	8.7
France	390.3	257.8	40.4	57.1	64.6
Greece	45.3	16.0	5.2	5.9	5.9
Croatia	16.7	10.3	1.6	3.9	2.6

Hungary	37.1	36.6	7.1	4.1	6.9
Ireland	24.9	15.9	4.1	5.8	3.8
Italy	260.6	215.9	57.1	48.5	72.7
Lithuania	11.7	8.0	3.7	2.1	1.5
Luxembourg	4.7	3.5	0.8	1.1	2.1
Latvia	6.2	7.6	1.7	3.9	1.5
Montenegro	2.8	0.9	0.5	0.7	1.1
Macedonia	5.2	3.1	1.9	2.6	3.4
Netherlands	107.7	62.8	30.0	28.1	42.5
Norway	106.6	34.0	4.8	30.7	2.6
Poland	145.1	98.0	23.6	40.8	42.5
Portugal	46.5	9.1	8.4	16.1	9.1
Romania	55.0	31.2	11.1	14.1	25.2
Serbia	32.7	11.2	6.8	9.6	12.0
Sweden	104.7	55.4	12.1	51.0	10.0
Slovenia	12.3	6.5	1.7	2.6	2.3
Slovakia	26.2	15.1	11.8	5.6	15.2
United Kingdom	256.4	271.8	46.9	68.6	42.1
Total	**3,110.5**				

In the transport sector, the model must meet the predefined driving kilometers for each mode of transport specified in Table 4.2B but can freely decide on the respective type of vehicle, for instance battery electric or fuel cell vehicles for private road transport. For aviation and navigation, we make the conservative assumption that no alternative to combustion is available by 2040 and as a result, decarbonizing these sectors requires synthetic fuels.

Table 4.2B. Assumed demand for transport services by country (from Göke et al., 2023 based on eurostat, 2020b, eurostat, 2020c and eurostat, 2023a).

country	**passenger transport [10^9 pkm]**			**freight transport [10^9 tkm]**			**synthetic transport fuel [TWh]**
	rail	road private	road public	rail	road heavy	road light	
Albania	0.1	8.6	3.0	2.5	3.8	0.0	0.0
Austria	14.0	83.8	11.0	12.6	25.6	0.9	18.1
Bosnia and Herzegovina	0.1	11.5	4.0	3.4	5.1	0.1	0.0
Belgium	11.7	117.8	14.9	5.7	30.9	3.9	51.7
Bulgaria	1.4	55.9	7.8	7.1	20.2	0.3	5.4
Switzerland	20.8	80.6	6.4	6.4	11.6	0.3	0.5
Czech Republic	10.0	76.5	17.7	19.2	46.6	3.8	5.0
Germany	101.7	950.7	64.8	84.8	303.3	8.6	151.0
Denmark	6.9	67.1	7.9	2.0	14.8	0.2	4.3
Estonia	0.4	11.3	2.4	4.1	4.7	0.1	0.0
Spain	31.0	370.9	35.0	11.4	213.9	3.1	6.1
Finland	4.6	67.8	8.1	11.8	28.4	0.5	16.7
France	95.3	770.4	59.2	19.5	169.3	4.8	114.2
Greece	1.2	106.0	21.0	0.6	27.0	1.2	69.5
Croatia	0.8	25.6	5.3	3.6	12.2	0.3	3.3

Hungary	6.7	55.1	16.2	14.5	35.8	1.1	6.1
Ireland	1.1	28.5	5.2	0.1	9.0	0.2	0.0
Italy	59.0	768.2	89.9	17.0	96.3	16.4	66.9
Lithuania	0.4	30.3	2.9	112.4	52.3	0.8	29.6
Luxembourg	0.4	7.2	1.1	0.7	7.3	0.1	0.0
Latvia	0.6	15.3	2.6	46.9	14.8	0.2	0.0
Montenegro	0.1	4.1	0.1	0.9	1.4	0.0	0.0
Macedonia	0.1	7.5	2.2	2.1	3.2	0.0	0.0
Netherlands	24.5	187.4	6.8	8.7	66.7	1.6	215.6
Norway	3.6	64.6	4.2	3.9	20.7	0.6	17.0
Poland	21.8	218.7	35.6	127.9	340.0	9.0	35.1
Portugal	4.0	85.2	7.0	5.1	30.4	0.6	29.1
Romania	4.4	81.4	15.6	40.1	60.3	0.8	11.6
Serbia	0.3	28.8	10.0	8.5	12.7	0.2	0.0
Sweden	11.7	100.0	8.7	19.2	42.0	0.6	7.7
Slovenia	0.5	26.3	3.6	13.1	23.7	0.3	0.0
Slovakia	3.7	27.9	6.1	17.2	32.5	1.5	2.5
United Kingdom	69.1	670.3	36.5	16.7	153.7	7.1	143.9

4.4. Electricity Supply in an Independent European System in 2030

Pathways that do not only achieve decarbonization in the long-term, but also independence from imports of fossil fuels build on a massive expansion of renewable energy supply. As a result, in the power sector, independence from fossil imports is achieved by 2030 and in the entire energy system until 2040.

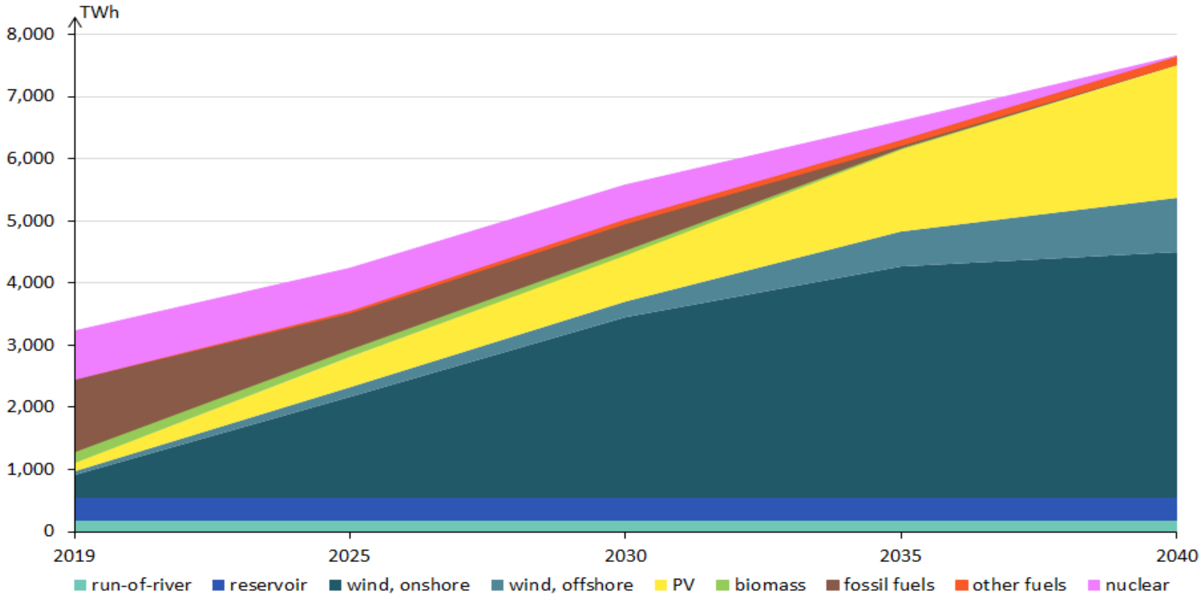

Figure 4.10: Development of European power generation for the modeled scenario.

Figure 4.10 shows how the supply of electricity develops from 2019 to a fully renewable system in 2040. Again, the most important lever to replace fossil is to increase the generation from renewable electricity from wind and photovoltaic. Compared to other renewable energy sources introduced in Sect. 3 (cf. also Sect. 6.5), wind and photovoltaic have a great energy potential and their costs are expected to keep dropping (cf. Fig. 6.3). The period until 2030 is critical and has the highest relative growth of renewable generation. Compared to 2019, generation from onshore wind increases by a factor of 8 to 2,900 TWh, PV generation by a factor of 6 to 750 TWh, and wind offshore generation by a factor of 4 to 250 TWh. After 2030, growth slows down in relative terms, but still increases substantially. In this period, PV generation still triples to 2,100 TWh. Offshore generation triples as well, increasing to 870 TWh, while onshore wind only increases by 36% to 4,000 TWh. Power generation from run-of-river and reservoirs remains constant, since we applied the common assumption that its energy potential is already fully exploited in Europe. Finally, the generation from biomass decreases since the limited potential of biomass is utilized in parts of the energy system more difficult to decarbonize, for instance the production of fossil fuels.

Corresponding to the expansion of renewables, fossil generation quickly declines from 1,160 TWh in 2019 to 420 TWh by 2030 until it is completely phased-out in 2040. From a climate perspective, the phase-out should prioritize emission-intensive lignite and coal power plants. Although fossil generation declines rapidly, it is sensible to decommission power plants slower and keep them as backup capacities for times with low generation from wind and solar. In the long-term, storage and other flexibility options will fill this role and replace a substantial share of firm capacity from fossil fuels, as discussed in depth in Sect. 4.6. This includes an uptake of thermal plants powered by hydrogen that only provide 35 TWh of generation in 2030 but increase their generation share to 130 TWh in 2040. For nuclear, the underlying assumption is that existing capacities are operated until the end of their technical lifetime, but no new plants are constructed. This results in an almost linear decrease from 770 TWh of generation in 2019 to 275 TWh in 2035 and a European phase-out by 2040.

Already phasing out the entire fossil generation by 2030 instead of 2040 would require an even faster expansion of solar and photovoltaic until 2030. In addition, the production of hydrogen and construction of corresponding thermal plants fuelled by hydrogen would need to be accelerated to cover demand when fluctuating generation from wind and photovoltaic is small. Although phasing out the few remaining fossils by 2030 would be beneficial, it is not the most important lever to reduce emissions and dependence on fossil fuels. As explained in Sect. 4.3, electrification of heating and transport is highly effective to replace fossil fuels and should be prioritized, even if it delays the full decarbonization of the power sector. Section 4.2 shows that the greatest share of gas and oil is used in the heating and transport sector. As a result, an energy system that largely replaces fossil fuels in these sectors with electricity but only achieves a 95% renewable share in the power sector would be a lot less dependent on fossil fuels than a system with 100% renewables in power, but still the same levels of fossil consumption in heating and transport.

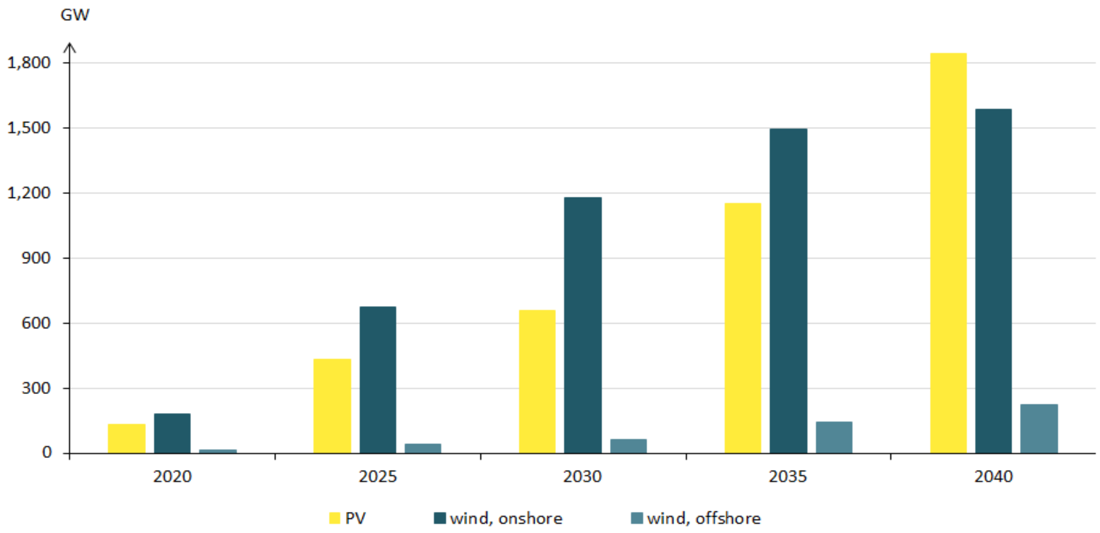

Figure 4.11: Development of wind and photovoltaic capacities for the modeled scenario

The key renewable sources to replace fossil fuels are wind and photovoltaic and the dynamic of their expansion shapes the transformation of the entire energy system. Figure 4.11 and Figure 4.12 show the development of total wind and photovoltaic capacities for the modeled scenario and the corresponding undiscounted investment costs arising in each five-year period, respectively. Table 4.3 shows the corresponding numbers in detail. These graphs again reflect that the expansion of renewables until 2030 is critical and that the greatest share of investments occurs in these periods. Faster growth after 2030 only occurs for offshore wind, because sites with great potential and large full-load hours for photovoltaic and onshore wind are mostly exploited by then. In addition, declining investments after 2030 reflect not only that added capacities are smaller but also that the assumed expansion costs for renewables decrease substantially due to learning effects, especially for photovoltaic. Until 2030, European countries must spend about 140 billion per year for the expansion of wind and photovoltaic, but this value decreases to an average of 100 billion per year for the decade from 2030 to 2040. As a reference to these costs, European countries are estimated to have spent 792 billion just to support consumers in the current energy crisis, a figure on top of the already substantial baseline costs of fossil energy (WEF 2023).

Table 4.3. Development of renewable capacities in Europe.

in GW	**2020**	**2025**	**2030**	**2035**	**2040**
Photovoltaic	134	430	660	1,150	1,843
Wind, offshore	14	38	63	142	223
Wind, onshore	181	677	1,177	1,495	1,588

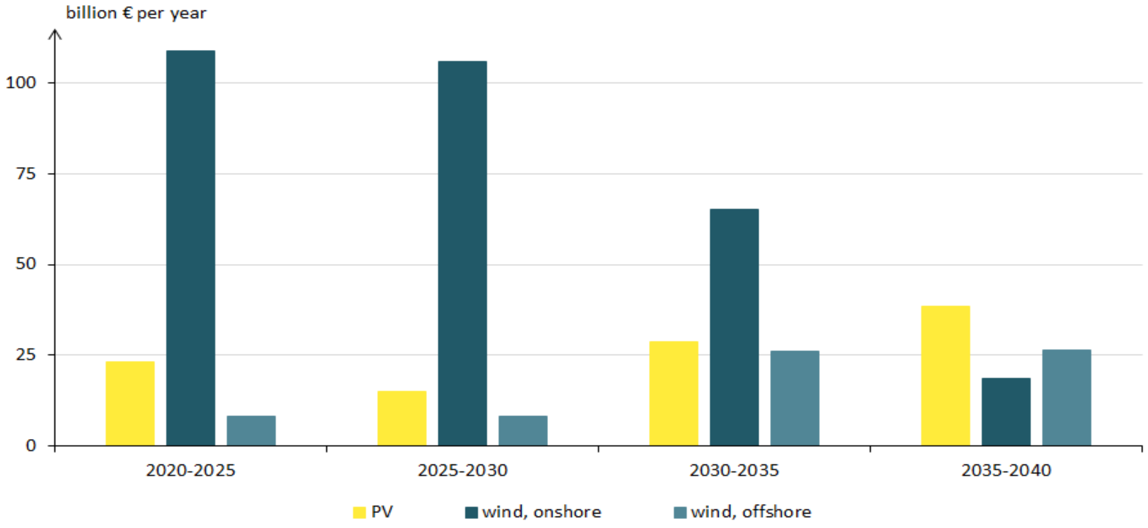

Figure 4.12 Annual investments needed for renewable expansion in the power sector.

The outlined expansion path is undoubtedly very ambitious, but not astronomical. For Germany, it implies adding 13.4 GW of PV and 12.7 GW of onshore wind on average per year until 2040. For comparison, in 2011 Germany achieved 7.5 GW of added PV capacity, a record so far. Current government goals even envision an expansion of 17.4 GW until 2025 and 22.0 GW afterward. For wind power, the highest expansion was 5.6 GW in 2017, and expansion plans are set at 6.5 GW until 2025, and 10 GW afterward (FfE 2022).

The spatial structure of supply and demand in 2040 is illustrated by country in Fig. 4.13. In the specific scenario, the power grid illustrated in the previous Figure 4.9 is restricted to today's level also limiting the amount of imports and exports between countries. Overall, the predominant share of power generation is covered domestically in each country. The greatest net importer within Europe is Germany. As a reference, in 2021 Germany imported 52 TWh and exported 71 TWh (Statistica/Eurostat 2022, cf. Tab. 4.4). Photovoltaic generation is more predominant in the Southern regions, while wind offshore is focussed on the North Sea. In all countries wind and photovoltaic dominate supply except Norway which has an exceptional potential for renewable and flexible generation from hydro reservoirs.

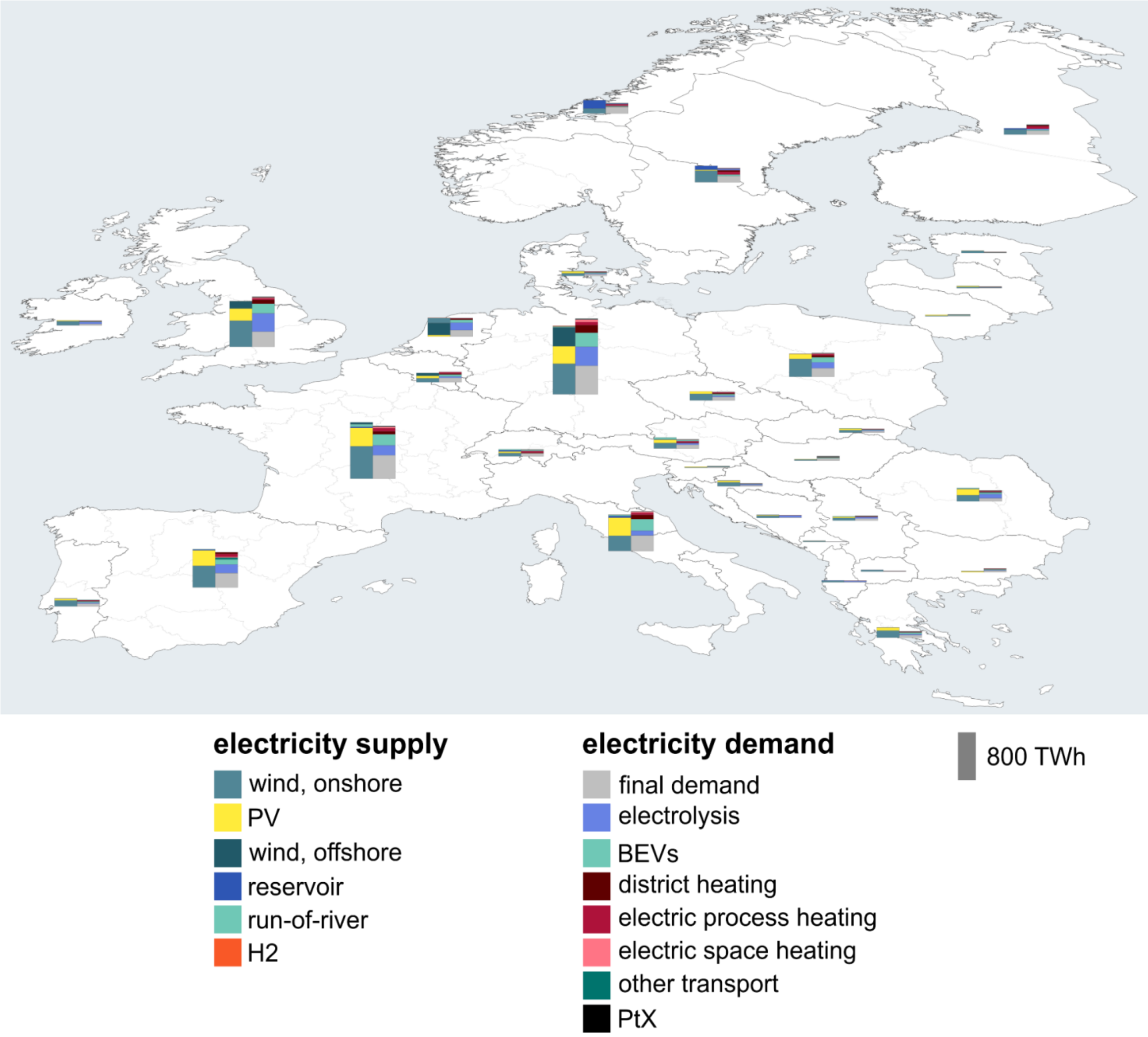

Figure 4.13: Spatial structure of supply (left bar) and demand (right bar) in 2040. Note, grey bar indicates 800 TWh and is the yardstick for the columns.

Table 4.4: Comparison of selected European Countries (year 2021) in regard to renewable power production and trade balance. Overall, 40% of the electricity produced is based on RES. Some countries like Spain, Portugal, UK, and Germany have based a large amount of renewable electricity production on wind and solar. The latter two RES are those with the highest potential and therefore with the largest cost advantages (cf. Tab. 6.1, cf. Fig. 6.6). For France, you can explain low values by the dependence on nuclear energy, while Norway benefits from its hydropower resources (Source: after World Energy & Climate Statistics – Yearbook/EUROSTAT 2022).

Country	**Share of RES in power production %**	**Share of wind and solar in power production %**	**Total Electricity production TWh**	**Electricity produced by RES TWh**	**TWh electricity produced by non-RES**	**Electrification of final energy consumption %**	**Trade Balance (negative = net exporters) TWh**	**Market dependencies**
Belgium	24	18	100	24	76	17	-8	EU27, UK
Czechia	14	3	85	12	73	18	-11	EU27
France	23	10	555	128	427	25	-42	EU27, UK, CH
Germany	42	29	584	245	339	19	-19	EU27
Italy	41	18	287	118	169	21	43	EU27, MNE

Netherlands	33	24	120	40	80	17	0	EU27, NO
Norway	99	8	157	155	2	47	-18	EU27, UK, RUS
Poland	17	11	181	31	150	16	1	EU27, UKR
Portugal	66	31	50	33	17	26	5	EU27
Romania	44	14	59	26	33	15	2	EU27, SRB, UKR
Spain	47	33	272	128	144	23	1	EU27, Morocco
Sweden	67	17	169	113	56	33	-26	EU27, NO

It should be noted that while the overall level of renewable generation is a robust finding, the mix of photovoltaic, wind offshore, and onshore is not, and the same level of independence could be achieved with a different combination of wind and photovoltaic, potentially at similar costs. This is especially true since costs depend on learning effects which again depend on the level of investments, but unfortunately linear models can hardly capture this effect. Second, estimating the total capacity potential for different renewable technologies is difficult as well, especially considering the conflicts related to renewable potentials discussed in section 6.1. For instance, underestimating the potential for open space photovoltaic in regions with high full hours will result in smaller generation from photovoltaics overall. Finally, practical constraints, like a slow ramp-up of industries, permission processes or trade dependencies, can substantially hinder the fast expansion of wind (cf., e.g. Sect. 6.4), but are difficult to represent in an extensive techno-economic analysis and have not been robustly quantified in the literature.

Especially, a stronger emphasis on photovoltaic could be advisable for two reasons: First, some sources expect cost degressions of solar that exceed levels currently expected (Victoria, et al. 2021). Second, and more importantly, there are less practical barriers to the expansion of solar generation compared to wind power. Construction of wind turbines often is a complex process starting with the designation of areas followed by the permitting process, potentially including conflicts with residents, and the construction itself. In case of offshore wind, the process is even more complex and additionally includes the grid connection to the mainland. Installing a photovoltaic rooftop system faces less bureaucratic obstacles. In addition, the risk associated with investments into photovoltaic rooftop systems are smaller thanks to fixed subsidy schemes opposed to the auctions based mechanism for wind turbines. Correspondingly, the DIW monitoring of the German "Energiewende" shows that the expansion of photovoltaic is where the German government is closest to meeting its long-term goals.[29]

A different composition of renewable generation is particularly viable in the timeframe until 2030 because despite their massive expansion, renewables do not reach a level of deployment that greatly challenges their integration into the system. Fluctuating generation from wind and photovoltaic in 2030 amounts to 74%, a level that does not require expensive seasonal storage systems, especially in the interconnected European energy system and with new potentially flexible demand from electric vehicles or electrolyzers (Victoria et al. 2019).

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[29] Based on data retrieved on the 07.02.2023. See this link or a continuously updated assessment: https://www.diw.de/de/diw_01.c.841560.de/ampel-monitor_energiewende.html

4.5. Electricity Demand in an Independent European System

The great expansion of renewables until 2030 is driven by two factors: First, the substitution of fossil fuels with electricity from wind and photovoltaic. Second, they need to cover the additional demand for electricity from electrification technologies at the consumer level. To quickly reduce dependency on fossil fuels and emission in the heating and transport, existing fossil systems in these sectors must be replaced with electric heat-pumps and battery electric vehicles. This is particularly critical, because without substantial subsidy programs, the expansion of new heating systems or vehicles is limited to the amount of existing systems reaching the end of their lifetime and being retired. So, a gas boiler installed in 2018 or a combustion engine vehicle manufactured in 2015 will be replaced with an electric alternative until 2030. As a result, expansion in these sectors is more moderate and reducing the dependence on fossil fuels more challenging. To avoid lock-in effects, new investments into fossil systems must be avoided as fast as possible.

The demand for hydrogen produced from electricity remains moderate in 2030 and the substantial ramp-up of electrolyzers, hydrogen grids, and applications using hydrogen, for instance to produce renewable fuels for aviation and navigation and provide high temperature heat for industrial processes, occurs after 2030. As discussed in section 5.5, the investment costs for the creation of hydrogen and synthetic fuels are also expected to start dropping in that period. In addition, synthetic fuels from hydrogen can serve as feedstock for the chemical industry, if the available potential of biofuels is insufficient. In this period, synergies arise between hydrogen generation and renewable shares close to a 100% because electrolyzers can utilize excess generation from fluctuating renewables to produce hydrogen at lower variable costs and prevent curtailment at the same time (Göke et al. 2023).

Highlighting the importance of electrification, the Sankey diagram in Fig. 4.14 shows the supply and demand for electricity in Germany for 2040. In total, final demand for electricity only amounts to 480 TWh and is exceeded by the electricity consumed for other sectors. Electric space, process, and district heating, predominantly with heat-pumps, requires 180 TWh of electricity; battery electric vehicles and rail transport in sum amounts to 240 TWh. The generation of hydrogen accounts for 330 TWh of electricity demand and provides excess heat to district heating networks as well. The ramp-up of hydrogen generation mainly occurs after 2030 when renewable supply starts to substantially exceed demand more frequently. In Germany, domestic production cannot entirely cover the demand for hydrogen, so 88 TWh are imported from other European countries. To some extent, hydrogen is used to fuel thermal power plants that cover demand when renewable generation is low. The greater share, not accounted for in Fig. 4.13, is used to provide high temperature heat for industrial processes that cannot be electrified and to create synthetic fuel for other applications, like aviation and navigation. To some extent, these fuels are also created using the available potential for biomass, for instance using the Fischer-Tropsch process.

As a comparison to results for Germany, Fig. 4.15 and Fig. 4.16 provide analogous Sankey diagrams for Spain and Norway. In all countries, electrification is predominant on the demand side. However, in contrast to Germany, Spain is a net exporter of electricity, hydrogen, and synthetic fuels, and relatively generates a lot more electricity from photovoltaic thanks to higher full load hours.

Norway is mostly an exporter as well, but here the most striking difference is the large share of generation from hydro reservoirs. In contrast to wind and photovoltaic, generation from reservoirs is also flexible substituting other types of flexible generation, like hydrogen fuelled thermal power plants or batteries, installed in Germany or Norway.

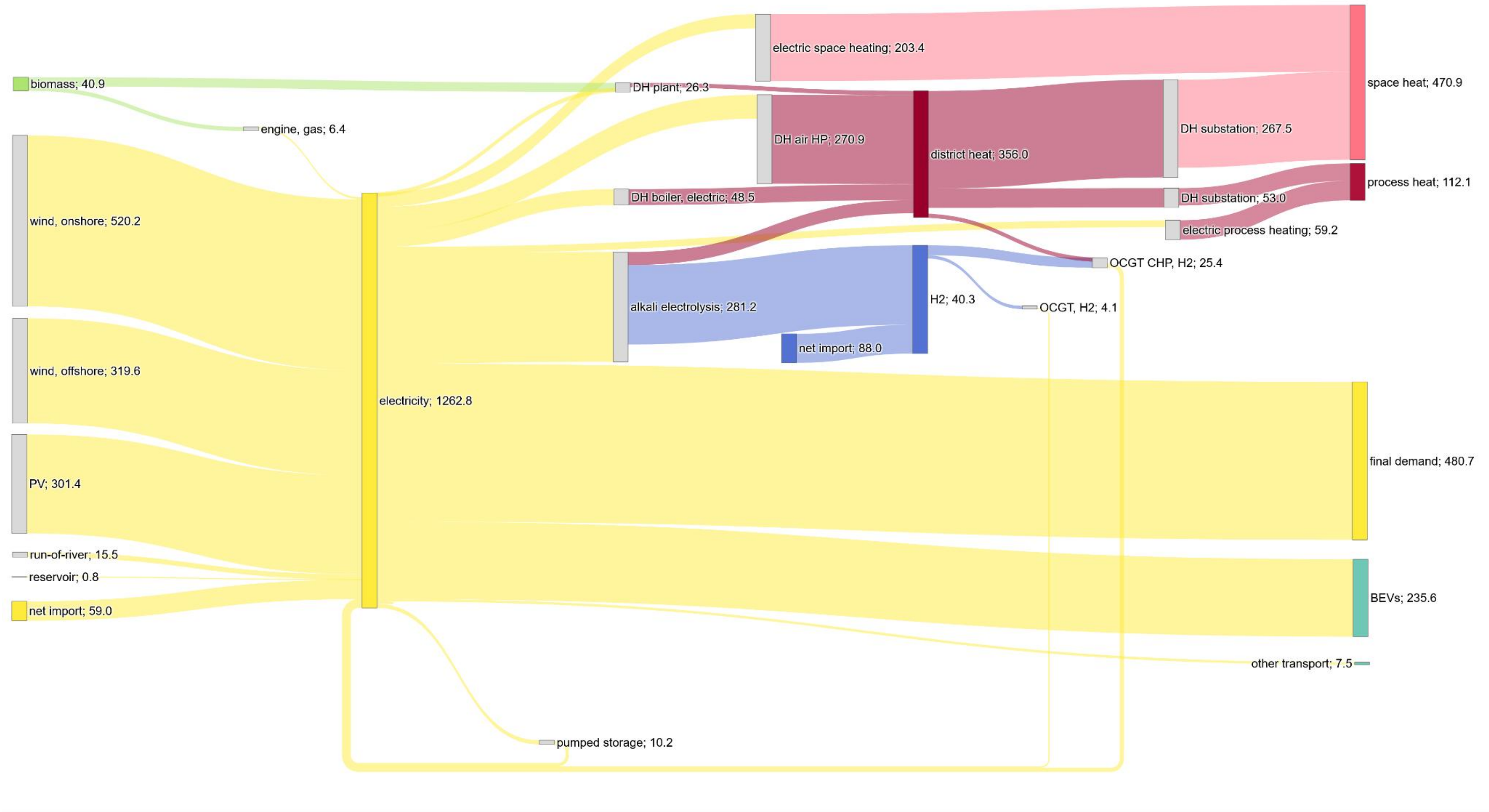

Figure 4.14: Sankey diagram showing the supply and demand for electricity in Germany 2040, all values in TWh.

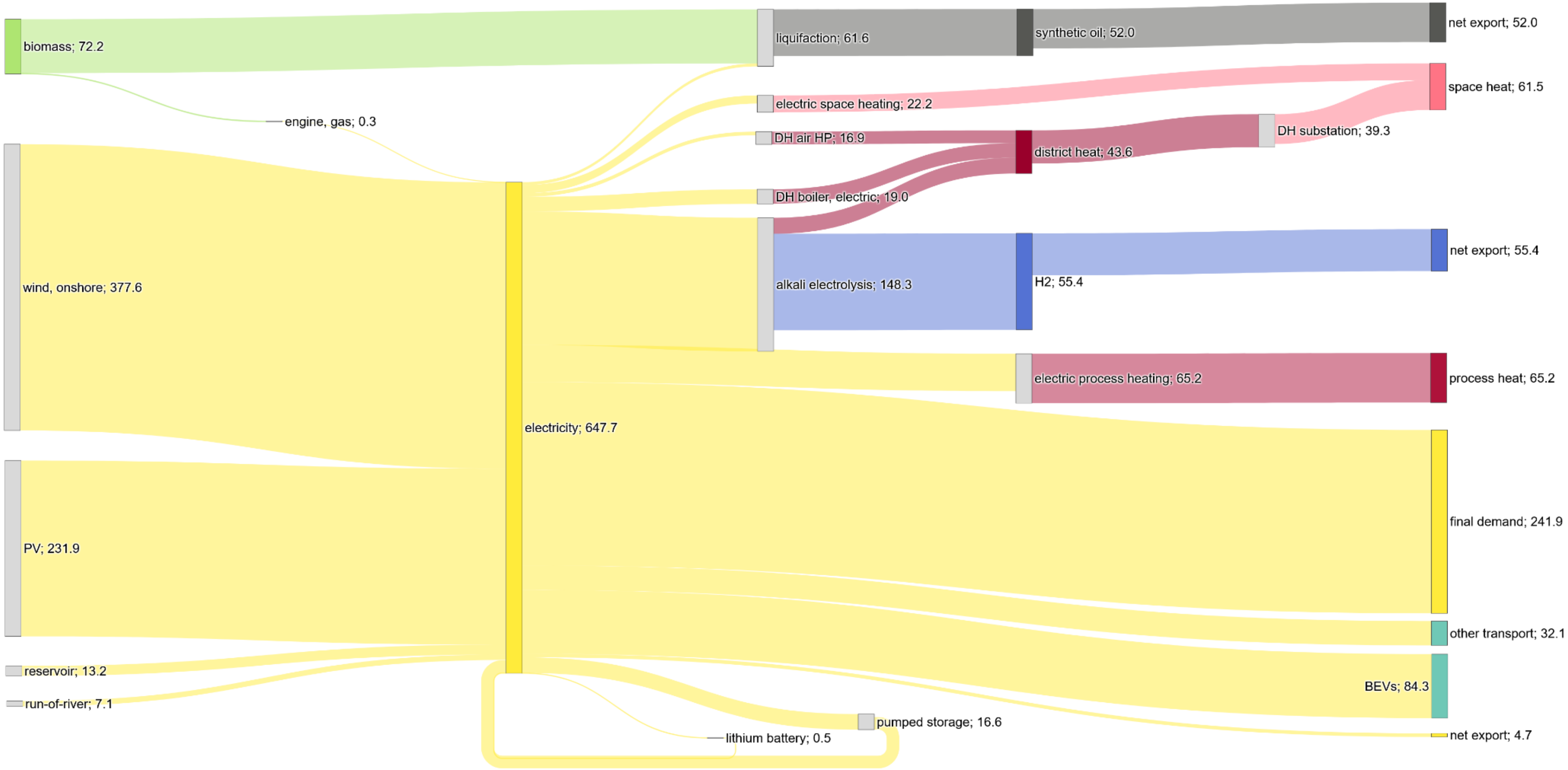

Figure 4.15: Sankey diagram showing the supply and demand for electricity in Spain 2040, all values in TWh.

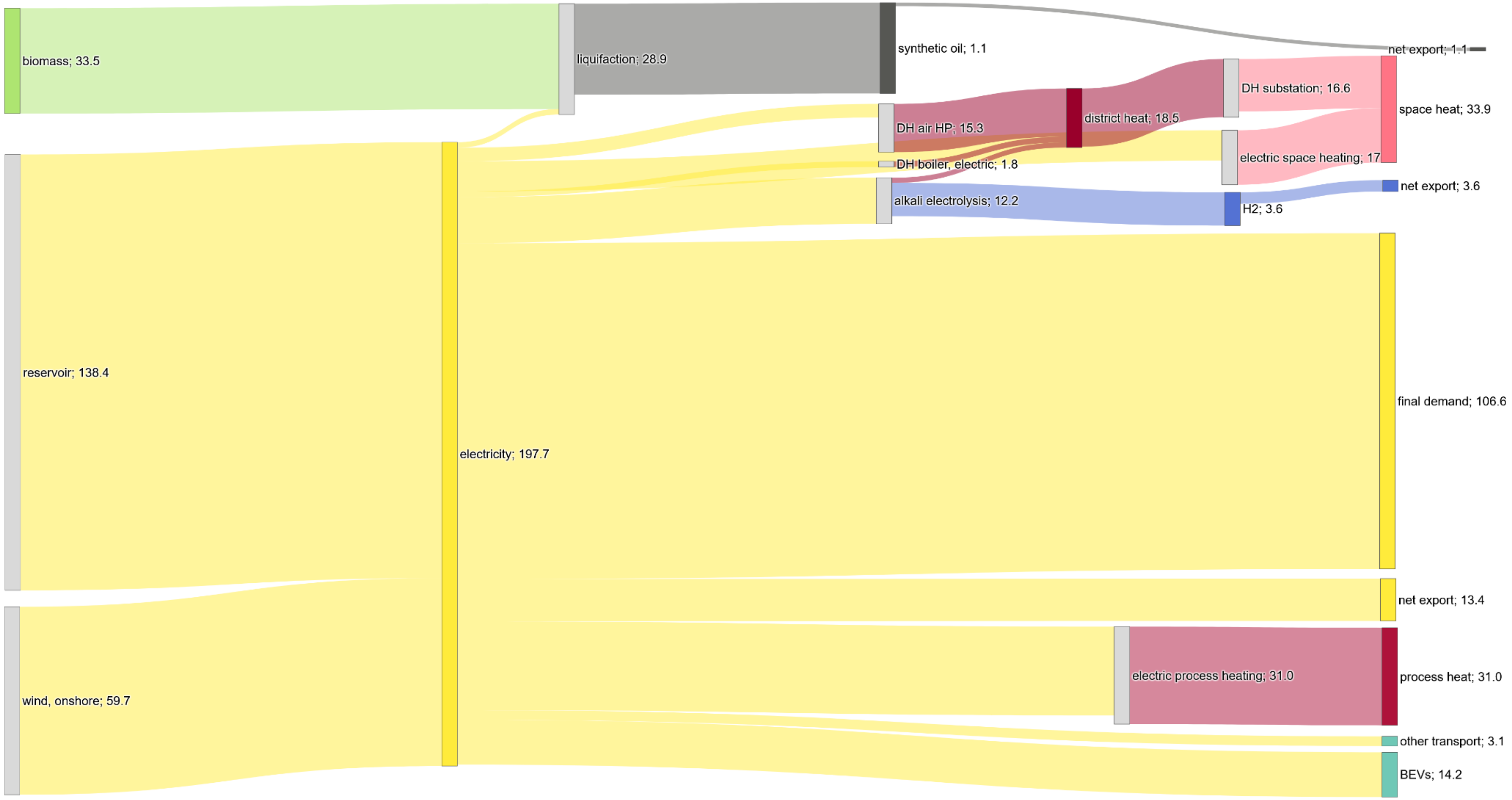

Figure 4.16: Sankey diagram showing the supply and demand for electricity in Norway 2040, all values in TWh.

4.6. Role of storage and flexibility

As further discussed in Chapt. 5, wind and photovoltaic, both fluctuating energy sources, require other parts of the energy system to flexibly adapt to supply, for instance storage systems. In this section, we will discuss how the modeled self-sufficient energy system presented in the previous sections provides this flexibility and to what extent these results are robust to input assumptions.

We will base this discussion on the residual load curve for Germany in 2040 as displayed in Figure 4.17. It is only shown as an example, since Germany is the largest consumer of electricity in Europe, but the results for other European countries are very similar. The only exceptions are small countries, such as Switzerland or Norway, that have a high share of flexible renewable generation thanks to hydro-reservoirs. The curve is, like the underlying model, based on an average weather year.

Residual load curves show total demand minus generation from fluctuating renewables sorted in descending order, i.e. they depict the energy that non-fluctuating sources must supply. As a result, the y-axis intercept of the residual load curve gives the maximum supply from non-fluctuating sources. The area above the x-axis corresponds to the energy they supply; the area below the x-axis to excess energy.

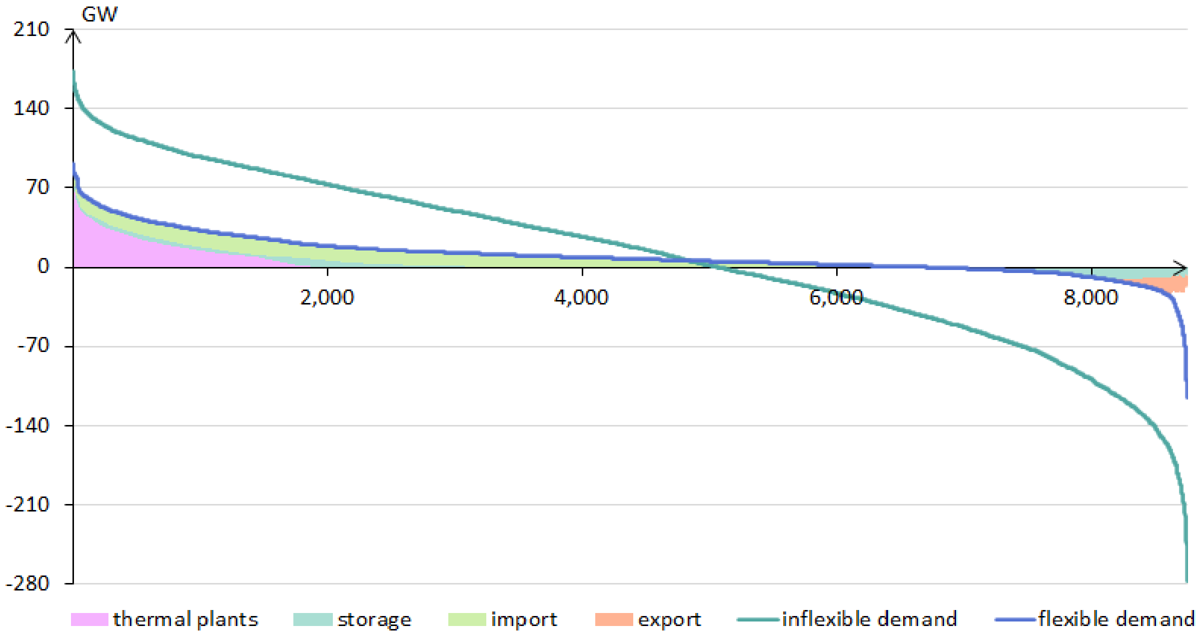

Figure 4.17: Duration curve and impact of flexible demand for Germany in 2040 (Göke, 2023).

The figure shows that the flexible use of excess energy is a key option for the system to adapt to fluctuating supply. Compared to the case with inflexible demand, it reduces the remaining peak load by 80 GW and the necessary generation from non-fluctuating sources by 200 TWh.

The greatest share of flexible demand is provided by electrolyzers adapting to supply and using hydrogen caverns to store hydrogen for later demand. In addition, flexible charging of battery electric vehicles and flexible operation of district heating systems add further substantial flexibility. In the results, this demand side flexibility largely substitutes grid connected batteries that can provide flexibility on a similar time-scale of a few hours up to one or two days. However, if missing infrastructure on the distribution level or a lack of price incentives for consumers hinders demand-side flexibility, substantial investments in grid-connected batteries might still be necessary. Due to high energy losses, hydrogen-based storage of electricity is not an appropriate substitute on this short time-scale.

Thermal power plants powered by green hydrogen or biofuels cover most of the remaining peak load, but only provide 36 TWh of generation in total, about 3% of demand. In addition, pumped storage systems[30] and the im- and export of electricity cover demand and utilize excess generation. The analyzed scenario did not consider further expansion of the European transmission grid. In case expansion is possible, the contribution of im- and export increases substantially, while thermal generation drops to 8.8 TWh.

Overall, the results on installed storage systems reflect the characteristics of the residual load curve for Germany. For the whole of Europe, grid-connected battery storage, meaning excluding electric vehicles, amounts to 8.3 GW of power capacity and 39 GWh of energy capacity resulting in a theoretical storage duration of 4 hours and 45 minutes.[31] Large water tanks in district heating networks that enable a more flexible electricity demand have a heating capacity of 1.3 GW but energy capacity of 81 GWh which results in a storage duration of about 62 hours. Pumped storage systems provide 75 GW of power capacity at a storage duration of 100 hours on average.

For even longer storage durations, the system deploys pit thermal storage for district heating to a great extent, significantly reducing electricity demand from electric heating systems during the winter. The total European capacity amounts to 847 GW of heat and can store up to 150 TWh. Finally, there are caverns and tanks for hydrogen storage to balance supply and demand on a seasonal scale. With a storage capacity of 50 TWh, caverns make up the largest share of this storage capacity. Their geological potential is concentrated mainly in Central Europe and is estimated to be a total of 24,000 TWh (Caglayan 2020). Tanks for hydrogen storage only amount to 2.4 TWh. To flexibly produce the corresponding hydrogen, alkali electrolyzers with a total electrical capacity of 571 GW are installed operating at 2,700 full-load hours. Correspondingly, 80 GW of hydrogen powered thermal plants use the stored hydrogen to supply electricity again at an utilization rate of 704 full-load hours.

There are two aspects the results on storage and flexibility discussed above do not cover, due to computational limits in modeling. First, the provision of ancillary services in the electricity sector, which are currently mainly provided by fossil generators. For the renewable system, it is plausible to assume that smart consumers, like heat-pumps or electric vehicles, are capable of covering these services to a large extent. If this approach fails due to technical reasons or concerns regarding data privacy, additional battery storage can serve as a substitute.

Second, the analysis only considers a single average weather year without rare extreme events, like prolonged periods with high demand but little generation from wind or solar. One option to guarantee adequacy in case of such an event is to increase the capacity of hydrogen powered plants. Since these plants have low investment costs and will rarely operate, the costs of such a security measure are reasonable. For example, assuming simplistically for Germany that once every 10 years, wind and solar do not generate any energy and electricity cannot be imported either, this would result in a supply gap of about 50 TWh assuming an annual demand of 1250 TWh. To supply this energy, roughly 87 TWh of hydrogen are needed, which only accounts for 5% of total hydrogen demand in the ten-year period and 20% of Germany's strategic oil reserves today.

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[30] Capacities for pumped storage in Germany and Europe are assumed to be at today's level in 2040.

[31] The model can freely decide on the ratio of power and energy capacity within the range from 1 to 10 hours.

4.7. Conclusions and Key Messages

The role of hydrogen in the energy system until 2030 critically depends on the level of import independence in terms of fossil fuels to be achieved. Battery electric vehicles are not sufficient to substitute oil imports until 2030 because the transformation speed of the existing car fleet is limited and substituting oil in aviation and navigation is even more challenging. As an alternative, one option to reduce the great dependence on oil imports is to create synthetic fuels to fuel pre-existing combustion engines before they are being replaced with battery electric vehicles until 2050. Because the use of the energy potential of biomass is limited and debatable (cf. Sect. 3.5) such strategies must be carefully developed as hydrogen will be also needed for further industrial processes. Since this hydrogen demand must be met with domestic production based on renewable electricity, it is also responsible for the extreme increase of photovoltaic and wind generation in the full independence case.

1. To substitute fossil fuels in the power sector and enable the electrification of heating and transport, independence from energy imports requires a massive expansion of photovoltaic and wind capacities in the years until 2030.
2. The composition between wind and photovoltaic is flexible and priority should be given to a fast expansion, ideally close to the demand.
3. Until 2030, yearly costs of renewable expansion on a European level, not only the European Union, are estimated around 140 billion €, but will drop substantially after 2030.
4. As a reference, European countries are estimated to have spent additional 792 billion € in the last year just to protect consumers from the effects of the energy crisis introduced by the Russian invasion into Ukraine.
5. Despite the massive expansion, renewable shares in the electricity sector will not exceed 74% by 2030, a share that can be managed with flexibility and storage technologies already market-ready today.
6. Beyond 2030, hydrogen becomes increasingly relevant as an energy carrier. It is needed to replace fossil fuels in applications that cannot be electrified directly and as a backup for power generation when shares of wind and photovoltaic increase further. At the same time, increasing shares of wind and photovoltaic reduce the production costs of hydrogen due to the rising amount of excess generation.

5. System Flexibility: the Way Towards Energy Autarchy

5.1. Overview

The capacity of energy systems to adapt to fluctuations in both energy demand and production is referred to as flexibility. With a growing inclination towards achieving decarbonization goals, the increased use of non-dispatched renewable sources like wind and solar continues to rise which consequently calls for various options of flexibility. This section discusses the benefits and trade-offs of using various flexibility options to deal with the variability and power surplus in electricity systems. It is noted that using multiple options such as network expansion, storage, wind/solar ratio, flexible generation, excess of capacity and curtailment, have synergistic and complementary effects that can greatly reduce the need for storage or grid expansion (Lund et al. 2015; Papaefthymiou and Dragoon 2016). Additionally, including sectors other than power (such as Power to X including fuels, heat and gas) in the scope of analysis can be beneficial as it provides more options for flexibility and results in lower storage needs compared to systems that only cover power (Brown et al. 2018).

In the long-term, flexibility is needed to address seasonal mismatches between demand and renewable supply patterns. An example of this is the mismatch between solar power generation during the summer and winter peak load. In the medium-term, dispatchable generators and medium-sized storages (e.g. pumped hydro storages) adjust to forecasts in advance to keep deviations small. And in the short-term, ancillary services are needed to balance out demand/supply deviations caused by forecast errors (Heggarty et al. 2020). As the penetration of renewables increases, the traditional power plants' stability becomes inadequate and imbalances lead to unintended frequency changes. This issue can be resolved by ensuring the use of synchronous compensators operating at no load or through the implementation of inverter-linked assets like renewables and batteries, which control the frequency and reduce frequency fluctuations (OSMOSE 2019).

A flexible demand side will aid in integrating non-dispatchable renewables, reduce renewable curtailment, and lead to a more efficient energy system (Dranka et al. 2021, Moura and de Almeida 2010; Zerrahn and Schill 2015). Integrating other energy sectors, such as transportation and building heating, can provide new opportunities for making demand more flexible (Verzijlbergh et al. 2014; Gunkel et al. 2020; Bloess 2019; Bernath et al. 2019). Three key measures for providing flexibility are the utilization of excess electricity, grid infrastructure, and energy storage (Schill 2020).

In the remainder of this chapter, we will give an overview of three key measures to provide flexibility: the utilization of excess electricity, grid infrastructure, and energy storage.

5.2. Role of Excess Electricity

An important feature of the future electricity supply should not remain unnoticed: As discussed above, a large part of our future energy supply will be electricity. In the future, the widely dominant energy source will be the fluctuating electricity generation from solar and wind. In order to secure a stable 24/7/360 electricity supply, it will be necessary to vastly oversize generation capacity. For Germany alone about 300 GW wind and 400 GW PV capacity should be installed (Fraunhofer 2020). These numbers should be compared with Germany’s peak power demand of 80 GW today. Whereas the total energy demand is expected to decrease in this model by 10-40% with increased energy efficiency, still the total electricity need in Germany is expected to double. However, even with a doubled peak power demand, there will be many hours annually where the electricity supply from 700 GW of combined PV and wind capacity vastly exceeds the power demand. Seeba (2014) predicted the future availability of abundant, superfluous electricity already in his book ‘Clean Disruption’. Already in 2022, about 6 TWh of available electricity is wasted annually, by curtailing wind- and solar power. This number will rapidly grow with future penetration of fluctuating wind and solar sources in our energy supply. The availability of excess electricity at certain times of the day underlines the necessity of flexibility. In general, three options are conceivable to handle excess electricity

1. Changed electricity load demand in companies and private households.

   Companies could also shift their production or services to the time of day when a lot of electricity is generated. The same applies to households, which could also change their consumer profiles in this respect.

2. Storage of excess supply in buffer batteries (distributed storage).

In this case, special inverters can be used to store excess energy in batteries or supply a local consumer/producer with electricity when it is demanded.

3. Storing electricity back into the network infrastructure via net-metering.

In any case, a sustainable future will require highly flexible grids. Large-scale electricity storage promises to be a game-changer and will eventually help RES achieve a breakthrough. The same applies to costs, as they will determine which storage technologies will prevail. However, a major focus must also be placed on the grids themselves. Modern technical systems, such as electricity grids, are characterised by the fact that they communicate and interact with numerous other system components, or even indirectly influence them. This makes the design of such distributed systems complex, but also makes them more resilient. How such dependencies are shaped is often not fully foreseeable at the design stage, even for experts, because system tasks can change over time. This means that systems must be granted properties and freedoms so that they can configure, optimize, or even adapt themselves within certain corridors. This also includes the ability to compensate for failures independently, for example. In this context, digitalization, artificial intelligence and also so-called organic computing will gain important relevance.

5.3. Grid Infrastructure

Most techno-economic analyses, including the ones mainly cited in Chapt. 4, show grid infrastructure benefits system integration of renewables because it can equal out local fluctuations of renewable supply and demand (Schaber et al. 2012, Brown et al. 2018). For electricity grids, this applies in the short-term, but also for fully renewable systems. A large-scale grid infrastructure for hydrogen may become more relevant in the long-term when supply and demand for hydrogen reach substantial levels as well (Neumann et al. 2022). Research already pricing in the costs of the grid expansion estimates that the expansion of the power grid reduces the costs of renewable energy systems by 5% to 10%. (Göke 2023, Neumann & Brown 2021). For hydrogen grids, cost reductions up to 6% are estimated (Neumann et al. 2022).

Although research suggests benefits, it offers alternatives to grid expansion and finds that further expansion of the power grid can maybe be avoided or least substantially reduced at moderate costs. Substitutes for the expansion of the power grid are battery storages to shift generation a few hours and placing renewables closer to demand centers (Tröndle et al. 2020, Göke et al. 2022).

5.4. Electricity Networks

5.4.1. Renewable-Based Electrification Requires Appropriate Networks

Electricity networks, both transmission and distribution, play a crucial role in the decarbonization of the energy system until 2030 and in securing the European sovereignty that we explore in this study.However, the call for appropriate electricity networks does not imply a limitless network expansion. On the contrary, currently most networks are already well-developed, and relatively modest network extension can yield significant results, when accompanied by efficient market design. This implies the full use of operational capacity, e.g. through a system of nodal pricing (as practiced in some restructured regions in the US (Neuhoff et al. 2013). Also, a decentral approach of deploying renewable energy production close to demand can save network extension. The construction of “Super Grids”, e.g. the EU-MENA Desertec project, is neither useful nor feasible, in this context (Hirschhausen 2010). The interdependence between central and decentral approaches and network extension has been shown in recent studies on Germany by (Kendziorski et al. 2022) and (Göke et al. 2022). In contrast to conventional generators, the costs and potential of renewables greatly vary by location. As a result, bottlenecks of the grids and the costs to resolve them should be factored in when placing renewable generation and other assets storing, consuming, or producing electricity, like batteries, electrolyzers, or hydrogen turbines (Kemfert et al. 2016).

Currently, centralized planning approaches are dominating the European energy system and create a bias toward sites with the highest yield. In contrast, decentralized planning considers both regional supply and demand. As a result, local suppliers can to some extent replace large-scale generators and directly match demand locally. This approach also mitigates the need for grid infrastructure and the corresponding costs. In addition, it can benefit public acceptance for the transformation of the energy system because it enables citizens to become local suppliers. In the current policy framework on the national and European level, the benefits of local production are not yet considered.

5.4.2. European Network Development Planning Needs to be Restructured

The sovereign energy Europe with renewables implies a fundamental restructuring of network planning at the European level (as well as the national level). As explained above, EU Reference energy scenarios depend on a political compromise to keep a certain balance within the triad between fossil fuels, nuclear, and renewables - costing Europe over €500 billion per year worth of energy imports. Clearly, the reorientation of the strategy towards a sovereign energy Europe working towards 100% renewable energy supply requires three fundamental adaptations of network planning:

- The scenarios upon which network planning is based need to be adapted, to include the objective of energy sovereignty and renewables into account.
- The focus of renewables implies that the “nuclear bias” in the reference and other scenarios need to be abandoned and substituted by RES. The nuclear bias consists of an ex-ante definition of a high share of nuclear power (currently in the range of 10-15% of electricity production), disconnected from the energy economic reality, i.e. very high costs of nuclear compared to other energy sources (von Hirschhausen 2017; Steigerwald, Weibezahn, et al. 2022). In addition, the almost complete reliance on uranium imports into Europe clearly conflicts with the point of departure of this study, namely energy autarchy (cf. Sect. 1.1).
- The focus on electrification and sector coupling implies that an integrated network planning is required, instead of the current independent optimization of electricity (by ENTSO-E) and natural gas (by ENTSO-G), and hydrogen network planning.

5.4.3. Natural Gas Infrastructure

Natural gas infrastructure has been a central pillar in the conventional fossil-fissile energy system, with a high dependency on imports from outside of Europe, and was generally believed to play a certain role in the energy transformation. However, this situation has undergone a major twofold change. Twofold, as on the one hand side supply perspectives have been shaken drastically following the Russian invasion of Ukraine on February 24th, 2022, while on the other hand side the narrative of natural gas as a so-called “bridge technology” has lost its significance, as fossil gas has been shown to have similar climate impacts as coal and therefore needs to be phased our rapidly (Kemfert et al. 2022; Hirschhausen et al.

2022). The following section concludes investigations by Holz et al. (2023a, 2023b) and can be summed up briefly in the following three points:

- Europe's historically dependency on Russian natural gas imports virtually disappeared in less than a year.
- Coordinated European response can quickly mobilize political and economic investments for significant system change.
- European countries are investing in alternative sources of gas, such as floating re-gasification terminals, and are also considering phasing out natural gas in the longer term to meet climate neutrality targets.

Facing the end of fossil natural gas imports from Russia, the German federal government has however decided to charter five floating re-gasification terminals. With one additional private project underway, this amounts to a total of more than 40 bcm of yearly floating re-gasification capacity expected to be in place by 2024. Therefore, the situation on European gas markets has stabilized and prices have come down. At the same time, considering the climate targets adopted by the European Union, namely climate neutrality by 2050, phasing out all fossil fuels including natural gas in the longer term has now become a necessity (von Hirschhausen, et al., 2022).

While floating import capacities are relatively flexible by nature and can, hence, have a limited lifespan in Europe to help bridge the short term supply gap, the opposite holds for investments into fixed onshore infrastructure. Not only does there exist no gap to fill in the long term (if fossil natural gas is phased out in accordance with European climate targets), but such investments are also likely to turn stranded. In addition, taking into account that new onshore projects are not expected to come online before 2026, with further delays possible as is common for such capital-intensive infrastructure investments, they further fail to address import needs in the short term. In the unlikely case of a natural gas shortages at later stages in time, temporarily prolonging the use of floating storage and re-gasification units appears favorable in comparison to investments into onshore terminals, as it has a much lower risk of stranding investments, thereby creating much less of a barrier to the energy transformation.

In conclusion, European countries will likely continue their efforts by relying on a greater deal of domestic European fossil natural gas production, with a strongly declining overall use of natural gas in the longer term. In the short term, relatively flexible floating storage and re-gasification units may help to bridge the supply gap left by disrupted imports. In the long run, investments into onshore re-gasification terminals (and thereby investments into infrastructure relying on importing fossil natural gas from outside of Europe in the long term) are likely to turn stranded in the light of recent climate targets. A similar logic applies to new large scale pipeline projects within Europe, which are also likely to turn stranded in the light of climate ambitions.

5.4.4. Hydrogen Infrastructure

Although electrification is the most efficient option to substitute fossil fuels in many applications, many industrial processes cannot be electrified, at least with the technology that we expect today to be market-ready in the near future. In these cases, hydrogen is a viable option for decarbonization, either directly or as a basis for the creation of other synthetic fuels. Since the demand will mostly arise from industrial applications, a concentration of demand in industrial regions can be expected and grid infrastructure can be beneficial to supply hydrogen generated elsewhere to these regions.

The role of hydrogen, a costly gas that is very energy-intensive to transform, in the future European energy system is highly uncertain. This is reflected in both scope, and scale of potential applications. At the moment, it is neither fully clear which economic activities will have made a switch to hydrogen by when, nor is it clear how much production and demand side capacity are available by then. Significant demand for hydrogen will only arise after 2030 when excess renewable generation becomes substantial and a high level of electrification is achieved already. Thus, hydrogen is expected to play a larger role in the longer term (until 2050) decarbonization of Europe, in particular in applications such as energy storage (PtG), industry, some district heating, and parts of transportation. Therefore, no excessive construction of hydrogen infrastructure needs to take place immediately, but long-term planning until 2050 and beyond should consider various options.

As discussed above, the medium-term prospects (until 2030) for hydrogen infrastructures are modest, given that hydrogen is not really a part of the energy system yet, that infrastructure is practically nonexistent, and costs are still rather high due to limited learnings. Therefore, infrastructure requirements are still uncertain. Another factor of uncertainty lies in the degree of centralization. While not importing hydrogen from outside of Europe certainly implies less large-scale centralized import infrastructure and a more decentralized approach, the precise degree of these remains to be determined. A further source of uncertainty is the actual form of hydrogen use. In the shorter-term, using hydrogen derivatives like e.g. ammonia reduces the risks of stranding assets. However, it is likely that for the energy transformation hydrogen-related infrastructure seems to be a prerequisite. Nevertheless, investments into hydrogen infrastructure are characterized by a high degree of asset specificity and potentially long lifetimes. Since infrastructure is complementary to the form of hydrogen used, initially going with hydrogen derivatives that have a relatively high valued next-best alternative yields a higher chance of quickly ramping-up necessary investments.

The European autarchy strategy is possible, even though at present, many national plans foresee a large share of imports from overseas. For example, domestic demand estimates in the German National Hydrogen Strategy (German Federal Ministry for Economic Affairs and Energy, 2020) range around 90 to 110 TWh of hydrogen by 2030, while only up to 14 TWh of hydrogen from renewables are assumed to be produced domestically. Given the limited European generation capacities and low energy efficiency of hydrogen-related conversion processes, direct electrification is a comparatively more attractive option, implying a smaller role for hydrogen in the European energy autarchy case, with less centralized import infrastructure.

Another issue is the role of hydrogen in reducing and finally eliminating greenhouse-gas emissions in industry, like from steel and concrete industry. This is not directly energy-related, the issue is the replacement of chemical reduction processes like iron ore, based today on carbon oxidation, by hydrogen oxidation, as the product is water instead of CO_2. For these purposes, some amounts of imported green hydrogen might be needed on a long-term basis. A fundamental connection lies on the hydrogen natural gas nexus and the repurposing of fossil natural gas infrastructure for hydrogen applications (cf. also Sect. 4.7). This plays a role for both fossil natural gas pipelines, and liquified natural gas import terminals. Repurposing of pipelines might be technically feasible and economically viable (Cerniauskas et al., 2020), although more substantial modifications may be required. The actual degree to which liquefied natural gas import terminals may be used for hydrogen or its derivatives remains highly questionable though (Riemer et al. 2022).

Overall, the role of hydrogen and hydrogen-related infrastructures in the energy sector remains subject to a high degree of uncertainty. Neither the scope, nor scale of potential applications is fully known yet and may be subject to new discoveries in the future. In case of a European energy autarchy strategy, limited power generation capacities make electrification a comparatively attractive option, resulting in a less centralized hydrogen supply infrastructure.

In the scenario study presented in section 5, grid infrastructure for hydrogen is mostly built to connect regions with large solar potential but small industrial demand in Southern Europe, especially on the Iberian Peninsula, with centers of the chemical industry in Central Europe. In addition, the geological potential for the underground storage of hydrogen that is mostly focussed on Germany is exploited to balance the seasonal mismatch of hydrogen production peaking in summer and demand peaking in winter. But since hydrogen only becomes relevant as an energy carrier after 2030, significant investments into this infrastructure only occur after 2030 in the discussed scenario.

5.5. Overview of Storage Technologies

Storage systems can be classified into technological types: electrochemical, mechanical, and chemical or by the duration they typically store energy: short-term, medium-term, and long-term (Sterner and Bauer 2017). They can be further characterized by their energy-to-power ratio (E/P), with short-term storage typically having a low E/P due to frequent charge and discharge cycles, requiring a higher installed power. Conversely, long-term storage must store energy over extended periods and tend to accumulate large energy amounts over time, resulting in high energy storage values. This is influenced by investment costs that can be separated into energy and power components. The role of storage in high variable power systems, with generation shares of fluctuating renewable above 80%, storage (and specifically long-term) plays a key role and reduces the overall system cost (Schill and Zerrahn 2018).

The characteristics of storage technologies vary substantially, and as a result different storage technologies compete with different options to provide flexibility in future power systems. The key difference is the amount of energy and the length of the timeframe when shifting energy supply. What kind of flexibility a storage system is suited best to provide decisively depends on its energy and power costs compared in Figure 5.1.

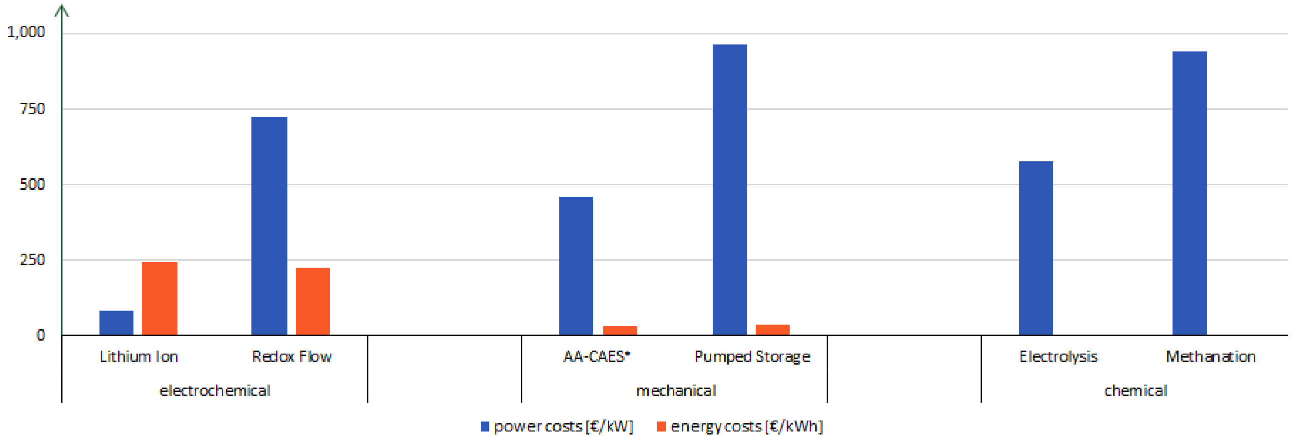

Figure 5.1: Energy and power costs for different storage technologies (OSMOSE 2019).

Electrochemical storage systems (batteries) are characterized by comparatively high energy costs, but small power costs. Besides the energy costs, high self discharge rates make long storage durations impossible as well. As a result, they are best suited to provide short-term flexibility and shift energy over a timeframe of less than two days, for instance to match photovoltaic generation peaking at noon with demand peaking in the evening. Therefore, these systems compete with interconnection and short-term flexibility on the consumer level, for instance local heat storage or flexible charging of battery electric vehicles (Göke et al. 2022). In addition, the expansion of photovoltaic generation, having a pronounced daily pattern, drives up the need for this kind of flexibility.

Mechanical storage systems are in between short- and long-term storage systems, having higher power costs than electrochemical systems but still significant energy costs. As a result, they are best suited to shift energy on a daily or weekly timeframe, but are not sufficient to balance out seasonal fluctuations. Conceivable substitutes are again interconnection or large scale heat storage in district heating networks using water tanks.

Finally, chemical storage systems only have negligible energy costs, rendering them capable of storing large quantities of excess generation during the summer to secure supply in winter. Generally, storage itself is not costly and comparable to existing gas storages potentially even deploying natural salt caverns (Caglayan 2020). However, due to the high energy losses, the process is only sensible at high shares of fluctuating renewables when excess generation is high meaning green synthetic fuels can be produced at lower prices and fossil plants cannot operate as backup during the winter anymore. On the other hand, substitutes for chemical storage to provide long-term flexibility are limited: Since photovoltaic generation generally decreases in winter, interconnection cannot greatly reduce seasonal mismatches of supply and demand. Biomass fuelled plants are an alternative to fossil backup plants, but the sustainable potential of biomass is limited and also needed in other sectors of the energy system. One of the few options to offset the need for chemical storages are large-scale systems for long-term storage of heat in district heating networks, for instance based on molten salt. In addition, countries with large hydro reservoirs, like Switzerland and Norway, can provide dispatchable renewable generation to the European energy system. These are opposed to smaller pumped storage systems discussed in the previous paragraph and for example predominant in Germany that cannot store great energy quantities. Nevertheless, it is generally assumed the available potential for hydro storage is already fully exploited today and no further investments are planned.

5.5.1. Electrochemical Storage

Electrochemical storage systems, also known as batteries, have made significant technological progress over the past decade. Often used in electric vehicles or with solar power systems, batteries are becoming increasingly important for the energy system. There are many different types of electrochemical storage systems: lithium-ion, redox flow, lead acid, zinc bromine flow, and sodium sulphur batteries (Stadler et al. 2017, Stenzel et al. 2015).

Lithium-ion batteries are popular because they are lightweight, have a high energy density and are relatively cheap. The lithium-ion cell is safer to use than previous, primary lithium-metal designs. In these batteries, lithium ions move between the electrodes during charging and discharging. The positive electrode is typically made of metallic oxides, such as cobalt, nickel, manganese, and aluminum, and can be a blend of these materials. The negative electrode is made of carbon, such as graphite. This combination of materials allows for a high nominal voltage. The electrolyte is usually made of organic liquid and a lithium dissolved salt (OSMOSE 2019; Buchmann 2015).

The main advantages of lithium-ion batteries, besides their high energy density, high nominal voltage, and long lifespan, are their low self-discharge rate, and the ability to recharge quickly. However, they are sensitive to overcharging and over-discharging, and must be carefully controlled during charging and discharging. According to literature research, costs are expected to drop sharply by 2030 and continue to decrease moderately until 2050 (depicted in Figure 5.2).

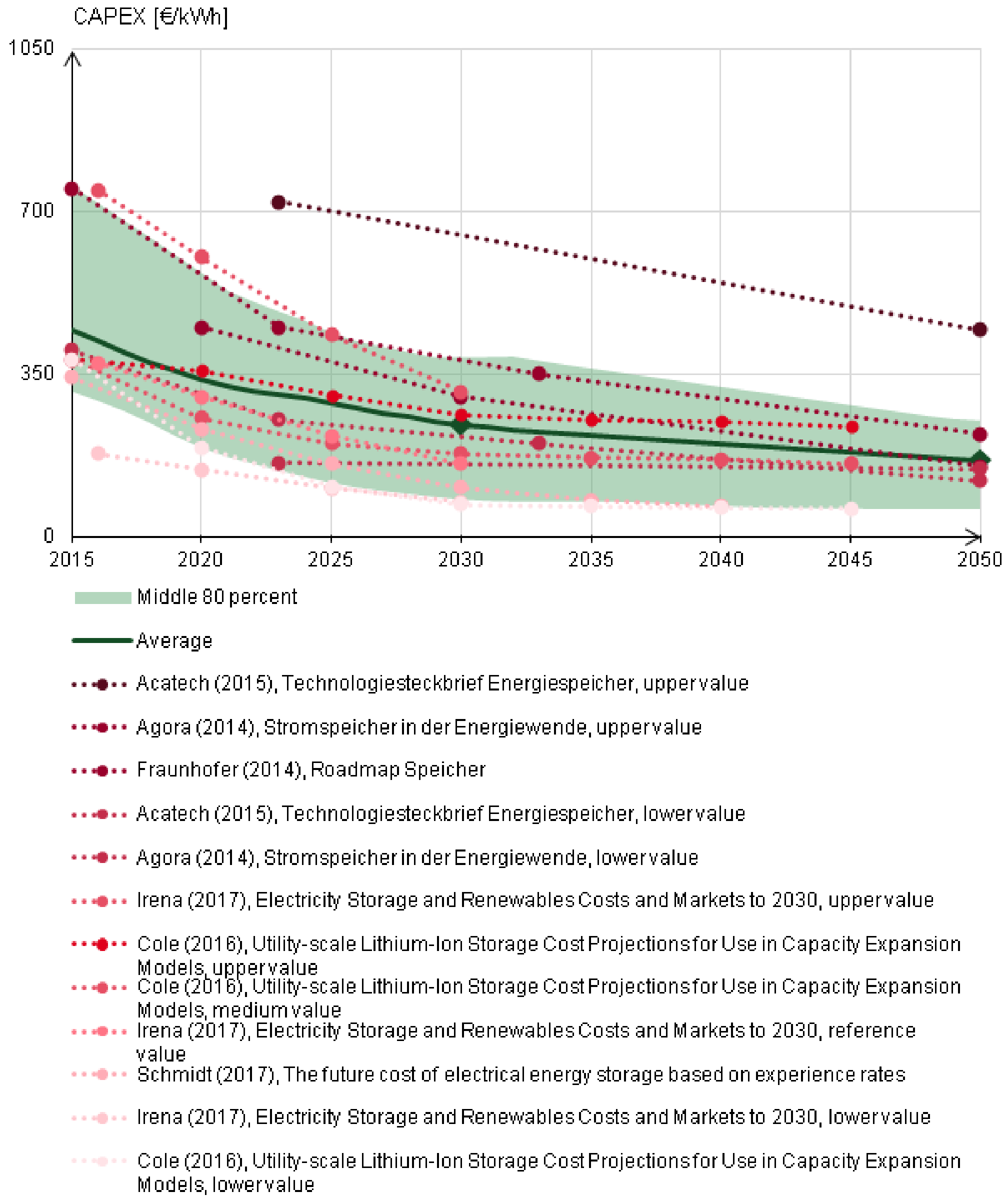

Figure 5.2: Projections of energy costs, lithium-ion battery (utility scale), Source: OSMOSE 2019.

A flow battery uses liquid electrolytes to store energy. Unlike traditional batteries where the electro-active materials are stored internally, the electro-active materials in a flow battery are stored mostly outside the battery. If all the electro-active materials are dissolved in a liquid electrolyte, these batteries are called redox (for reduction/oxidation) flow batteries. Most of these batteries consist of two separate electrolytes, one storing the electro-active materials for the negative electrode reactions and the other for the positive electrode reactions. As a result, the components which determine the installed power and the amount of energy which can be stored can be designed mostly independently. Another advantage is safety, which comes with storing the active materials separately. Combined with quick response times, high conversion efficiency, and the ability for deep discharges without affecting the cycle life, makes flow batteries an attractive option for large-scale energy storage (Stadler et al. 2017, Stenzel et al. 2015).

However, flow batteries come with a set of challenges that need to be addressed before widespread commercialization can take place. The maintenance requirements for pumps, sensors, flow, and power management, and secondary containment vessels, make flow batteries more suitable for large-scale storage applications. Additionally, flow batteries are relatively new, and it is difficult to determine their long-term durability and efficiency (OSMOSE 2019).

In order to overcome these challenges, further research is required in areas such as low-cost capital and operational expenses, efficient and durable electrodes, chemically stable redox couples, highly perm selective and durable membranes, and large-scale power and system management and grid integration. The primary barriers for economical use are the round-trip efficiency, cost for energy storage, and cost for power capacity. Due to the characteristics of (redox) flow batteries, they have the potential to serve as grid-level batteries due to their suitability for large-scale operation, but are unlikely to be used in residential applications. The investment costs are expected to decrease significantly in the next decades (shown in Figure 5.3).

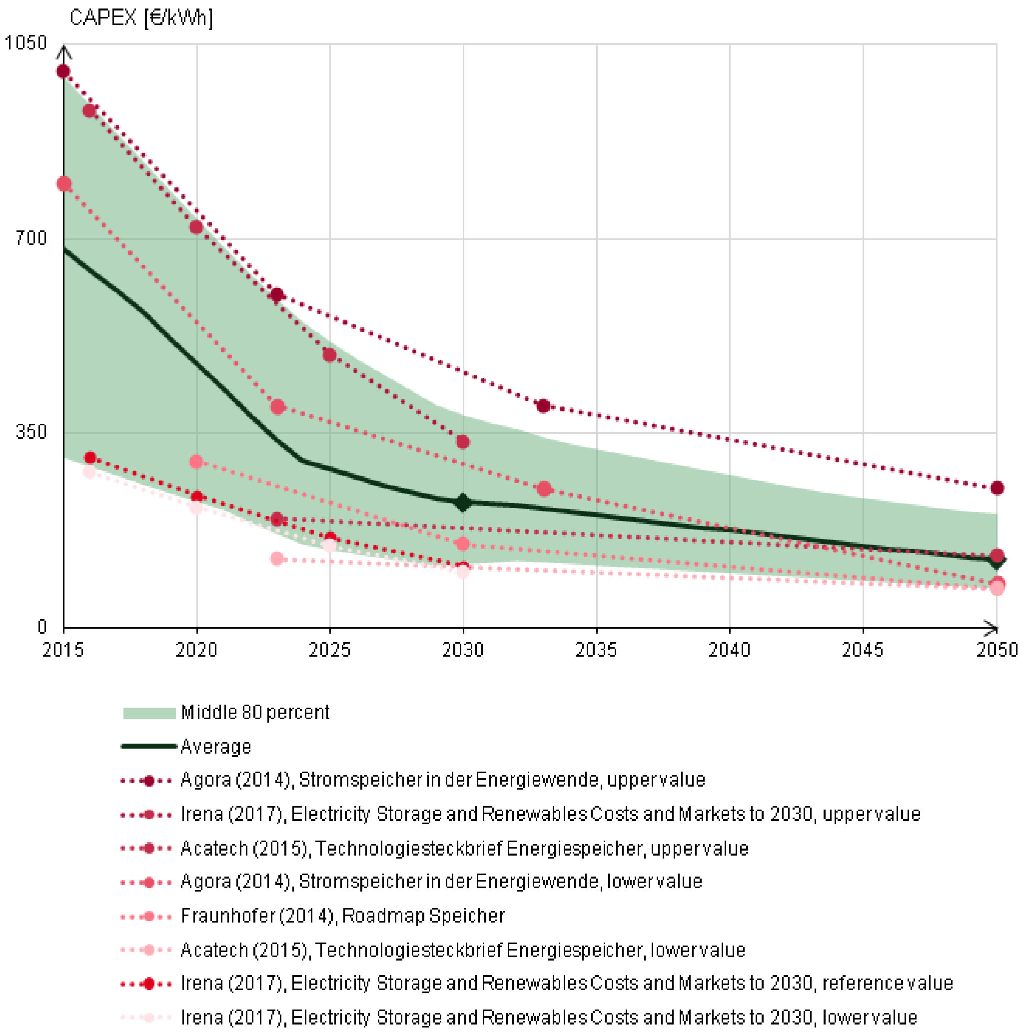

Figure 5.3: Projections of energy costs, Redox flow battery (utility scale), Source: OSMOSE 2019.

5.5.2. Mechanical Storage

Mechanical energy storage systems are a way of storing electrical energy by changing the potential energy of a fluid, such as air or water, through the use of compressions and pumping. The most important types of mechanical storage systems are compressed air energy storage (CAES), pumped storage, and flywheel storage systems (FSS).

CAES systems work by compressing air and storing it in underground reservoirs. The stored air is then released through a turbine to produce electricity. The efficiency ranges from 40-60%, with adiabatic systems having the potential to reach 70%. One main disadvantages is the high self-discharge rate of around 25% per month, which makes it unsuitable as a long-term storage. Another limitation is the dependence on appropriate geological conditions. CAES is a mature technology and the costs are expected to decrease slightly until 2050 (OSMOSE 2019).

Pumped storage systems are the most widely used storage systems and account for almost the entire storage capacity (approx. 97%) installed in the power system today (cf. Sect. 3.4). They consist of two storage basins at different levels and work by pumping water from one basin to another via a turbine. Pumped storage systems have round-trip efficiencies ranging from 70 % until 85% (Stadler et al. 2017). However, they are also limited by the geographical conditions and can have a negative environmental impact. The majority of Europe's technical potential for pumped storage has already been exploited, with limited unused potential mainly in Scandinavia, the Alps, and the Pyrenees (eSTORAGE 2015), as discussed in Sect. 4.6. Depending on the size of the basin and the installed power of the turbine, pumped hydro storages can serve as long-term and short-term storage. However, in most cases they are typically utilized as mid-term storage, which help to offset imbalances that occur over the course of several days or weeks.

FSS systems store kinetic energy instead of potential energy, and consist of a rotating mass, a bearing, and a motor/generator. FSS systems reach high round-trip efficiencies above 85% and can switch between charging and discharging modes with high pace and low material wear. However, the high self-discharge rate of at least 20% per hour and the unsuitable nature for providing mid-term or long-term flexibility make FSS better suited for stabilizing grid frequencies in the short-term (OSMOSE 2019).

Overall, mechanical storage systems are mature technologies but have limitations, such as high self-discharge rates, but can be efficient and useful for specific purposes. They also depend on specific geographical conditions, which limits their potential.

5.5.3. Chemical Storage

Chemical storage systems, such as Power-to-Hydrogen or Power-to-Gas (PtG), convert electricity into chemicals like hydrogen and methane, which can be converted back into electricity at a later time. For example, hydrogen can be re-electrified by using a fuel cell or hydrogen turbine. Methanation combines hydrogen and carbon dioxide to create methane. The cost of electrolysis as well as methanation has decreased in recent years and is projected to continue to decrease (depicted in Figure 5.4). While electrolysis costs are expected to decrease until 2050, methanation costs are expected to decrease until 2030 and then stay constant. However, technical and economic barriers must be overcome before PtG can be commercially successful (Götz et al. 2016). In contrast to electrochemical storage, energy costs of chemical storage are small compared to power related costs. Compared to other storage technologies, the current roundtrip efficiency of chemical storage is comparably small and ranges from 30 % to 40 %. Although further technological advancements can be expected, the roundtrip efficiency cannot be increased greatly above 50 % due to physical limits (OSMOSE 2019). Nevertheless, the technology can be beneficial, because losses can become negligible if processes are powered by excess energy curtailed otherwise. However, as discussed in the previous section, if fluctuating generation from wind and photovoltaic constitutes a great share of electricity generation, the amount of excess energy can be substantial and greatly reduce the costs of chemical storage.

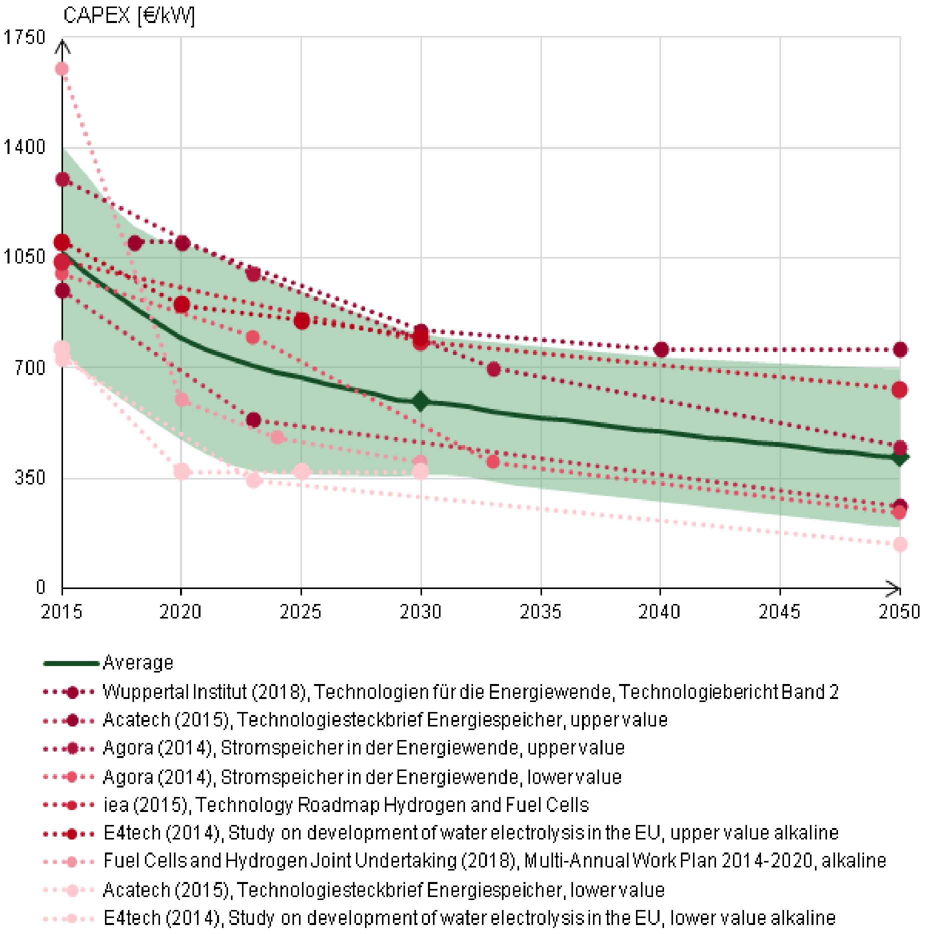

Figure 5.4: Projection of power costs, electrolysis (OSMOSE 2019)

5.6. Conclusions and Key Messages

The massive production of power with solar and wind power, the fluctuations in the supply and demand can cause instability in the grids and therefore requires more flexibility in the energy system as such. A common methodology is to use pump-storage solutions (cf. Chapt. 3), but further capacities are limited in terms of this technology. However, a variety of other technologies can be applied, for example:

1. For short term fluctuations, energy storage, e.g. in batteries (mobile and immobile) is a suitable way to tackle the grid stability issues with renewable energy.
2. To equal out seasonal fluctuations of supply, these short-term storage options are not viable due to their technological characteristics. Instead, chemical storage systems based on creating hydrogen or synthetic methane will become necessary for this purpose when the share of renewable approaches 100%.
3. Further the built-up of more smart grids combining, e.g. huge number of reactive power compensation plants and building HVDC transmission lines from the generation centers to the load centers with a dynamic load flow management system with fast-response load flow controllers is another beneficial option.

Although solutions ensuring more grid stability is an issue of ongoing developments, the necessary technology is to a large extent available today.

6. Further Aspects

6.1. Conflicting Interests

Tröndle et al. (2019) have presented a study on European electricity self-sufficiency, which takes into account the continental, national, regional and municipal levels (i.e. GADM, NUTS, LAU resolution). The focus was on the necessary area shares for onshore and offshore wind power, as well as photovoltaics. Different types of potentials were assessed, for example theoretical, geographical, technical and economic, whereby the authors see the technical component as central as it defines the amount of renewable energy that can be used. Tröndle et al. (2019) underlines that such studies for Europe have not yet been carried out in an integrated manner and are characterized by the use of, different assumptions, e.g. whether all roof areas can be used for rooftop PV or whether protected areas can also be used for open field PV (see for, example, cf. e.g. Buffat et al. 2018, EEA 2009, Hoogwijk et al. 2004). They therefore introduce a so-called sociotechnical potential (cf. Table 6.1), which excludes the use of PV on agricultural land or in nature conservation areas. In addition, they only use roof areas with S-E-W orientation and flat roofs. Thus, according to their analysis, ground-mounted photovoltaics are more restricted, for example, in the criteria of land cover and use as well as slope than wind power.

Table 6.1: Measured potential technical capacity (TC) for open field, rooftop, onshore, and offshore wind turbines on the national level and the so-called sociotechnical potential (ST) considering restrictions of land and water bodies (cf. above), based on Tröndle et al. (2019).

Country	Potential Capacity								Demand (TWh/yr) year 2017	Surplus (TWh/yr)
	Rooftop PV (TWh/yr)		Open field PV (TWh/yr)		Onshore wind (TWh/yr)		Offshore wind (TWh/yr)			
	TC	ST	TC	ST	TC	ST	TC	ST	(1)	(2)
Albania	17	17	417	4	110	13	50	5	7	32
Austria	87	87	1.027	9	307	34	0	0	64	66
Bosnia & Herzg.	43	43	787	4	327	41	0	0	13	75
Belgium	90	90	466	6	101	10	172	12	87	31
Bulgaria	92	92	4,803	48	531	71	195	13	39	185
Croatia	74	74	1,722	29	317	30	573	43	18	158
Cyprus	30	30	271	9	24	3	39	4	5	42
Czech Republic	100	100	2,634	20	493	72	0	0	66	126
Denmark	61	61	1,301	16	158	27	4,921	405	33	477
Estonia	13	13	979	10	582	62	1,088	76	8	153
Finland	43	43	4,350	293	4,618	402	2,189	180	83	835
France	820	820	19,298	280	1,721	341	3,609	128	477	1,092
Germany	739	739	9,608	104	1,467	152	3,282	188	493	690
Greece	101	101	3,235	46	709	68	905	54	52	217
Hungary	106	106	5,989	22	238	102	0	0	43	187
Ireland	31	31	2,358	198	451	31	1,193	89	28	321
Italy	496	496	6,623	141	1,008	141	1,169	90	291	577
Lithuania	31	31	1,984	8	375	61	179	11	12	99
Luxembourg	5	5	64	4	18	1	0	0	4	6
Latvia	16	16	1,521	7	635	78	761	55	7	149
Montenegro	8	8	152	2	75	9	8	1	3	17

North Macedonia	13	13	635	13	101	14	0	0	7	33
Netherlands	147	147	640	23	73	13	3,961	297	114	366
Norway	22	22	7,071	530	2,717	236	2,351	218	133	873
Poland	251	251	11,143	39	1,773	213	804	45	168	380
Portugal	156	156	3,544	129	449	60	302	18	50	313
Romania	202	202	11,249	46	1,046	237	396	17	60	442
Serbia	91	91	2,803	17	305	72	0	0	40	140
Slovakia	57	57	1,467	10	335	40	0	0	30	77
Slovenia	24	24	138	2	104	4	5	0	13	17
Spain	331	331	28,340	650	2,876	453	968	54	253	1,235
Sweden	64	64	6,557	433	5,898	511	3,253	219	138	1,089
Switzerland	67	67	162	7	52	5	0	0	60	19
United Kingdom	339	339	6.582	252	2,081	189	9,548	440	307	914
Total	***4,765***	**4,767**	***149,920***	**3,411**	***32,072***	**3,796**	***41,919***	**2,662**	**3,204**	**11,432**

Table 6.1 shows what this implies in terms of potentials and current demand. It is obvious that Europe has huge exploitable RES capacities. Taking into account the technical potential only, more than 200,000 TWh/yr. However, due to restrictions (so-called sociotechnical potential), only a small amount of land can be utilized, i.e. less than 10%. This holds in particular for open field PV for which only 2.3% of land area can be exploited (Tröndle et al. 2019), whilst the potential of rooftop can be exploited by approx. 100%. In so far, it is astonishing that in these regards many cities have planning deficits. Figure 6.1 shows that a broad variety exists in terms of utilisation of PV rooftops, exemplary for German cities.

Figure 6.1: Utilisation of potentials for rooftop PV on new buildings in different German cities. While in Essen, approx. 63% of newly built roof areas are covered by rooftop PVs this holds only for 10% in Hamburg. Thus, cities do not exploit their full potential. Note, these numbers are also biased by the underlying construction activities in the respective cities, although the trend may persist (Source: LichtBlick Solarcheck 2021[32]).

potentials. However, even if one takes into account all limitations, each European country can fulfil its own demand by national PV and wind power supply. The European-wide surplus would amount to more than 11,000 TWh (the total supply would amount to more than 14,000 TWh).

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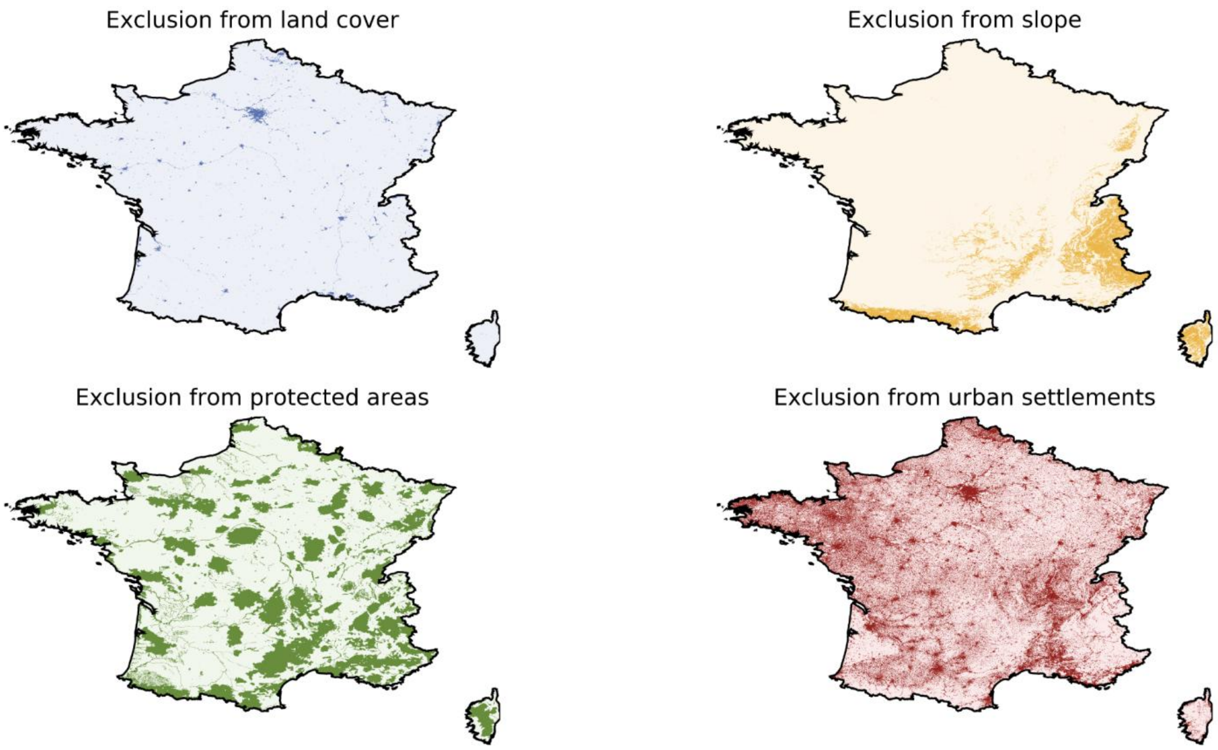
[32] https://www.lichtblick.de/solarcheck21/

These findings were complemented by other studies. For example, Victoria et al. (2021) started from the electricity consumption worldwide (27,000 TWh) and related this to an assumption on the average efficiency of 17% for PV cells and estimated that only 0.3 % of land cover is needed for sustaining the actual global electricity demand. Joshi et al. (2021) provided an additional study, estimating rooftop PV potentials under consideration of a seasonality index (cf. Sect. 3.1ff, for comparison) for Europe in particular.

Fig. 6.2 shows how different the situation can be across countries regarding RES-based power production. While in the upper left figure for each country water surfaces and other non-accessible areas are considered, it is obvious that in a densely populated country like Germany settlements and natural reserves create the largest limits for RES production potentials. In any case, according to current estimates, land use conflicts do not play a role with regard to self-sufficient RES production. This is also likely to be the case in the future.



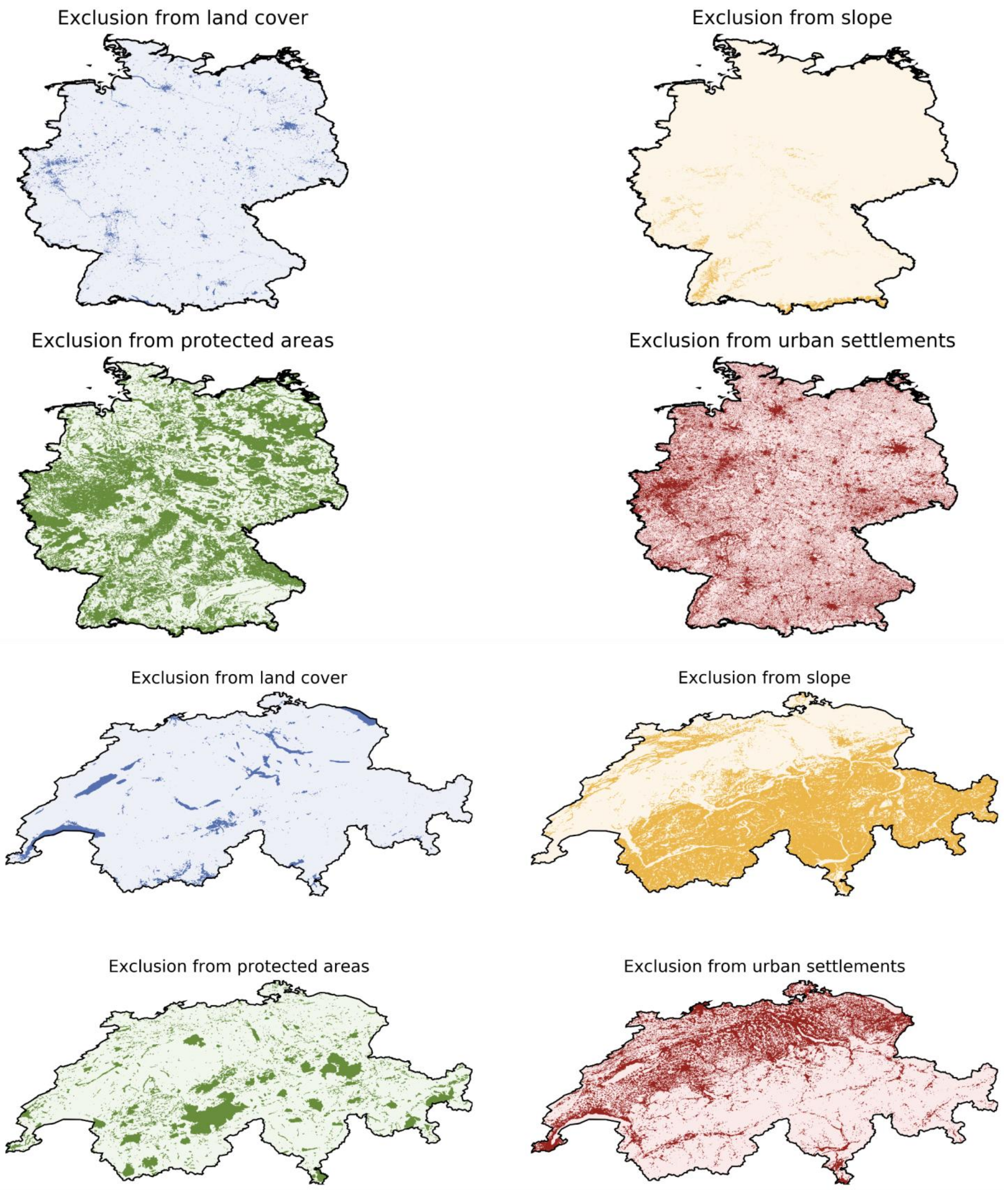


Figure 6.2: Land use limits for France, Germany and Switzerland for RES based power production (refer to Tab. 1.1). After Tröndle et al. 2019. Light colored areas are available for RES production, while dark-colored areas are not.

In terms of wind power, the potential for an increase in installed wind power capacity is still quite high. However, there are several opponents against a further increase of wind power. One of the prominent examples is the phenomenon known as “shadow flicker,” in which active turbine blades cast a moving shadow on nearby homes and yards. Further, threats to wildlife, its low-level (infra-sound) noise, and their aesthetics are further arguments. They further shrink the potential locations suitable for wind turbines onshore and offshore. However, these issues are not so much caused by limited overall space. Enevoldson et al. (2019) estimated that the environmental footprint of wind power is lower than previously envisioned. Thus, development targets can be still achieved, but taking into account better communication and the involvement of various stakeholders (Månsson 2015, Koelmann et al. 2022).

RE systems depend on exploiting flows rather than extracting stocks (as it holds for fossils). These flows are geographically more evenly distributed for RES, while the energy density is lower. According to the above analyses, it seems rather unlikely that this would create conflicts about resources. In the analyses of the PV sector in Europe, fertile land for agro-production was excluded. Similar holds for protected areas. However, whenever the demand for RE PV or wind power will increase, one can consider a relaxing of existing restrictions. The resource biomass is the focus of the European bioeconomy program and is used for electricity production, for bio-based fossil fuel production and should additionally supply construction material. Yet, numerous conflicts restricting its use at larger scales are also apparent. For example, concerns have been raised in terms of increasing the pressure on natural ecosystems and limiting water resources or food security (e.g. Babin et al. 2021, Behringer et al. 2021). Consequently, Searchinger et al. (2018) stated that biomass for power production could harm should not be a first-order solution for power production.

Apart from the above described conflicting interests at local or regional levels, one also has to take into account so-called tele-connections. Renewable energy may be natural, but the components used to harness it is not. Energy independence is only as resilient as the sourcing of components and raw materials necessary for the likes of solar panels, wind turbines and batteries, such as cobalt, nickel, rare earth elements, lithium, and necessary water resources (cf. Sect. 6.4). Consequently, it is desirable that PV, wind power engines and other necessary components undergo also life cycle analyses in order to ensure sustainability not only in Europe, but also in the countries from where materials will come from.

In summary, green energy projects can cause or exacerbate conflicts and tensions, nowhere more so than in the world's most fragile areas. If investments are misdirected, there is a significant risk of the world's green transition coming at the expense of higher levels of conflict and suffering.

6.2. Centralized and Decentralized Solutions

Due to the shift towards renewable energy and a growing desire for autarchy, more decentralized models for managing energy systems and networks, in particular in the electricity sector, are one prerequisite to achieve independence from fossil fuels. In the previous decades, centralized power grids have been the norm in Europe. Irrespective of the energy source, centralized power grids rely on large-scale power plants that enable economies of scale and facilitate energy distribution. However, this proven model is now facing new decentralized competition, mainly driven by two technological changes: the widespread development of renewable energy and the emergence of smart grids.

In the context of the European Green Deal and the move towards climate neutrality, efforts are intensifying to deploy renewable energies at all levels, from highly centralized generation, such as large-scale offshore wind, to decentralized generation, e.g. local wind parks and solar rooftop installations. The EU has adopted a strategy to spur citizen engagement and give local communities the option to self-produce and, to a certain extent, self-consume. The current centralized system is not without its shortcomings, which can be summarized as environmental, economic, technical, and social impacts on grid operators, power suppliers and consumers.

A decentralized approach refers to the use of relatively smaller power generation facilities that are located closer to consumers. This approach aims to bridge the physical gap between producers of electricity and its consumers, allowing for more efficient use of renewable energy. Instead of being dependent on a single centralized power source, a decentralized system allows for multiple sources of energy to be utilized. This not only helps to prevent blackouts or power outages in the event of a failure at a single power plant, but it also promotes a sense of community among energy providers and consumers since they have the choice of a diversity of sources. This improves reliability, and at the same time reduces the dependency on energy imports.

6.3. Enhancing Renewables and Energy Independence through Digitalization

Arguably the greatest single enabler of energy transformation and in general of sustainable development to 2030 and beyond will be the digital revolution, constituted by ongoing advances in artificial intelligence (AI), connectivity, digitization of information, additive manufacturing, virtual reality, machine learning, blockchain, robotics, quantum computing and synthetic biology (TWI2050 2018). As in the industrial revolution, where explosive development was initiated through the convergence of steel, steam and railways, coal, and textile and other new manufacturing processes, the convergence of these new digital technologies could be even more explosive with great winners and losers.

Technological change plays a key role in long-term social, and in particular energy transformations. With the advent of ‘knowledge societies’, many current technological transformations favor renewable, non-material and shared benefits that support human wellbeing (TWI2050, 2020).

This is particularly important for transforming European energy systems from the current reliance predominantly on fossil energy sources to a renewable future without leaving anyone behind (European Green Deal). The Herculean challenge is the intermittent nature of solar and wind to supply most energy needs and lead to multiple benefits for people and the planet. The transformation toward this goal would require fundamentally new energy transport infrastructures (electricity and hydrogen), storage, and end use.

Digital technologies provide new possibilities for coordinating intermittent electricity generation from wind and solar with energy needs by the consumers and storage. Many consumers themselves would be producers, what some call prosumers, producing electricity when wind and sun are available, storing electricity in their batteries or electric vehicles. Smart meters and smart end-use devices would help adjust the load to the availability of energy. This would all lead to enhancing the efficiency of the energy system. Sufficiency may become another development enhanced through digitalization, namely not to over-use and waste energy. Thus, efficiency and sufficiency may become key characteristics of the renewable energy future in Europe (cf. also Chapt. 2).

The envisaged deep transformation towards full European energy autarchy, would need to be accompanied by further new patterns of energy end use and services. This could be possible as the digital revolution is already reshaping work, leisure, behavior, education, and governance. Digital technologies are disrupting production processes in nearly every sector of the economy, from agriculture (precision agriculture), transport (self-driving cars), mining (autonomous vehicles), manufacturing (robotics. 3D printing), retail (e-commerce), finance (e-payments, AI trading strategies), media (social networks), health (AI diagnostics, telemedicine, drug discovery), education (online learning), and public administration (e-governance, e-voting). In general, these contributions can raise labor, energy, resource, and carbon productivity, lower production costs, expand access to services, and dematerialize production.

Digital systems would be the key to disrupting the current energy systems toward the import independence and renewable energy. Increasing shares of electricity and perhaps larger-scale introduction of hydrogen are particularly suitable for digitalization both in terms of technological solutions and institutional and market innovations like the shared economy, peer-to-peer services and integrated services so that prosumers would trade energy and increasingly more energy services.

Yet there are also clear dangers and downsides to the digital revolution, including the loss of jobs, rising inequality, and the further shift of income from labor to capital. With automation and advances in AI and robotics, many more workers, even those highly skilled, may find their jobs and earnings under threat. While new jobs might replace old ones, these new jobs may come with lower real earnings and working conditions (TWI2050, 2020).

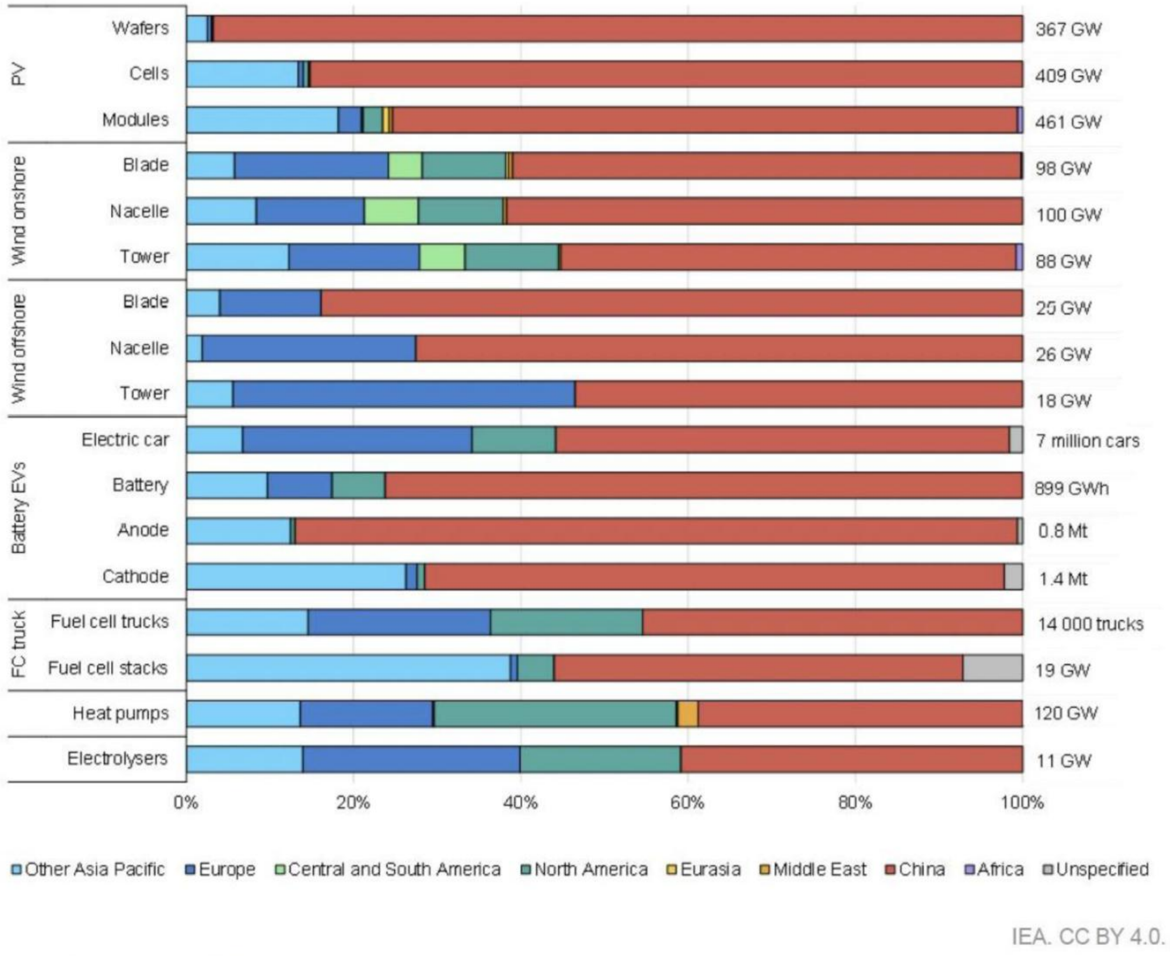
There are several other perceived threats from the digital revolution. Digital identities can be stolen, or artificial identities can be created. Governments and private businesses can invade privacy and monitor individuals against their will or without their knowledge. A few digital portals may use their advantages in amassing big data to gain a dominant monopoly position in their respective markets (e-commerce, digital advertising, social media, cloud services, *etc*.). Cyberattacks or cyberwarfare can interrupt or degrade private and public service delivery. Social media can be manipulated, undermining democratic processes. The most fundamental question is whether the digital revolution as a self-evolving evolutionary process that has generated huge global monopolies is even amenable to ‘social steering’.

The digital revolution will have even deeper impacts on our societies, creating the next generation of sustainability challenges. General purpose AI and other digital technologies will be used in more and more decision-making processes embedded in devices (like self-driving cars), in our economies (in banks, trading firms, stock markets) and in our societies (in courts, parliaments, health care organizations, and security organizations such as police and army), complementing, substituting, and challenging human-driven decision-making processes. Humanity is moving toward new civilizational thresholds. Super-intelligent machines might even develop a life of their own, with the capacity to harm human agents. The renewable and the digital transformation calls for a comprehensive set of regulatory and normative frameworks, physical infrastructure, and digital systems, to capture the benefits of the digital revolution and carbon-free energy while avoiding the many potential downsides – it calls for ‘social steering’ of the digital revolution, so it benefits all and helps catalyze the deep transformation toward renewable energy systems across Europe.

6.4. Europe's Sovereignty in the Field of Sustainable Electricity Production

Ensuring that Europe has more than sufficient RE potential (see Chapters 3, 4) is an important prerequisite, but it is not sufficient on its own. In order to achieve a self-sufficient European energy system based on renewable energies, the corresponding renewable energy technologies (RET) are also needed. Important core components of the future energy system that will have to be procured in the coming years for an ultimate goal of 100% renewables are dependent on imports, especially from Asia. This is particularly evident in photovoltaics (PV), electricity storage (batteries), or other key technologies.

As Fig. 6.3 shows, the dependence on China is overwhelming and, given the need to increase installed capacity of RE by up to 20% per year (cf. Sect. 8, 4.4), it is likely that world market prices for the purchase of technologies would rise significantly in such a case. Nevertheless, the IEA also notes that China, for example, has contributed significantly to lowering the costs of solar technologies for the benefit of the entire world (IEA 2020). However, it is also a fact that dependence on China also has important energy and security policy implications from a European perspective. For example, producers from Asia accounted for around 94% of total c-Si PV (solar cell) production in 2021. China is the biggest player with a share of 75%, while Europe with 1% and the USA and Canada with a total of 3% are negligible (source Fraunhofer/ISE, 2021). The same applies to the expansion of global cumulative PV and onshore wind capacities, of which about one third was located in China in 2021 (IEA 2020). There are therefore considerable dependencies on the Asian market, especially on the Chinese market, which cannot be changed in the short term and which were self-induced by past policies. The thesis that change can be generated through trade has not been fulfilled. Moreover, there is only limited evidence that states such as Russia and China will take energy transformation as seriously in the future as they do in Europe and the USA, for example.



Notes: FC = fuel cell. Heat pumps capacity refers to thermal output.
Sources: IEA analysis based on InfoLink (2022); BNEF (2022); BNEF (2021b); Benchmark Mineral Intelligence (2022); GRV (2022); UN (2022a); Wood Mackenzie (2022).

Figure 6.3: Regional manufacturing capacities for energy technology and components in 2021 (Data Source: IEA). The market dependency of china with regard to key technologies is significant.

Europe has not only benefited from the price advantages of cheap Russian gas, but also from those made possible by cheap solar cells from China. But in the course of the dependencies discussed above, the assessment is now changing. While Germany was still one of the world market leaders in the solar sector at the beginning of the 2010s, politics cut off subsidies. China took over technologies and production capacities, and more than 100,000 jobs were lost in Germany alone.

The situation is somewhat better in the wind energy sector. In 2021, approx. 53.5% of all wind turbines installed that year (approx. 30,000 turbines) were built by Chinese companies. Europe follows with approx. 36.1%, with 17.7% accounted for by a single European supplier, namely VESTAS, DK. US suppliers, finally, contributed with approx. 8.5 % of all turbine installations to the total installation of 104.7 GW.

In the case of battery systems, the dependency was recognised earlier as it affects the future of the European automotive industry. Corrective action in the form of accelerated research and transfer of technologies to pilot and later series production is already underway. This began with the joint declaration by the EU Commission and member states that battery manufacturing technology is an "important project of common European interest", an IPCEI that justifies special national and EU funding programmes. Similarly, renewable hydrogen, microelectronics and other technologies have been declared IPCEIs, allowing EU member states to grant subsidies for these technologies that go beyond the normal limits of EU competition rules. In the case of PV manufacturing, the European Solar Manufacturing Council (ESMC), in cooperation with the European Solar Initiative partners, officially launched an IPCEI for photovoltaics on 20 May 2022. The aim is to focus on breakthrough technologies and innovations along the solar value chain in the future.

On this basis, not only the turnaround in terms of green energy production must now secured, but also the (re-)development of key industries within Europe, which will not be easy in view of the lack of expert staff shortages and the fierce and low-cost competition from Asia. It is estimated that production capacities for solar cells and their precursors will have to at least double by 2030 in order to achieve the global climate targets. Especially in this context, the discourse should be kept open after the experience of blackmail by gas energy suppliers, such as Russia. This means that there should be trade policy responses. And it is precisely these that are under public discussion in the wake of the US Inflation Reduction Act (IRA). However, it must be remembered that trade dependencies can end up being expensive, either through increased world market prices for the demand for technologies, blackmailing, or through the development of domestic industries. The latter also means a partial de-globalisation. However, the latter is only functional if common guiding values are valid for trading partners, but it is also clear that the climate change problem is closely linked to these trade policy challenges.

In principle, of course, climate change can only be tackled in a meaningful way if we all act towards the same goal. Therefore, it is necessary that in democracies cooperation and worthy competition instead of confrontation should remain a guiding principle. The US Inflation Reduction Act and the European Green Deal must be interpreted in this context. So far, following the passage of the anti-inflation bill, the dominant European reaction has been fear of Europe's deindustrialization and the US taking advantage of its key political partner through the IRA. However, you have to look at the matter from various perspectives.

From a climate policy perspective, the IRA is finally bringing the USA closer to the goals of the Paris Agreement (Jiang et al. 2022), because with around US$ 370 billion for clean energy and possible, but capped tax credits, around US$ 800 billion will be invested in climate protection over the next 10 years. This really means that the US are back on the climate stage after years. The Congressional Research Service estimates that IRA could reduce US greenhouse gas emissions by 32% to 40% by 2030 from 2005 levels (CRS 2022). None of this is a panacea for climate protection, and we will have to wait and see to what extent US climate policy has survived under the following administrations. Undoubtedly the IRA does bring a stimulus to the production of clean energy and green hydrogen though. In addition, electricity from renewable energies will continue to become cheaper and this will then be possibly based on US technologies.

However, this is also the focal point of the discussion, because the IRA grants tax credits to energy producers (BDI 2023b). For example, in the production of clean electricity in the amount of 2.6 cents per kWh or a full investment tax credit of 30%. Likewise, US$3/kg credits will be awarded for clean hydrogen with less than 0.45 kg CO_{2eq} per kg H_2 and up to US$ 6.6 ltr. (gallon) for sustainable aviation fuel. Projects can also receive stacking bonus credits of 10% if domestic production requirements are met, or if the projects are located in energy communities, increasing the investment tax credit to 50%, for example. This combination of credits can will definitely have a significant impact on the economics of the value chain for these green fuels, and this might result in the fact that Europe could become an importer of green hydrogen from the USA. This certainly requires ideas at European level how investments can be made in the European hydrogen industry so that it remains competitive. First and foremost, conditions would have to be mentioned here that would provide for a less bureaucratic and tax-free/tax-reduced market framework for such projects. Independent of this perspective, however, it must be noted that the political approaches in their traditions are completely different in the USA and Europe. While the IRA mobilizes tax incentives, but is largely open about which technologies can be used to achieve the defined goals, Europe takes a more regulatory approach with regard to applicable energy technologies. This creates an apparent conflict, which is not a first in transatlantic relations.

Under this focus, the critique with regard to the future market framework should be subsumed. Europe argues that EU-based manufacturers are disadvantaged because i) they have to compete in a distorted market, and ii) the domestic content requirements are discriminating for EU industries. In these regards, it must be noted that the market is already distorted due to the overdependence on China, as the non-diversified supply chains are already producing major national, economic and even climate policy problems (cf. above). Assuming that energy infrastructure is an important critical infrastructure, one has to conclude that dependence on an autocratic system that rejects our democratic value system is also worrying in any case.

In this respect, the IRA should be understood as a competition among friends for the green transformation (BDI 2023a). After all, there are also extensive subsidies in the EU with a view to a future low-carbon economy. While Europe should adopt a cautious trade policy response to the IRA, one must also clearly see the advantages that have always existed (skilled labor, low energy costs). An over-competition of subsidies must be avoided, through European policy must take complementary measures that make IRA and EU policy a catalyst for future sustainability. In other words, clean and sustainable and diversified production chains among allies instead of one-dimensional dependencies. To achieve this, incentive schemes are inevitably needed, but they should have Europe as a whole in mind and not fragment into national claims. So green industrialization in the EU and the US require a new transatlantic global vision for trade, development and the necessary energy transition.

However, the fact that a world market for goods and technologies that can be organized under common values is not unproblematic to organize is not only a realization from the Ukraine war, but has also manifested itself earlier, for example through the so-called Supply Chain Act. This means nothing other than a new energy policy, which must also be a security policy. Nevertheless, it is now necessary to also create sufficient intra-European production capacities for PV cells and modules for an adequate industrial and technological basis. Although much time has passed and the technological leadership that existed in the first decade of the 21st century was carelessly given away, the price reduction driven by China can also be seen as a repayment to the world for climate protection. This should be used to ensure rapid diffusion, but in the above sense, a graduated European policy is needed (cf. Raimondi 2022). In any case, Europe must implement its future energy policy in a coordinated and cautious manner. Energy conflicts have not only existed since the Ukraine crisis, but since the oil price crisis in the 1970s. If one recapitulates this event, it seems like a kind of anachronism to have become dependent on cheap Russian gas and oil in the 21st century, because even after the events of the 1970s, attempts were made to become more independent through domestic exploration. Today, the situation is different in that, in addition to the energy crisis, there is also a climate and sustainability crisis at the forefront. These and the experience of recent events make a rethink of energy policy inevitable. With all the necessary measures, it must not be forgotten that China, in addition to near-monopolies in wind and solar energy plant technology, is also the world market leader in lithium production (approx. 80%) and also supplies approx. 60% of the world's demand for rare earths - further independence is also necessary here (Castillo & Purdy 2022, Simon 2022). This was also not an accidental development, but a planned one. Already in the 10th Five-Year Plan and again in the 12th Five-Year Plan, China noted that RE is central to the further growth of the republic and therefore decided to invest around €420 billion in key industries from 2010.

This goal is also prominently mentioned in the new 14th Five-Year Plan (2020), as China wants to become the world market and technology leader in more areas. This would change the global economy and Europe must find a response to this and not leave these developments to market forces, but make more strategic decisions. This is particularly true for the energy sector. It is essential to avoid replacing one dependency with another. This is especially true for China, which is also very ambivalent about the Ukraine conflict. Unfortunately, it is not so easy to find a common line even between friendly nations. An example of such an approach, already planned for the longer term, could be Japan, which has made economic security an important focus of its governance. In any case, Japan, the US and the European economic area should not focus so much on the challenges of the IRA, but on its opportunities. First steps to keep the conversation going have already been taken, as the EU and the US have established the EU-US Inflation Reduction Act Task Force and used the framework of the Trade and Technology Council to address such concerns, while the Europeans will eventually present an EU-wide response, the Green Deal Industrial Plan and the Net Zero Industry Act (NZIA) (EC 2023).

The coming months and years will therefore show whether current initiatives such as the EU-supported "EU-Solar Industry Alliance" EU-ISA will succeed in building up a viable production base in the European Union. The only consolation in this unpleasant situation is the fact that imports from the US will be more reliable than imports from Asia, especially China. So, together with the US and the EU, it seems possible to create a sufficient production base to continue the European course towards 100% RE sources in the energy sector by 2035 or 2040.

6.4.1. The risk of European Deindustrialization

Europe is in the midst of a complex energy crisis, which will ultimately result in a structural change that requires a rethinking of energy production and supply. All in all, the current energy problem is not a consequence of the Ukraine war, but the latter was only the trigger that made politicians and economists aware of so far neglected priorities. It is hardly surprising that climatic consequences also plays a role in this context. In France, for example, electricity generation fell to a minimum in 2022, i.e. to the lowest level in 30 years (Reuters 2022). A large part of this was due to maintenance work. To a lesser extent, however, the unprecedented drought last summer also limited cooling water resources. In addition, the production of electricity from hydropower was also limited (Bloomberg 2022).

Thus, the recent energy crisis is a stress test for the European Union, i.e. for the resilience of key industries but also of societies (Raimondi & Bianchi 2022). Indeed, despite warnings, some European economies have become heavily dependent on cheap Russian energy and have profited greatly from it.

In order to find a way out of this crisis, however, a coordinated European approach is required, because otherwise, national reactions will tend to lead to intra-European competition and ultimately would weaken the entire European economy (Tocci 2022). Although the European countries have managed to reduce gas consumption and substitute missing resources with other sources, the energy crisis has not been overcome. The current energy crisis undoubtedly affects the industry in particular, as it is one of the largest energy consumers along with the transport sector. Above all, the German manufacturing sector, which accounts for about one-third of the total value added of the manufacturing sector in Europe, is particularly hard hit by the current energy crisis. The reason is that the cheap natural gas from Russia was planned as a "bridging resource" for transition to a climate-neutral economy.

This makes obvious what has not been so much in the foreground: the energy crisis needs a rethinking of the climate strategy and possibly a much faster shift from fossil and fissil resources to renewables than ever than taken previously into account in political calculations. Conversely, this means that a new industrial vision must be developed rapidly, which 1) must be reconciled with climate goals and 2) must be complemented with an energy autarchy strategy. This would not only achieve that Europe a swift turn to renewable energy but also to energy independence, i.e. Europe's risks to becomes blackmail in the future will be considerably reduced. This need arises simply from the fact that the main gas-consuming industries in Europe generate an economic value of more than 600 billion US dollars per year and employ almost 8 million people (Birol 2022).

A powerful control element in this context is that of the carbon border tax. It allows the European Union to impose a price for pollution on certain imports into the European Union (in compliance with WTO mechanisms). While in Europe carbon-intensive industries are required to comply with strict emission standards, this tax is designed to ensure that these companies are not out-competed in intra-European competition by rivals in countries with weaker environmental regulations (EP 2022[33]). Although internationally denounced in part as environmental protectionism (e.g. by BRICS, LDCs), it is an essential protection of European industries. Thus, importers will have to buy carbon credits equivalent to the carbon price that would have been paid in the EU if the goods had been produced locally. The EU Border Carbon Adjustment Mechanism (CBAM) is set up to align the price of carbon paid for EU products under the EU Emissions Trading Scheme (ETS) and the price of imported goods. This will be achieved by requiring companies importing into the EU to purchase so-called CBAM allowances to make up the difference between the carbon price paid in the country of production and the price of carbon allowances in the EU ETS. This mechanism will be implemented from 1 October 2023 onwards, with a transition period.

This also includes the energy sector, which needs to provide renewable resources for this transformation in the future. Although there is speculation about the risk of possible de-industrialisation in the context of the transformation itself, this is unlikely, because important decisions have already been made. If electricity production were to be switched quickly and efficiently to renewable sources, this would also create new jobs. The Ukraine crisis has therefore not triggered the problem, but merely increased the pressure on European policy bodies to act.

Germany, in particular, has been strongly affected by the current energy crisis due to its great dependence on Russian gas. Although energy prices, and electricity prices in particular, are always subject to certain fluctuations, the price increase for electricity is evident, as the course of electricity prices in European countries for quarters 1-3 of the year 2022 shows (Fig. 6.4). This increase is

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[33] https://www.europarl.europa.eu/news/en/press-room/20221212IPR64509/deal-reached-on-new-carbon-leakage-instrument-to-raise-global-climate-ambition

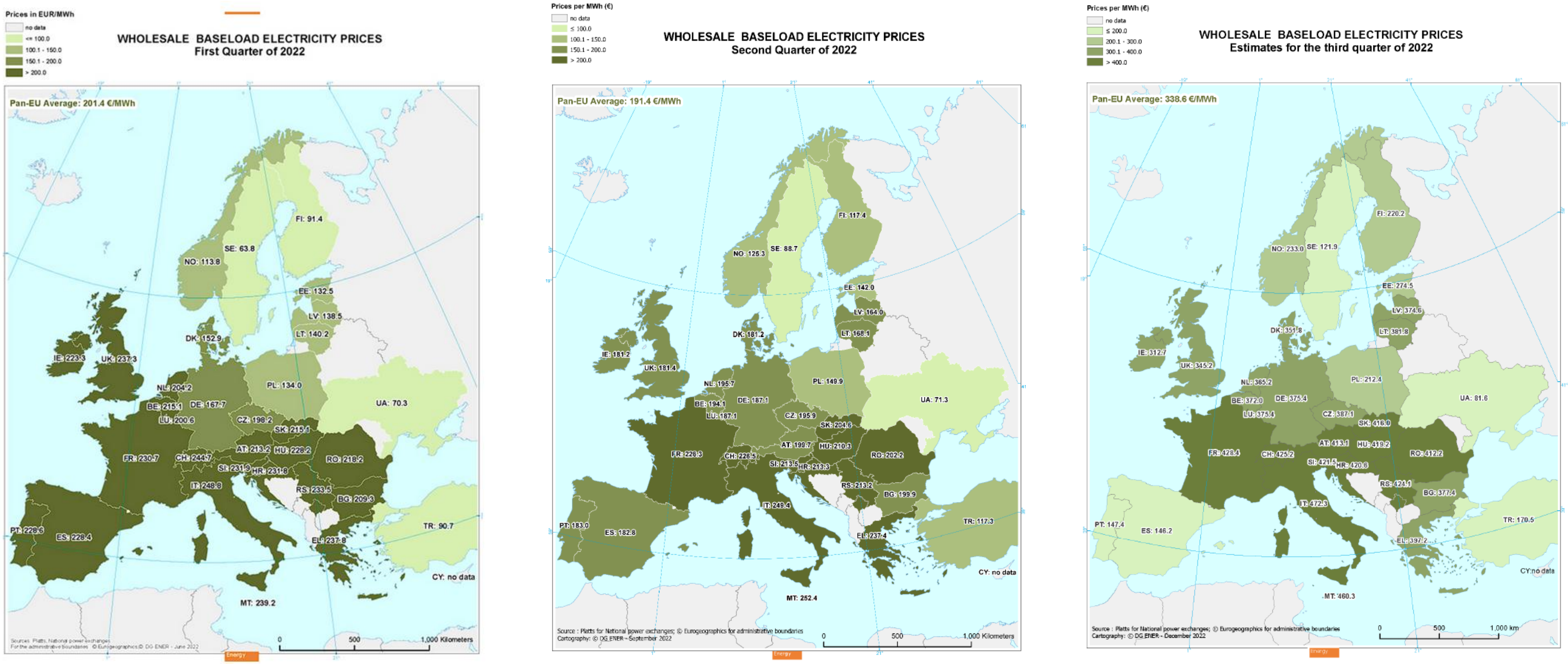

Figure 6.4: Wholesale price development for electricity by country in Europe for Q1-Q3 2022 (EC 2022a). The Ukraine shock is obvious, but price levels development are very different from Q1-Q3 2022. While In Germany the price level increased by 124% it increased in France by 86% and Poland by 59 percent.

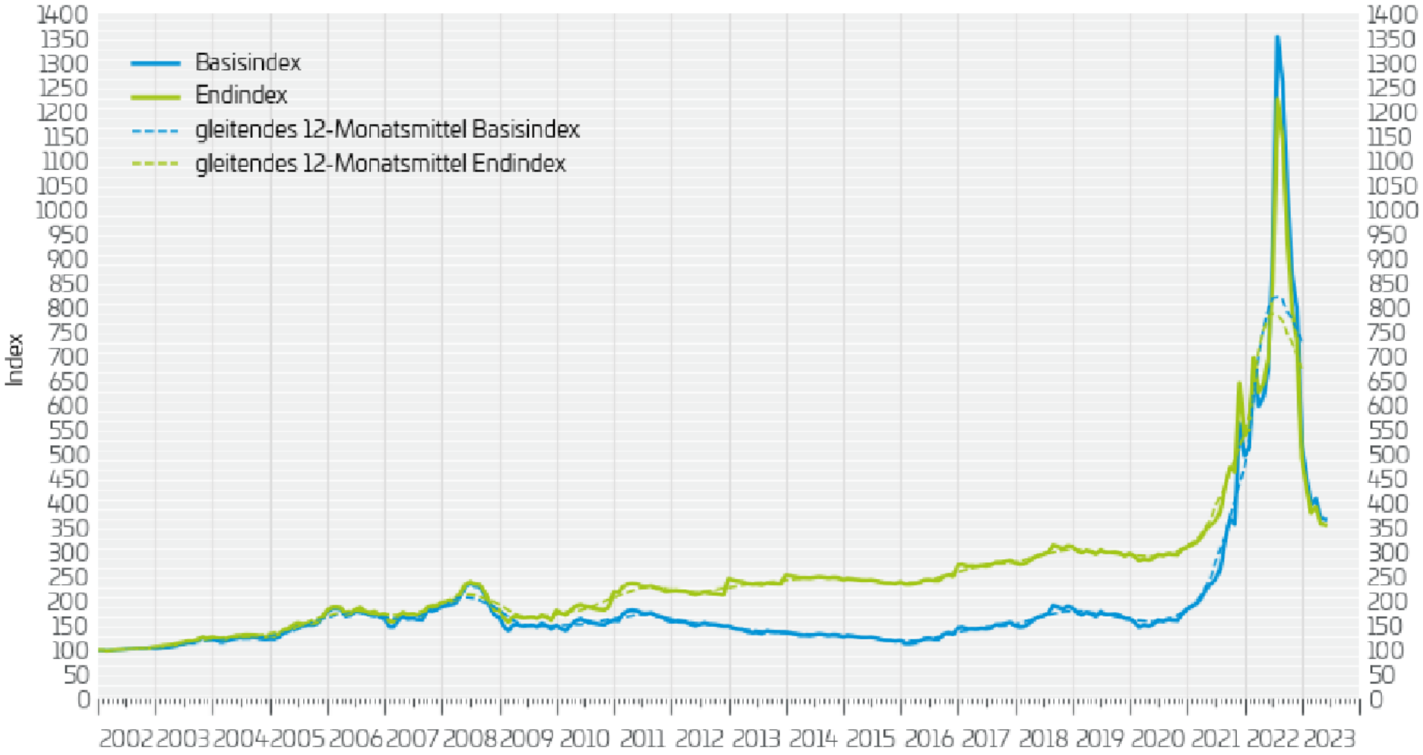

Figure 6.5[34]: The relevant quarterly electricity prices (Q1/2022 to Q2/2023) provided by the Verband für Energie und Kraftwirtschaft (2023) for the calculation of the indices show an increase mainly in December. The background was concerns about possible supply shortages in a cold winter. However, electricity quarterly prices then fell sharply again due to a decline in the corresponding gas and coal prices as well as the currently stable supply situation. In the trading month of December 2022, the wholesale power prices on the EEX, which were decisive for the current VIK indices, fell by an average of €26.57/MWh to €312.70/MWh (base) and by €43.08/MWh to €401.27/MWh (peak) compared to the previous month. For June 2023 the decreasing trend of power price reduction is still valid and fell by 0,82 €/MWh to 124,77 €/MWh (base) and 3,03 €/MWh to 146,69 €/MWh (peak). It is obvious that the power market is step by step developing to a price level which is similar to a situation before Russian invasion in the Ukraine.

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[34] Both VIK indices include quarterly prices of the EEX for the following four quarters and grid charges of grid level 5 (Stromnetz Berlin GmbH, Stromnetz Hamburg GmbH, Westnetz GmbH, Bayernwerk AG, Netze BW GmbH, MITNETZ STROM). All prices and charges are weighted for different consumption profiles with 3,000 to 6,000 annual usage hours.

particularly pronounced for the fourth quarter of 2022, as shown by the electricity price index of the Verband für Energie und Kraftwirtschaft (2022) (Fig. 6.5). However, it is also clear that electricity prices have decreased again considerably by the end of 2022, which can be justified by eliminating reasons for uncertainty. Overall, it can be deduced from the observations made so far that the electricity market will remain volatile and electricity prices high. The reason for this are the dependencies that have already been mentioned several times, and from which the European economies must now gradually free themselves. This process, as challenging as it is at the moment, is already being flanked, because the European member states of the EU have initiated a process of liberalisation and harmonisation of their electricity markets in recent years, which will increasingly lead to an internal energy market whose goals and potential are unique in this way. This process must continue in terms of European integration.

Thus, it is the only chance to shape the price development through an intelligent and future-oriented energy planning in such a way that European industry remains competitive and acceptable energy prices can be made possible again for end consumers. The question is how and whether this can be achieved (cf. also Chapt. 4)?

Clearly, renewable energies not only provide a sustainable and self-sufficient solution, but they are also cost competitive, in connection with flexibility instruments to assure system stability. In order to make energy prices comparable, the weighted average levelised costs of energy (LCOE, e.g. Hansen 2019) are calculated for certain technologies (see Figs. 4.7 and 6.6). These include, among other things, the net present costs of electricity generation for a generator during its lifetime. This means that costs for the construction and operation of a power plant over its lifetime, costs for fuel, utilisation, discounting are divided by the electricity produced.[35]

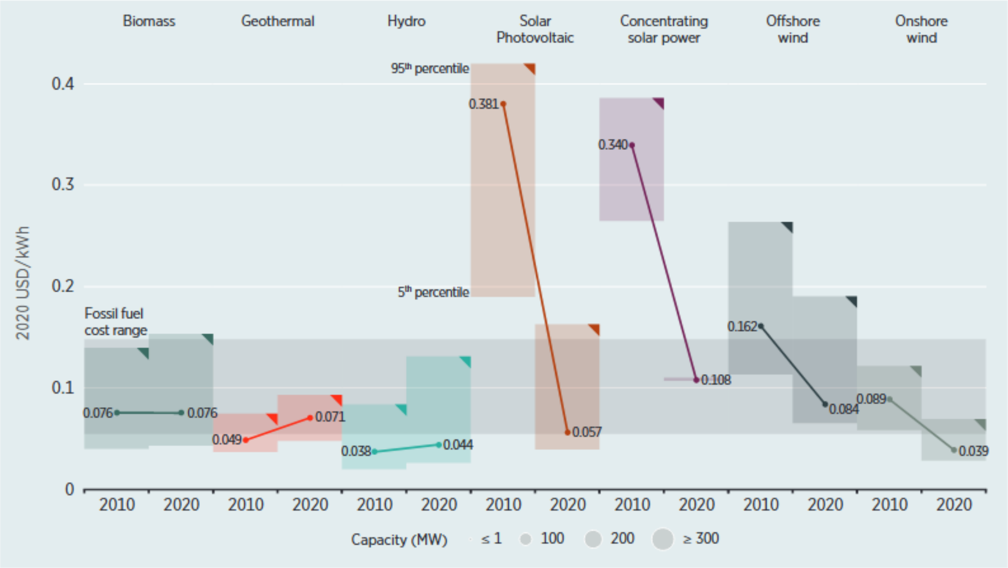

Figure 6.6: Global LCOEs from newly commissioned, utility-scale renewable power generation technologies, 2010-2020 (IRENA 2021).

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[35] In contrast to this method, the Energy System Analysis (ESA) can also be used. It has a more macro perspective, i.e. focuses on an entire energy system rather than a specific technology. Instead of calculating the costs in comparison to the energy produced, the total costs of the entire energy system are determined. In this method, not only the energy costs but also the carbon emissions and fuel consumption as well as other indicators are added. In this section, however, the LCOE method is used to illustrate the cost development for electricity production for reasons of practicability.

Overall, the competitiveness of renewable energies has further improved since 2010, as Figure 6.6 shows. All renewables that are newly connected to the grid have reached the cost of fossil energy in one decade (2010-2020). For example, the marginal cost of fossil fuel power generation in 2022 has increased to such an extent that a new onshore wind power plant that would have been connected to the grid in January 2022 and sold its electricity on the wholesale market could have generated revenues in 2022 alone that are between two times (in Mexico) and thirteen times (in Brazil) the required annual return on investment resulting from the potential avoided marginal cost of fossil fuel power generation for the entire year. The fact that countries have not prioritized the accelerated expansion of renewable electricity generation capacity, but have largely left the response to private individuals and companies, has therefore likely cost national economies billions of US$ over the next few years (IRENA 2022). However, this process that renewables are becoming cheaper also continues year after year and is also visible for the years 2021/2022 (IRENA 2022) and this holds most likely even during a year characterised by shock price signals like 2022 (Fig. 6.7). Only for concentrated solar power, a certain limit seems to have been reached in the meantime.

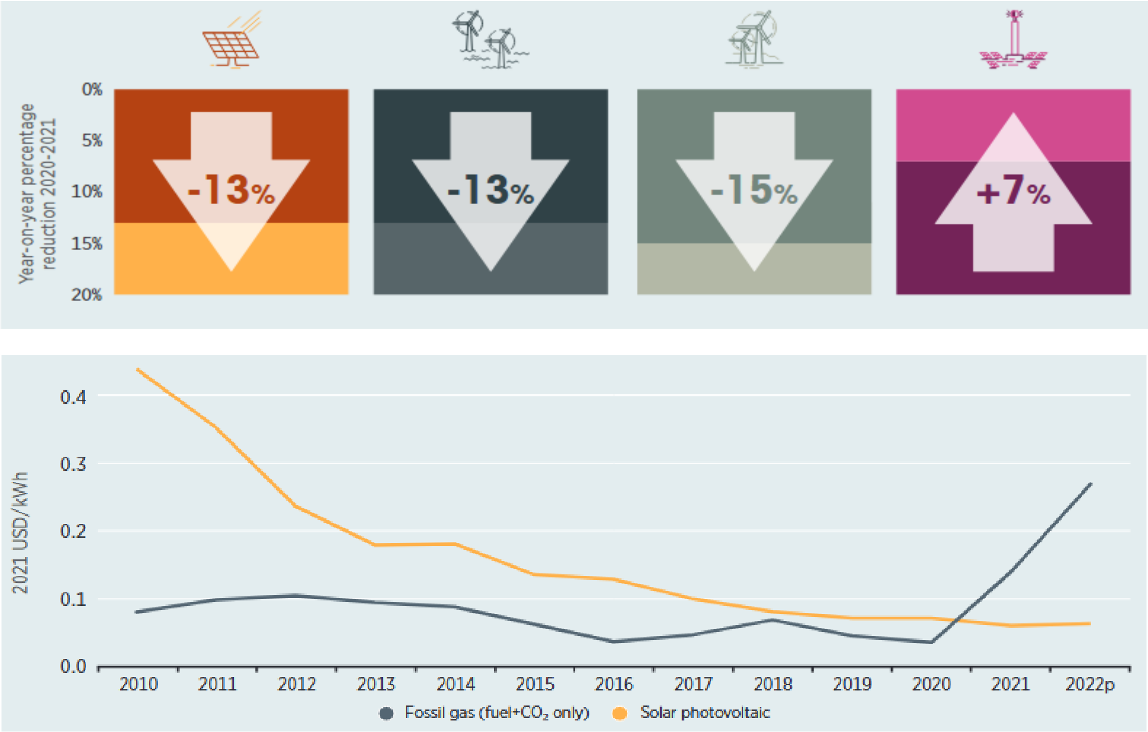


Figure 6.7: top: Change in global weighted levelised cost of electricity by technology, 2020-2021, bottom: The weighted average LCOE of utility scale solar PV compared to fuel and CO_2 cost only for fossil gas in Europe, 2010-2022 (IRENA 2022).

Irena (2022) consequently assumes that the advantage of renewable energies was already unprecedented in 2022. They estimate that the price of gas plus the price of CO_2 will exceed that of electricity from photovoltaics by more than 600%. To put this order of magnitude into context: this is about 4 to 6 times more expensive than the new solar and onshore wind capacity that will be added in Europe in 2021, and exceeds the average retail tariff (before taxes and levies) that households in about half of the EU countries had to pay for transmission, distribution, wholesale, marketing and overheads in 2020 - before the Russia invaded the Ukraine!

Taking these numbers into account, the issue that the necessary energy transformation will create a de-industrialised Europe is not supported by recent development and analyses. However, this does not imply that European economies can wait and see, but this shift needs to come fast and well-planned. Then it would be rather likely that Europe is benefitting from the energy crisis.

6.5. Conclusions and Key Messages

The Russian invasion of Ukraine fundamentally changed the world's energy systems. While on the one hand the traditional suppliers of fossil energies are trying to secure their markets, massive efforts are underway in Europe, North America, etc., which are driving the transformation of the energy systems. On the one hand to ensure climate protection and on the other hand to achieve energy self-sufficiency. In Europe, there is no lack of good intentions and corresponding political documents, but although the efforts are not yet sufficient in some sectors, the European top-down policy in the energy sector still needs to be accelerated.

1. A sustainable transformation of energy systems also means that RES are used where they are available. This requires a quasi decentralization of energy production, but also of the underlying grids and storage systems. In addition, decentralized structures are less susceptible to disruptions if the appropriate digital and IT requirements are in place. In the future, far-reaching digitization will also be mandatory for controlling energy demand. Politicians must create a suitable framework for this, i.e. by ensuring a level playing field through fiscal levers and legislation, considering externalities.
2. The climate crisis and Ukraine shock have made Europe realize that there is a possibility of blackmail with regard to the provision of energy. However, it is becoming apparent that a dangerous dependency on China has established itself in world trade with regard to available technologies. This dependence was even encouraged in part by Europe, which frivolously sold technology to Asia. Here, it is the order of the day in the sustainability sector to build a competitive mechanical engineering infrastructure that reduces this dependency.
3. With regard to overcoming the climate crisis, the USA implemented the Inflation Reduction Act, which from a European perspective was partly regarded as an unfair influence on the market, which could put the EU industry further behind. It should be noted that energy policy in Europe is characterized more by quotas and technological regulations, while in the USA tax incentives are primarily used to achieve corresponding goals, although the way to get there remains largely open. Both mechanisms should be viewed as complementary and healthy competition. As in the past, both approaches have advantages, what matters in the end is the result in the context of energy self-sufficiency and climate protection.
4. The argument that European regulations could lead to increasing deindustrialization of the continent is not shared, because on the one hand the Carbon Border Tax will be implemented from October 2023, which will make non-sustainable products more expensive. On the other hand, a forward-looking and ambitious industrial policy that invests in AI, sustainability, climate protection and technological foundations will create highly qualified jobs in the future. It needs to be emphasized that Russian invasion in Ukraine did not create the underlying problem, but brought it more prominently back onto the agenda. The actual low costs of energy technologies should be seen as an opportunity to implement the transformation quickly, while at the same time to open up new technological paths.

7. Case Study: Renewable Potentials of the Mediterranean and a Focus on Andalusia

Since the client has special relations to Spain and in particular to Andalusia, the situation in Andalusia will be explained again in the following chapter. Already in section 4.5, Spain's development in the energy sector is shown in a Sankey diagram (Fig. 4.14) and it is shown that, due to the considerable production of PV electricity, Spain could also become a net exporter of electricity, hydrogen and synthetic fuels. In this respect, the development potentials in the Andalusia case study region are quite interesting. The exploitation of renewable energy potential in the Mediterranean is important for the region, but for the energy sector as a whole in Europe. Specific steps towards this direction need to be taken in the frame of the European Green Deal, to replace the fossil-fuel energy production by renewable technologies until 2030. The available renewable energy forms in the Mediterranean include onshore and offshore wind, solar energy, tide-current and wave energy, hydroelectric and geothermal energy. The complex territory, the extended coastlines and the numerous islands in this region require a dedicated approach for the development of renewable energy installations both over land and offshore. Meanwhile, the discovery of natural gas reservoirs in the Mediterranean could contribute to energy security in Europe, but are a hindering factor for an in-depth transformation as discussed in this study. This section highlights the potentials of the Mediterranean, and then reports on the dynamics of renewable investments in Andalusia.

7.1. The Mediterranean as a European Hot-Spot for Renewables

The Mediterranean region will play a major role in future energy security, in particular for Europe as a whole. However, this is not only in terms of solar potential, but also in terms of other RES. As Fig. 7.1 shows, there are considerable development opportunities for wind farms not only for Andalusia, but also for other areas in the region.

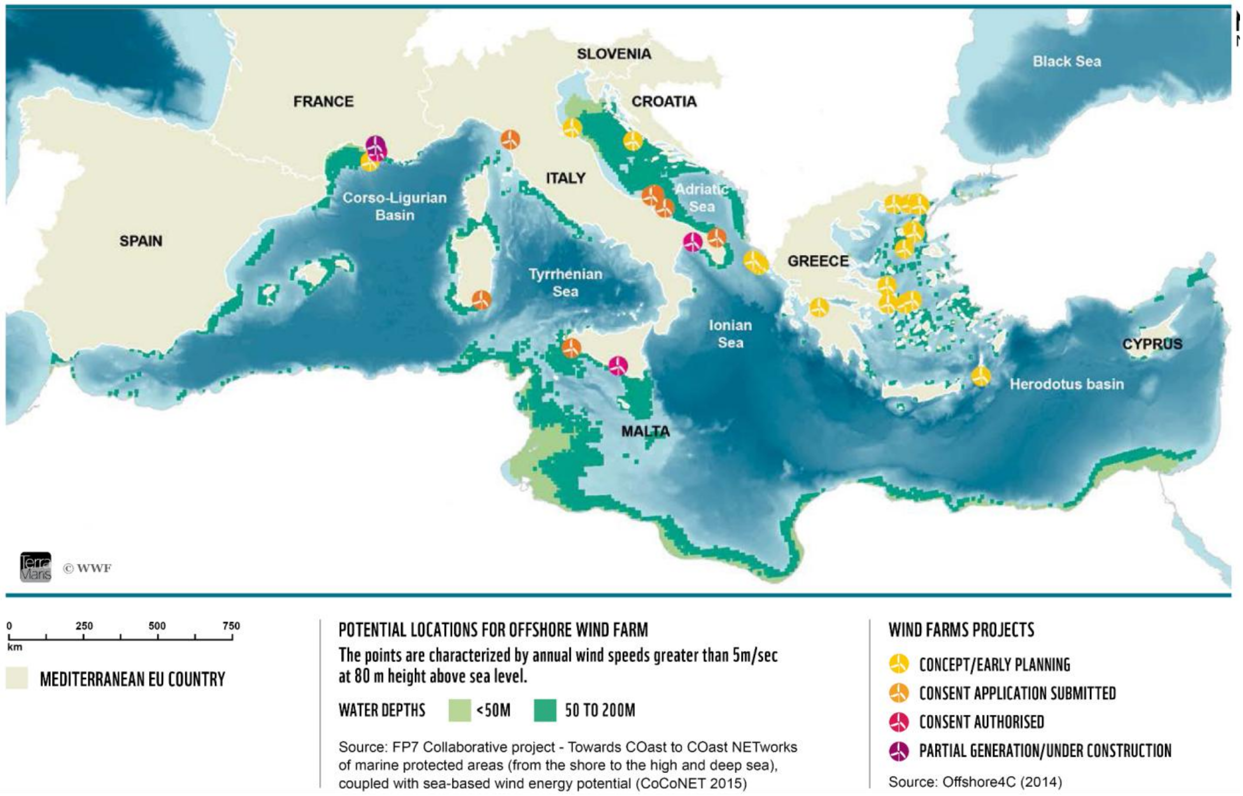
The potentials for the Mediterranean region are outlined in detail below:

Solar potential in the Mediterranean is comparable to that of North Africa and the Middle East. For example, the yearly total solar potential exceeds 1,700 kWh/kWp for Portugal, 2,000 kWh/kWp for Spain, 1,600 kWh/kWp for France, 1,700 kWh/kWp for Italy, 1,800 kWh/kWp for Greece and 1,800 kWh/kWp for Cyprus (cf. Fig. 3.7). Especially on the Mediterranean islands, the solar energy exceeds 5 kWh/m^2/day (EC 2020). An additional consideration for the installation of offshore and island-based power plants needs to take into account the power grid availability and connectivity options.

Wind potential in the Mediterranean is higher during the winter months, due to the passage of the low-pressure systems from the Atlantic at lower latitudes and also due to cyclogenesis in the gulfs of Genoa in Italy and Sirte in Libya. During the summer, wind generation is limited at most regions in the Mediterranean. However, the local Etesian winds at the Aegean Sea reach up to 20 m/s during the summer months and last for several consecutive days, making this area ideal for wind farm installations throughout the year. Other local wind patterns such as the Mistral in southern France can also be exploited for wind energy production, while Andalusia has fewer capacities in comparison. Since the higher wind speeds are found over the sea and since the deep bathymetry of the Mediterranean prohibits fixed-bottom installations, the most promising technology for the exploitation of wind potential is the installation of floating wind farms (Fig. 7.1). According to the Directorate-General for Energy of the EU (EC 2020), the expected annual production from floating wind parks in the

Mediterranean is about 4,600 TWh/a by 2030 and 4,700 TWh/a by 2050. For Europe overall, added 14.7 GW new installations to the grid, of which 80% are onshore. Also in the future it is expected that 70-75 of new installations will be onshore (Windeurope 2021)

Wave energy depends on the amplitude and the period of the sea waves. As a result, the western coasts of Europe that are exposed to the Atlantic fetch present high wave energy fluxes, between 33 - 55 kW/m (CRES, 2002). However, the aggressive weather conditions at such open seas impose certain technological and financial limitations on the installation and maintenance of wave energy turbines in these areas. On the other hand, the most sheltered Mediterranean Sea allows a more sustainable exploitation of wave and tidal potential. The annual wave energy flux in the Mediterranean is about 8 - 13 kW/m (CRES, 2002). The most prominent regions for wave energy production in the Mediterranean are the entire Greek marine territory, the Italy-Tunis Strait and the Italian and France islands and coastlines.



Source: FP7 Collaborative project - Towards COast to COast NETworks of marine protected areas (from the shore to the high and deep sea), coupled with sea-based wind energy potential (CoCoNET 2015)

Source: Offshore4C (2014)

Figure 7.1: Potential locations for offshore wind farms in the Mediterranean (from Piante and Ody, 2015).

Geothermal Energy for heating and for electricity production is also abundant in the Mediterranean, mainly due to the volcanism of the region (Manzella et al., 2019*).* The geothermically heat flow exceeds 200 MW/m^2 in Italy and Greece and 100 MW/m^2 in central France (Majorowicz & Wybraniec, 2011). In general, the inland geothermal potential in the southern parts of Europe is higher compared to the north. Moreover, the observed heat flow at marine areas in the Mediterranean is comparable to that of the north seas. For example, the overall highest observed value of mean heat flow for Europe is 113.2 MW/m^2 and is found in the Tyrrhenian Sea (Cermak et al., 1979)**.**

Hydroelectric power is also abundant in the Mediterranean due to the existence of numerous rivers and lakes. The combination of these water reservoirs with the steep topography provides natural resources of clean energy to produce electricity. The hydroelectric technology is mature and accounts for 33% of the total renewable energy production in Europe[36]. Hybrid hydroelectric and wind / solar power plants (Pump-storage stations) consisting of two reservoirs at different elevations, provide an excellent solution for the storage of renewable energy and for the stabilization of the distribution network.

Summing up, the Mediterranean is a major pillar for renewable energy production in Europe, in the frame of the European Green Deal and the carbon-free era. Solar energy is always abundant in the region, especially during the summer, when the demand for electricity is higher due to tourism activities. Wind potential is also high. In several areas, for example in Greece, significant amounts of wind and solar potential coexist throughout the year. In this frame, already existing technologies such as solar panels, wind farms and hydroelectric plants need to be expanded and modernized, including hybrid installations for the storage of power production. At the same time, as seen in Tab. 7.1 the renewable potential is even higher offshore, especially for wind and wave energy. Thus, it is important that future developments in offshore technologies will improve their readiness level and allow the exploitation of marine renewables. Finally, the often-neglected geothermal systems can provide stable and significant contributions to the energy balance, taking advantage of the volcanism in the Mediterranean.

Table 7.1: Annual technical resource potential for offshore technologies in TWh/yr (from EC 2020).

Country	Bottom-fixed wind potential 2030	bottom-fixed wind potential 2050	Floating wind potential 2030	Floating wind potential 2050	Wave potential 2030 and 2050	Tidal potential 2030 and 2050
Croatia	18	23	313	325	0.0	0
Cyprus	0	0	110	128	0.0	0
France	0	0	271	277	175	0
Greece	0	0	840	858	1,810	0
Italy	24	32	1,610	1,663	624	0
Malta	1	1	431	440	341	0
Portugal	2	3	427	436	888	0
Slovenia	0	0	0	0	0	0
Spain	1	1	581	594	661	22
Total	**46**	**59**	**4,582**	**4,722**	**4,498**	**22**

Nevertheless, thanks to fast learning and sustained growth, solar photovoltaics (PV) is today a highly cost-competitive technology (e.g. Fig. 6.6), ready to contribute substantially to CO_2 emissions mitigation.

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[36] https://energy.ec.europa.eu

7.2. Renewables in Andalusia

7.2.1. State of Play in Andalusia

Andalusia is a representative case study for the Mediterranean and European energy transformation towards renewable energies. On 12 January 2021, the Governing Council of the Regional Government took note of the document entitled Andalusia Energy Guidelines, Horizon 2030, drawn up by the Andalusian Energy Agency. This strategy will guide policy on the promotion of renewable energies, savings, energy efficiency and the development of energy infrastructures in Andalusia over the next 10 years to enable a green revolution that will position Andalusia as a benchmark region in the energy transition, as Spain made it a policy priority (Fig 7.2).

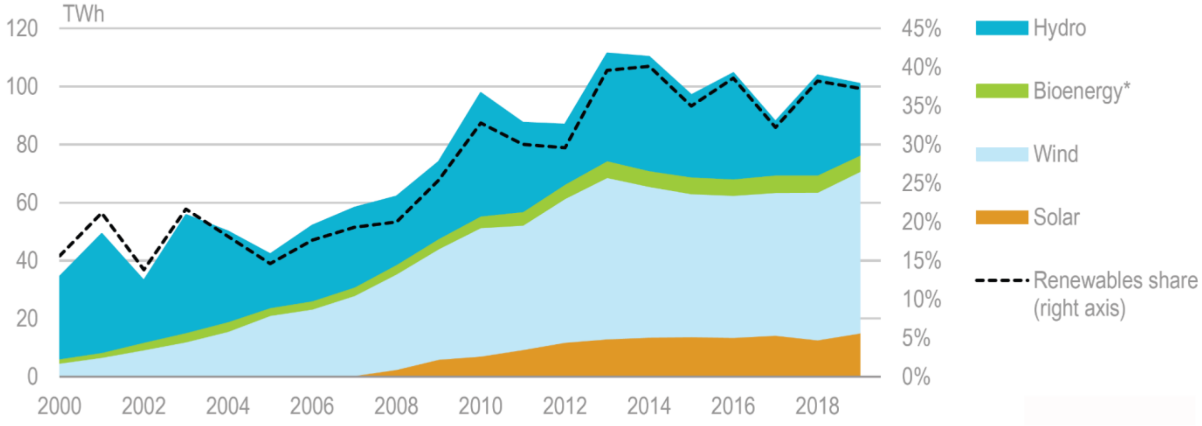
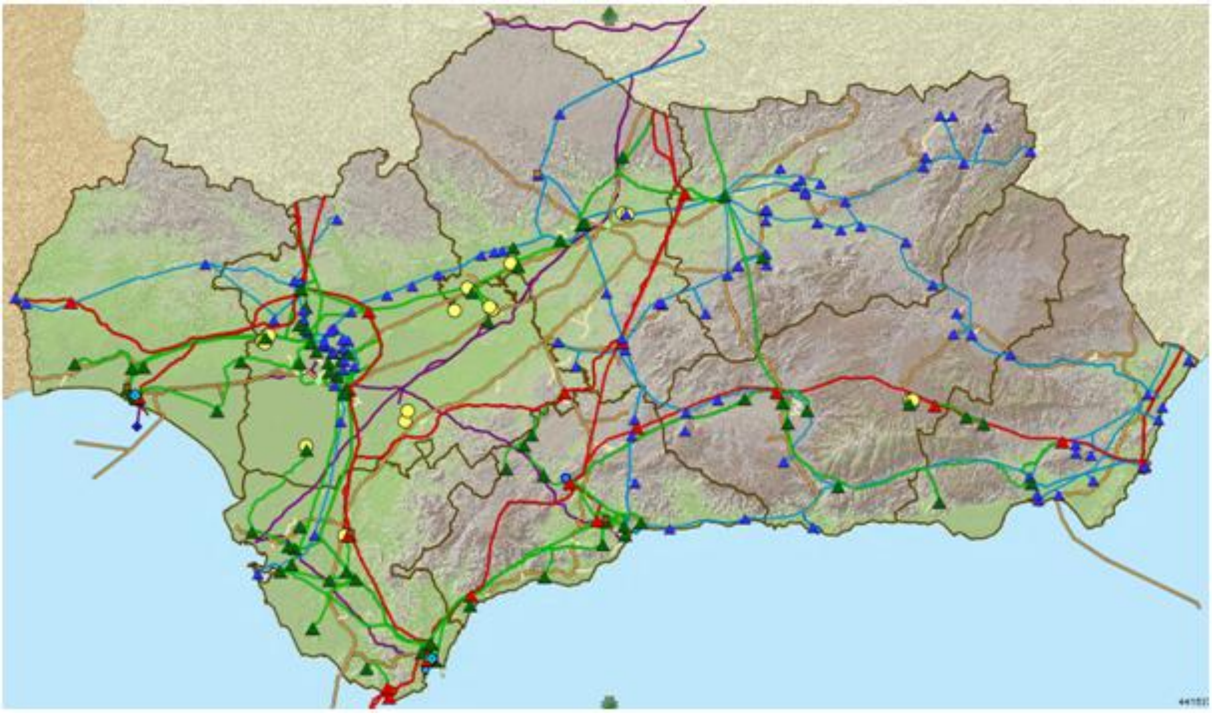


Figure 7.2: Spain as a whole shows a boost in the RE power, which is mainly driven by investments into solar and wind, Source: IEA (2021a).

The main challenge identified is to promote the transition to a carbon-neutral energy model more efficiently by incorporating the premises of the circular economy, which guarantees access to safe and sustainable energy for all, and which impacts on economic growth and job creation by offering opportunities from the business, industrial and employment point of view. The Andalusia Energy Strategy 2030 was approved by the Governing Council, by means of the Agreement of 7 June 2022 (BOJA number 112 of 14 June 2022). Overall, the Andalusian energy infrastructure is highly diversified (Fig. 7.3) and still relies to a large extent on fossil energy sources, but the RES sector is steadily growing. However, renewable production now accounts for more than half of the electricity generated in Andalusia. Overall, Andalusia added 787 new MWs of renewable energy to its power generation fleet in 2020 and making it the second region, behind Castilla y León, in terms of installed renewable power capacity and in total more than 51% of the electricity generated in Andalusia is based on RES.

7.2.2. Investments

While the share of thermo-solar power plants remained constant between 2014 and 2021, it increased from 884 to 3,466 MW installed capacity for photovoltaics in the same period. All other RES, e.g. electricity production from biogas (increase approx. 12%), biomass (increase approx. 6%), hydropower (increase approx. 5%), wind (increase approx. 6%) play a minor role in Andalusia in terms of newly installed large scale capacity. The production of wind power, however, reaches a similar order of magnitude with 3,466 MW installed capacity. Based on the growth potential, only the photovoltaic sector experienced a boost under the actual circumstances (IEA 2021a, JdA 2023). Consequently, companies are still investing in this field, e.g. Iqony Solar Energy Solutions started in summer 2020 with the further construction of a 180 MWp solar plant[37]. Overall the company estimated to have constructed approx. 500 MW in Spain by end of 2021.



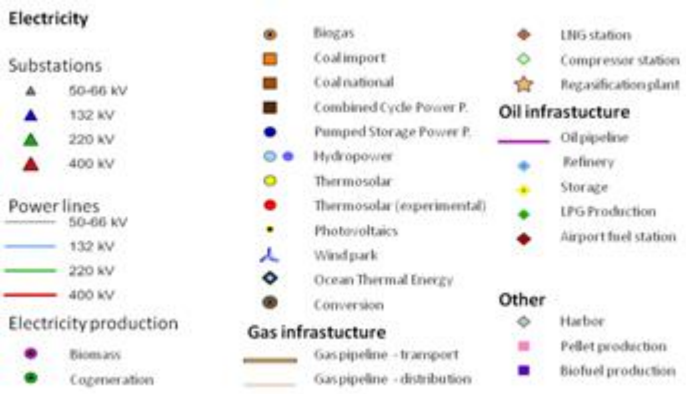


Figure 7.3: Energy infrastructure for the Spanish autonomous region of Andalusia. NB! more detailed maps can be obtained by changing the resolution under: https://www.agenciaandaluzadelaenergia.es/miea/miea/init.do

Source: Agencia Andaluza de la Energia

However, apart from these activities, investments in other sectors are also still ongoing. Capital Energy, for example, decided in 2022 to invest in new wind farms[38], namely Pinarejo I and II - which add up to 60 megawatts (MW) of capacity and will produce enough renewable electricity to cover the annual consumption of some 55,000 Andalusian homes. This activity indicates that even in not so favorable regions (cf. Fig. 6.1), it can be economically beneficial to invest into RES.

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[37] https://www.sens-energy.com/en/sens-constructs-a-further-180-mwp-in-andalusia/

[38] https://www.evwind.es/2022/12/28/capital-energy-promotes-wind-power-in-andalusia/89498

Other areas of activity in Andalusia focus on the production of green hydrogen. CEPSA, a leading Spanish energy company, plans to invest 3 billion € in Andalusia to build the largest green hydrogen hub in Europe. Based on 2 GW wind and solar energy projects in which CEPSA with invest alone 2bn €, the hydrogen hub is planned to generate 10,000 jobs. If it has been finalized it will produce up to 300,000 tons of green hydrogen at two new plants in Campo de Gibraltar (Cádiz) and Palos de la Frontera (Huelva). Overall, CEPSA will allocate 60% of investments in 2030 plan to Andalusia. It is a goal to establish an Andalusian Green Hydrogen Valley, which should help decarbonize industry and heavy land, air, and maritime transport, by reducing CO_2 emissions by six million tons. This indeed, will only make sense if Andalusia will be connected to a future European hydrogen grid. As Fig. 4.8 indicates, will this be possible to affordable costs. In general it can be observed that the Iberian peninsula, including Andalusia, needs to be better connected to the central European power grid.

If one looks at the solar thermal power plants in Andalusia, the installed capacity has hardly changed, but in terms of the areas used, the land consumption amounts now to approx. 1.1 million m^2. This is 25% of the total land used in Spain for solar thermal plants. However, it has decreased in recent years, which indicates that the capacities for solar thermal energy are tightening in Andalusia in terms of land use (JdA 2023).

The other aspect of sustainable energy production in Andalusia relates to the production and consumption of self-produced renewable energy in homes, companies and industries. It is the goal of Andalusia to increase economic savings and achieve greater independence from the electricity grid. In the first nine months of 2021, a total of 11,515 Andalusians decided to start producing their own electricity by adding to their own consumption, which represents a growth of more than double compared to the same period in 2020, when 5,613 facilities were registered, according to the data of up to 100kW power plants provided by the European Ministry of Finance and Finance (Telework Andalucia 2021).

Of these facilities, 28% are located in the province of Seville; 14% in Malaga, 13% in the provinces of Jaén and Córdoba, 12% in Cádiz, 11% in Granada, 5% in the province of Almería and 4% in Huelva. In the period between October 2019 and September 2021, there are already 20,600 Andalusians that currently generate their own renewable energy, a figure that, according to the Andalusian Energy Agency[39] estimates, will greatly increase when thanks to the incentive programs currently underway. In the first half of 2021, the new self-consumption facilities in Andalusia contributed a total of 77 new megawatts of installed power that were added to the renewable electricity generation park deployed in the Andalusian community. Overall, Andalusia produces approx. 51% of its electricity from RES.

In terms of energy safety and affordability, a recent study tried to examine the actual situation in Andalusia. Up to now, Andalusia has still a high dependency on energy imports, but it is also one wealthiest autonomous communities of Spain from the perspective of RE resources. In their work, Bekhrad et al. (2020) defined three categories of indicators which could measure energy security, namely reliability, affordability and sustainability (Fig. 7.4). The results indicate room for improvement in any category. In particular, in the area of affordability, Andalusia takes the last place in the group of regions studied. As the study was done before the Ukraine war started, it is likely that affordability has become even worse – as elsewhere in Europe. As Andalusia is lagging behind countries like Poland, Slovenia or Estonia in terms of affordability, the government needs to have an eye on this aspect. Andalusia has still an important primary sector (agriculture, forestry, fishing, etc.), although the service sector is dominant. This could be a reason that salaries are on average lower than in other regions, and

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[39] https://www.agenciaandaluzadelaenergia.es/en/know-agency

therefore energy might be more costly for citizens in these regions. However, overall the Andalusian energy system is clearly further progressing towards sustainability and smart loans for individuals may create further achievements and will mitigate price effects, in particular for the poorer people.

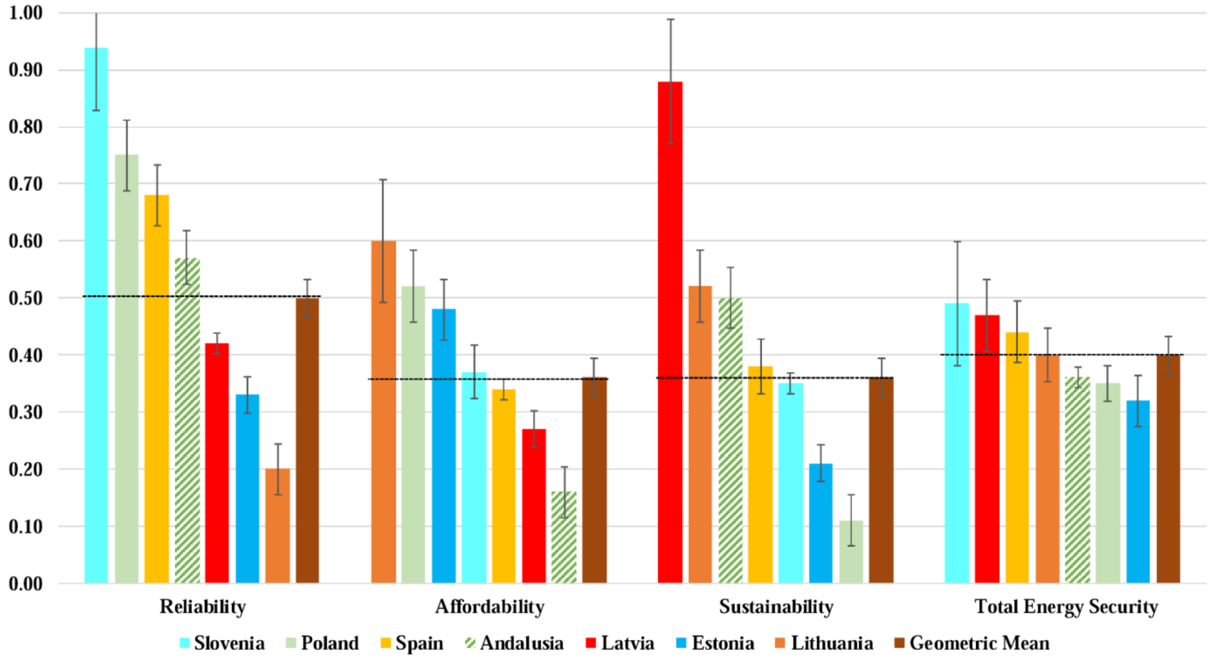

Figure 7.4: Comparison of the energy sector in Andalusia/Spain according to a set of indicators. The data set includes measures (overall 12), like grid efficiency, emissions/cap, gasoline and electricity prices, energy supply sources, net import dependency, etc., for details, refer to Bekhrad et al. 2020.

7.3. Conclusions and Key Messages

Similar to the rest of Europe, the greatest potential in the Mediterranean lies in wind and solar.

1. With regard to the autonomous community of Andalusia, it should be noted in particular that this region, together with another region in Spain, is at the forefront in terms of the pace of expansion, but is still dependent on fossil energy.
2. In terms of energy affordability, Andalusia also lags behind regions that, for example, entered the European Union later than Spain itself.
3. In terms of other resources, directly used geothermal energy in the form of heat could be an option in the region. However, the potentials have hardly been exploited so far.
4. In contrast to Europe as a whole, there is also potential for hydropower in the Mediterranean region, which is a good combination due to the partly mountainous orography in combination with various lakes. However, it should be noted that climate change can quickly lead to water shortages in the region.

8. Overarching Findings and Recommendations

In summary, it can be stated that on a European scale, there is a considerable potential to run the electricity sector exclusively with RES. There are a number of very detailed studies dealing with different methods of calculating RE potentials. The possibilities for the European continent are tremendous and diverse. Currently, only negligible amounts of electricity are imported and exported (cf. Tab. 4.4), mostly between European countries. The challenge of a self-sufficient European electricity sector in 2030 lies in the fact that the necessary climate-relevant restructuring of the European economy and the corresponding binding climate agreements will entail major changes. These require in particular that large parts of the (fossil) primary energy, which is currently still used to a considerable extent for electricity generation or also for heat generation (cf. Tab. 8.1), must be substituted by 2030.

Table 8.1: Primary energy consumption and electricity production in Europe as a whole and in the EU27 (Source: Our World in Data, based on Ember's Yearly Electricity Data (2023); Ember's European Electricity Review (2022), WID 2023.

Continental Europe, energy by source 2021, in TWh										
Energy	**Oil**	**Natural Gas**	**Coal**	**Nuclear**	**other RES**	**Wind**	**Solar**	**Hydropower**	**Share of RES**	**Total**
Primary Energy	9,088	10,074	3,253	2,790	230	1,242	485	2,116	4,073	29,278
Percentage	31%	34%	11%	10%	1%	4%	2%	7%	14%	100%
Electricity	125	1,192	698	1,111	219	473	188	777	1,657	4,783
Percentage	3%	25%	15%	23%	4%	10%	4%	16%	35%	100%
European Union (EU27), energy by source, primary energy 2021, electricity 2021 and 2022, TWh										
Primary Energy	5,922	3,966	1,871	1,838	369	1,019	420	901	2,709	16,306
Percentage	36%	24%	12%	11%	2%	6%	3%	6%	17%	100%
Electricity (2021)	103	552	419	732	176	387	164	349	1,076	2,882
Percentage	4%	19%	15%	25%	6%	13%	6%	12%	37%	100%
Electricity (2022)	100	557	447	612	173	420	203	283	1,079	2,795
Percentage	4%	20%	16%	22%	6%	15%	7%	10%	39%	100%

Another challenge for the European energy sector is, that large parts of the energy demand of industry must be electrified directly or through power-to-gas (PtG) technologies. Added to this, one has to be taken into account a further increase in electricity demand from e-mobility and heat pumps. Considering these factors, the electricity demand for Europe as a whole could rise to about 5,500 TWh by 2030 and even to almost 8,000 TWh by 2040 (Sect. 4.4).

To generate such an amount of electricity based on renewable resources, a massive expansion and increase of electricity generation based on renewable resources would be required until 2030 and beyond. Taking the 2,795 TWh generated in the EU in 2022 as a basis, and considering that 1,079 TWh were produced on the basis of RES in the same year, as well as the projected electricity demand until 2030 (about 4,000 TWh, including savings due to changes in consumer behavior, cf. Chapt. 2), an annual growth rate of RES supply of about approx. 20% per year in terms of production is required (cf. Sect. 4.4). In other words, Europe as a whole, but also the European Union, is far from a sustainable and self-sufficient electricity system. Although there has been an increase in plant construction of over 40% in individual sectors, such as solar, this growth does not equate to production, as PV elements are usually only calculated with an efficiency of 15-20%. This circumstance is, of course, also related to the fact that ambitious climate protection targets cannot be achieved at the current rate of expansion.

As a consequence, the share of energy imports in Europe remains high (over 57% in 2020, mainly from non-EU countries). This applies to primary fossil energy sources such as oil, coal and gas, but also to uranium. It is important to bear in mind that Europe imported about 4,300 TWh of natural gas in 2019, about 50% of which came from Russia. If you also consider that, on average, the provision of thermal energy for heating is based on gas to the tune of about 50%, the blackmail potential becomes immediately clear. However, in the country with the highest energy consumption (Germany), 50% of electricity is also generated on the basis of gas-fired power plants, which means that here too there is a clear dependency (Leopoldina 2022). Although the dependencies have been quickly eliminated by politically more calculable suppliers, the fundamental dependence on fossil energy has not changed, but has even increased (see Tab. 8.1).

Nevertheless, it should be noted that European electricity self-sufficiency is possible by 2030 with the existing technologies (cf. Sect. 4.4). Even if one takes into account the necessary substitution of fossil and nuclear power generation capacities. However, this means a massive expansion and, above all, at a greater speed than ever before. To realize this, corresponding and pathbreaking political decisions are needed. Although the European Union in particular has already launched corresponding policies such as the REPowerEU, Green Deal and Fit for 55 Package, these programs are far from being able to achieve the necessary goals. At best, the pace can be described as stagnant, at least in some regions of Europe. For example, the expansion of solar energy in Italy has been stagnating for several years (EMBER 2023). The reasons for this include overly complicated national approval procedures. Such mechanisms urgently need to be simplified, if necessary, through further EU framework directives.

Another aspect of the necessary energy transition is the electrification of industry (e.g. through renewable hydrogen production), which is currently being discussed intensively. The timing of this discussion is somewhat surprising , as a functioning and sustainable hydrogen economy only makes sense once European electricity generation has also switched to sustainable sources. Of course, the future of the European energy architecture and the role of imported hydrogen need to be reconsidered. But this should be secondary in time to a necessary massively accelerated expansion of renewable energies. Moreover, the role of hydrogen in the energy system by 2030 depends crucially on the extent to which independence from fossil fuel imports can be achieved. According to current expansion targets, battery-powered electric vehicles are not sufficient to replace oil imports by 2030, as the speed of conversion of the existing vehicle fleet is limited and the substitution of oil in aviation and shipping is an even greater challenge.

It is therefore interesting to note that there are discussions about whether synthetic fuels can be produced via hydrogen in order to operate existing combustion engines. From a climate protection perspective and in relation to the actual potential for RE-based power generation, this discussion is simply an anachronism. Taken together, what is needed is a European energy strategy that looks ambitiously into the future and does not try to keep technologies that are no longer opportune alive through the back door.

However, even with a strong increase in RE electricity demand, Europe would be able to easily meet the additional demand under natural conditions, as only 8-10 % of the potential capacity in Europe needs to be used, mainly wind and solar energy. All other RE sources hardly play a role in terms of quantity (see Table 8.2), which does not mean that they can also be used profitably in preferred locations.

With regard to the transformation challenges facing the energy sector, it must also be noted that misguided industrial policy in recent decades has led to the relocation of formerly promising sectors such as the PV or wind industry to China, for example. If we want to enable independence today, this means rebuilding an industrial basis in the respective sectors, which cannot be obtained for free. Moreover, this has also led to a lot of time being lost. If there is no ambitious thinking on power generation and climate protection, there is a non-negligible probability that energy dependence on Russian gas will be replaced by industrial dependence on China (cf. Sect. 6.4). In the past decades, it has been repeatedly emphasized that energy policy is also security policy. And as the COVID19 pandemic has also shown, global supply chains can be extremely vulnerable. This applies to plant engineering and the production of key components necessary for the energy transition. For this reason, technology and resource dependencies should not be left out of the focus of European policy.

An important rule for RE expansion must therefore be: Effectiveness before efficiency! This means that policy-makers must maximize the expansion of wind and solar energy at reasonable costs, instead of minimizing the economic costs and failing to achieve any significant expansion rates. This is also a strong argument for building domestic (European) production capacities for PV and wind power plant construction instead of resorting, if necessary, to somewhat cheaper producers on the world market who may not be able or willing to ensure supply. Incidentally, this strategy also strengthens the intra-European labor market. In view of the many crises, not only in the energy sector, a rethink is necessary in the hunt for ever better prices on the world market. Ultimately, the aim should be to regain technological leadership in order to make Europe truly self-sufficient and independent. This is particularly necessary to strengthen European markets, also to avoid the risk of deindustrialisation (cf. Sect. 6.5).

The investment required to achieve the goal of true sustainable energy self-sufficiency is estimated at around €140 billion per year across Europe (cf. Sect. 4.4), with these costs falling significantly after 2030, to around €100 billion per year by 2040. For comparison, to deal with the current energy crisis, it is estimated that European countries have spent around € 792 billion to support consumers. So there is no reason why the pace of RE expansion could not be massively accelerated. Moreover, RES are unbeatably cheap, as detailed studies show (see Chapt. 6).

Finally, another aspect to consider in this context is cyber security. Increasing digitalisation in the electricity sector will make it easier to control grids and monitor consumption, but such infrastructures are also vulnerable to cyber-attacks (see Sect. 6.3). Here, too, politics, but also individuals, must be held more accountable in the future. One consolation in this context is that distributed network infrastructures can be made more resilient. Section 4.3 explains how the European pipeline system for electricity (HVAC, AVAC as well as hydrogen) can be expanded. Again, it is necessary to take a pan-European perspective. The expansion of an electricity grid that maintains a self-sufficient European electricity system can only be organized locally to a very limited extent, because all RES are distributed across the European continent. This alone requires European initiatives for grid expansion. And according to the results of this study a better connection of the Iberian Peninsula into European power and hydrogen grids is desirable.

Finally, another aspect remains important in the context of European (energy) integration. Although there are only a few quantitative studies on the energy sector that show the advantages of energy system integration for the European countries, this is imperative due to the aspects discussed in the previous section. But there are clear indications of what happens when a country leaves the EU. In Sect. 1.2, the consequences of reintroducing customs regulations and other rules between the EU and the UK are illustrated for trade volumes. Indeed, taking into account the respective trade volumes, technologies and energy mixes, this would mean an increase in emissions included in UK imports of around 215 Mt CO_{2eq}. Replacing EU imports into the UK with imports from the rest of the world (RoW) under the same conditions means that each dollar of imports into the UK generates 0.35 kg CO_{2eq} on average. Conversely, the impact for the EU is not so clear. Closing the gap in UK imports by increasing EU production would only lead to additional emissions of 12 Mt CO_{2eq}. This shows the benefits of an integrated European market that adheres to common environmental standards and climate policies. It is very likely that this also applies to energy policy, especially since energy is an essential component of all traded goods. It becomes clear that the so-called "effort sharing" decision leads to the development of affordable and fair burden sharing between Member States, where high-income Member States pay for low-income countries while ensuring overall cost efficiency. This also applies to emissions and the common energy market.

Table 8.2: The table sums up the actual state of the art in the European RE system. It is shown that the main burden of a transformation of the European electricity sector need be covered by wind and solar. Overall the capacity is there, in particular when taking into account that also geothermal or wave energy are additional resources, for, e.g. local solutions. The light red columns indicate the result of model simulations, while the other date refers to existing publications from the respective sectors.

Technology (installed capacity in GW)	Total installed capacity (GW) 2021	Generated (TWh/yr) 2021	Efficiency	"Pathway 2030"		Top five European countries (installed capacities in GW); NO=Norway, TR Turkey, FR=France, DE=Germany, ES=Spain, AT=Austria, UK=United Kingdom, SE=Sweden, FI=Finland, PT=Portugal				
				Capacity installed GW	Power generated TWh/yr					
Hydropower[a]	255	659	30%	248	541	NO	TR	FR	IT	ES
						33.4	31.5	25.5	22.6	20.4
of that: pump storage	55	-	-	-	-	IT	DE	ES	FR	AT
						7.6	6.2	6.1	5.8	5.6
Windpower[b]	236	437	21%	1,219	3,170	DE	ES	UK	FR	SE
of that offshore	28	80	33%	-	-	8	0	12.7	0	0
of that onshore	207	357	20%	-	-	56	28	14	19	12
Photovoltaics (2022)[c]	193	203	11%	617	745	DE	IT	ES	FR	NL
						58.5	22.7	16.0	14.7	14.3
Of that commercial	82	-		-	-	-	-	-	-	-
Of that utility solar	68	-		-	-	-	-	-	-	-
Of that residential	43	-		-	-	-	-	-	-	-
Biomass Electricity[f]	0.4	109[g]	3%	34	77	DE	UK	SE	IT	FI
						0.105	0.073	0.045	0.034	0.028
Geothermal (2022)[h]	3.5	22[i]	72%	N/A	N/A	TR	IT	FR	DE	PT
						1.7	0.9	0.038	0.04	0.02
CSP (EU 2020)[j]	2.3	5[j]	25%	N/A	N/A					
Tidal, wave (EU 2020)	0.2	N/A	N/A	N/A	N/A					
Total RE supply[g]	648	1,371	24%	2,118	4,533					

a) Assessment for continental Europe, *theoretical generation includes 70 GW non-exploited resources in Europe, cf. IHA (2022)
b) Source Windeurope (2021)
c) SolarPower Europe (2022): EU Market Outlook for Solar Power 2022-2026, NB! that a PV plant have also a low efficiency as it cannot produce power during the night; download at: https://api.solarpowereurope.org/uploads/5222_SPE_EMO_2022_full_report_ver_03_1_319d70ca42.pdf
d) Enevoldsen et al. (2019), excludes infrastructure, protected areas, waterways, etc. onshore potential only, 30% load

e) Tröndle et al. (2019), excludes, waterways, agri, protected areas, but includes particular roof tops and open field PV, onshore and offshore wind
f) Statistica.com, 2022
g) IEA 2020, OECD Europe
h) European Geothermal Congress Summary, load >75%
i) IEA 2020
j) State of Renewables 2019
k) Eurostat 2023: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_production,_consumption_and_market_overview

In summary, this study comprehensively analyses policy documents as well as the latest scientific findings on the European energy market. Although the Russian invasion of Ukraine has fundamentally changed the view of European energy security and also the climate debate, the speed of transformation with regard to climate protection and sustainability has only changed marginally (see Tab. 8.2). Although many studies published in 2021/2022 show high expansion rates, e.g. for the European PV market more than 40% in 2022, installed capacity is not synonymous with electricity generation. Thus, the efficiency of energy use varies greatly between the individual RE.

Comparing Table 8.1 and 8.2, it becomes obvious that the goal of self-sufficiency in the electricity sector can be achieved. Not only is the increase in RE capacity calculated by the model sufficient, but the amount of electricity generated with it also covers the demand that is generally projected for 2030. This means that all options for action are obvious to the European states, i) with regard to the exploitable resources, ii) the necessary investments and iii) also with regard to positive aspects of European integration and climate protection. Further, aspects related to market dependencies, however, should be taken into account as well in energy policy related decision making.

9. References

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