



M Ű E G Y E T E M 1 7 8 2

Nemzeti Felsőoktatási ösztöndíj
Publikációs adatlap
2022/2023. tanév

Adatok:

Név:	Illés Gergely
Neptun kód:	COZJ2Z
Képzés neve:	Fizikus MSc
Képzés kódja:	9N-MF09
Beszámolási időszak:	2021. 07. 01. - 2022. 06. 30.
Melléklet sorszáma:	1
Téma kódja:	A

Publikációra vonatkozó adatok:

A megfelelő bekarikázandó:

HAZAI	NEMZETKÖZI
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Publikáció pontos címe:	Comparative analysis of national energy strategies of 19 European countries in light of the green deal's objective
Publikáció nyelve:	angol
Elfogadás dátuma:	2021. 11. 16.
Megjelenés helye:	Energy Conversion and Management X, Volume 12
Impaktfaktor/ folyóirat szakterületi rangsor:	IF: - R: D1 – Nuclear Energy and Engineering
Elektronikus elérhetőség (amennyiben van):	https://doi.org/10.1016/j.ecmx.2021.100136
ISBN/ISSN:	2590-1745
Témavezető neve, oktatási szervezeti egysége:	Dr. Aszódi Attila, Atomenergetika Tanszék

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Budapest, 2022. 06. 28.

témavezető aláírása



pályázó aláírása

Nemzeti Felsőoktatási ösztöndíj
Idegen nyelvű tevékenység összefoglalója
2022/2023. tanév

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Idegen nyelvű tevékenység rövid összefoglalója:

Ebben a cikkben 19 kontinentális európai ország (Ausztria, Belgium, Bosznia és Hercegovina, Horvátország, Csehország, Franciaország, Hollandia, Horvátország, Lengyelország, Magyarország, Németország, Olaszország, Portugália, Románia, Spanyolország, Svájc, Szerbia, Szlovákia, Szlovénia, Szlovénia és Ukrajna) villamosenergia-ágazatának fejlődési pályájáról gyűjtöttünk információkat. A tervezett fogyasztási forgatókönyvek és a tervezett erőművi portfóliók figyelembevételével óránkénti felbontású szimulációs modelleket fejlesztettek ki és használtak fel a 2030-as és 2040-es évre várható villamosenergia-ellátási helyzet értékelésére, a 2019-es tényadatokat alapul véve.

Az erőművek előre meghatározott elosztási sorrendjét figyelembe véve a szimulációk segítségével kiszámították, hogy az év 8760 órájában hogyan fedezhető az óránkénti villamosenergia-igény.

Meghatároztuk továbbá azon rendszerállapotok számát, amelyekben az egyes országokban nem lenne elegendő kapacitás a szükséges villamosenergia-ellátáshoz, vagy ahol az időjárásfüggő megújuló túltermelését tapasztalnánk. Meghatároztuk továbbá a vizsgált országok mindegyikében az összes primer energiaforrás óránkénti és éves termelési adatait.

Az egyes országok elemzése után, és kvázi végtelen határkeresztező kapacitásokat feltételezve az összes modellezett ország között, megvizsgáltuk, hogy az egyes országok megújuló forrásainak potenciális túltermelését fel lehetne-e használni egy másik ország ugyanazon órában jelentkező villamosenergia-igényének kielégítésére, amelyet nem lehetne szén-dioxid-mentes hazai forrásokból kielégíteni.

A szimulációk során nem vettük figyelembe a hálózati veszteségeket. A villamosenergia-rendszer megbízható működéséhez szükséges elsődleges, másodlagos és harmadlagos tartalékokat nem vettük figyelembe a modellekben. Az erőművi terheléskövetés technikai korlátait nem vettük figyelembe, bár ezeket a korlátokat az energiasztratégiákban sem vettük figyelembe. Hasonlóképpen nem modellezték a diszpozícionálható erőművek karbantartásához szükséges időt és a karbantartás ütemezését. Ezek az egyszerűsítések nem konzervatív közelítései a szükséges kapacitás mennyiségének, így figyelembe vételük valójában még magasabb kapacitásigényhez vagy több ki nem szolgálható villamos energiához vezetne. Ez azt is jelenti, hogy a jövőbeli villamosenergia-rendszer az itt bemutatott adatokhoz képest több diszpozícionálható kapacitásra és nagyobb rugalmasságra lesz szükség.

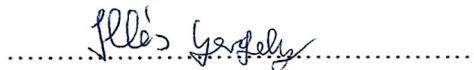
Véleményünk szerint az Európai Bizottság klímacéljainak teljesítése az országok jelenleg közzétett nemzeti energia- és klímaterveinek peremfeltételei mellett nem lehetséges, figyelembe véve az ellátásbiztonsági célokat is. További probléma, hogy a tagállamok a jelek szerint nem vették figyelembe terveikben az összekapcsolt európai villamosenergia-rendszer export-import potenciáljának korlátait.

Modelljeink bemeneti adatainak összeállítása során nemcsak a vizsgált országok energiastratégiai dokumentumait néztük át, hanem az ENTSO-E nyilvános adatbázisából is nagy mennyiségű adatot gyűjtöttünk össze és dolgoztunk fel. Ennek során megállapítottuk, hogy az ENTSO-E által gyűjtött és nyilvánosan hozzáférhetővé tett adatbázisban számos ellentmondás, pontatlanság és hibás adat található. Nagyon hálásak vagyunk az ENTSO-E szakértőinek, hogy válaszoltak számos megkeresésünkre, és számos feltárt hibát kijavítottak. Másrészt viszont arra kellene ösztönözni az országokat, hogy pontosabb adatokat szolgáltatassanak az ENTSO-E számára. Véleményünk szerint az európai villamosenergia-rendszer jövője olyan nagy jelentőséggel bír, hogy ezekben az adatbázisokban nem szabadna ennyi hibának lennie. A múltbeli rendszerállapotokra vonatkozó pontosabb adatok birtokában pontosabb modellek és szimulációk készíthetők a jövőre vonatkozóan.

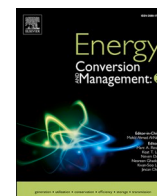
Svájc esetét különösen problematikusnak találtuk: Svájcnak pontos, óránkénti felbontású adatokra lenne szüksége a szivattyús tároló erőműveiről ahhoz, hogy a többi vizsgált országhoz hasonlóan modellezni lehessen az országot, de ezek az adatok nem állnak nyilvánosan rendelkezésre az ENTSO-E adatbázisában. Megjegyzendő, hogy Svájc központi elhelyezkedése és nagy szivattyús tárolókapacitása miatt az egész európai rendszer modellezése szempontjából kulcsfontosságú lenne, ha a tudományos vizsgálatok számára átláthatóan rendelkezésre állnának legalább óránkénti felbontású adatok a szivattyús tárolós vízerőművek töltéséről és ürítéséről (a folyóvízi vízerőművektől elkülönítve). Ennek hiányában a modellezés európai szinten is jelentősen torzulna.

Érdekesnek találtuk a spanyol koncentrált naperőművek adatait, amelyek éjszaka is termelnek napenergiát. Ez fizikailag helyes, mivel éjszaka a nappal tárolt hőenergiából termelnek villamos energiát, tehát az éjszakai napenergia-betáplálás valós, de a jövőbeni modellezés érdekében ezt külön kellene megjeleníteni az ENTSO-E adatbázisában, mint a tárolótartályok ürítéséből származó energiát. Ellenkező esetben nem lehet jól figyelembe venni a modellekben.

Budapest, 2022. 06. 28.



Hallgató aláírása



Comparative analysis of national energy strategies of 19 European countries in light of the green deal's objectives

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ARTICLE INFO

Keywords:

Energy strategy
Green deal
Security of energy supply
Intermittent renewable energy sources
Coal phase-out
Nuclear energy

ABSTRACT

The European Green Deal is setting clear objectives for the transformation of the economy into a cleaner and at the same time competitive working model. The energy sector and especially the electricity sector faces serious challenges in order to comply with the objectives set by the policy. Aging power plants and grid infrastructure, phasing out fossil based energy production, the nuclear phase-out in some countries, increasing weather dependent intermittent power sources, the requirements of the security of electricity supply are also individually stressing issues, but all together are even more challenging.

In line with the Treaty on the Functioning of the European Union (TFEU) the energy strategy is the competence of the individual countries, based on the fact that the different countries have very different geological, socio-economical and ecological conditions, and their access to natural resources can be diverse. Therefore the national governments and national Parliaments are setting the national strategies which has to be in-line with the European framework. An important question arises evidently, namely, whether the national pieces of the big European Puzzle will result to a picture that has been set by the European Green Deal published on 14th July 2021?

In the research presented in this paper, we tried to answer the abovementioned questions by investigating the energy strategy of 19 countries situated in continental Europe. We ran simulations for the year 2030 and 2040 using full year models with hourly resolution to investigate if the power plant portfolios of the individual countries could cover the electricity needs foreseen by their national energy strategies. Possible curtailment and unserved demand of the 19 countries in question were summed and final conclusions were drawn based on the simulation results.

Introduction

The focus of the European Union's policy is on the environmental protection, including climate protection and the climate-neutral transition. The European Green Deal aims to transform the European economy, while increasing its competitiveness, to make the most efficient use of resources and to develop and deploy technologies that can serve as a model not only for the region but also for the whole world [1].

The goals include the elimination of greenhouse gas emissions by 2050, making Europe the first climate-neutral continent by then, and ensuring that the transition takes into account the interests of individuals and regions to maximize the opportunities offered by new technologies.

On 14 July 2021, the European Commission announced a new

implementation programme, "fit for 55" [2], which aims to achieve a 55% reduction in net greenhouse gas emissions by 2030 compared to 1990 levels. The legal framework for implementing the programme has also been announced [3].

Energy transformation and energy use are responsible for the vast majority of greenhouse gas emissions. Within this, the production of electricity, which is the most important source of energy, is responsible for most of the carbon-dioxide emissions. At the same time, the replacement of today's still largely fossil-based electricity generation by solar and wind power, which is the preferred choice of the public and politicians, raises technological issues, as the need for continuous supply and the security of supply requirements is not in question.

This paper examines the extent to which the conversion of the generation side of the continental European electricity system, as currently

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envisaged, can serve the abovementioned climate protection and security of supply objectives.

In our study, we have analyzed the recent energy policy documents of 19 European countries (not all being member states of the European Union) and examined the power plant portfolios planned by the individual countries for 2030 and 2040. The countries studied were Austria, Belgium, Bosnia and Herzegovina, Croatia, Czech Republic, France, Germany, Hungary, Italy, Netherlands, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Switzerland and Ukraine. From this list Serbia is a candidate country being in the process of integrating EU legislation into its national law, while Bosnia and Herzegovina is a potential candidate for EU membership. Ukraine is a priority partner for the EU, which signed Association Agreement with the EU earlier. Switzerland is also not an EU member, however it is associated with the Union through bilateral treaties.

We also assessed the expected changes in electricity demand, based on the values estimated in the energy policies of the countries concerned. Future plans were assessed on the basis of real data from 2019. This year was chosen as the base year because it was the last year not affected by the coronavirus pandemic, so the electricity consumption data reflect the pre-crisis period.

Using the public database of European Network of Transmission System Operators for Electricity (onwards ENTSO-E) [4], we collected national electricity generation and consumption data for 2019, the energy mix of generation, and hourly resolution schedules for the entire year of 2019. We also collected hourly resolution generation data of weather-dependent renewable power plants per country, from which we calculated specific generation and availability data per country, considering relevant installed capacities. These data series were used in the production of simulations for 2030 and 2040 for each investigated country. In our view, the rapid increase in energy prices at the end of 2021 could encourage countries to review their energy strategies in short-term, for which this article aims to provide a contribution.

Literature study

The analysis of different energy policy scenarios and methodological issues related to this topic are widely analyzed areas in the literature. In this literature review, we focus on those recent articles which are more closely related to the investigation of the European policies. We must state already here, at the beginning of this chapter, that the breadth and detail of the analysis presented in our paper was not found during our literature study.

In study [5], the authors used the Relative Aggregate Footprint (RAF) concept to evaluate energy technology alternatives. The RAF is an indicator based on a System of Systems approach that assesses technologies along multiple performance criteria. In the paper, 11 electricity generation technologies have been evaluated by cost, carbon-, water- and land use footprint. There are many multiple-criteria decision-making (MCDM) methods, but a single best solution does not exist. So instead of choosing one method, the authors used five different approaches: Maxmin, Lexicographic, TOPSIS, SAW and Dominance and aggregated the rankings results into a single number between 0 and 100, the RAF. When $RAF = 0$ that technology is strictly dominant, meaning it is better than all alternative technologies according to all MCDM methods. Where $RAF = 100$, that technology is strictly dominated. The results showed that no single technology was strictly dominant. Nuclear, geothermal and onshore wind perform relatively better than the other technologies. The worst relative performers are biomass, oil, and large-scale hydropower. Then the member state specific RAFs were calculated by weighing each criterion based on the local availability of the respective resource: gross domestic product per capita, carbon emissions per capita, freshwater withdrawals as a share of renewable freshwater, and land availability per capita. RAFs from Croatia, generally deviated most from the EU average RAFs, closely followed by Bulgaria, Spain and Sweden. The varying water availability in these countries was the key

driver of these differences from the EU level average. Based on the results, a diversified portfolio of technologies will be best suited to the EU's future power generation system and it is crucial to include local concerns when choosing the technologies.

Huang and Purvins [6] present a technological-economical analysis and validation covering the entire European electricity system. The analysis was carried out using a software tool called PLEXOS and aimed to ensure that the model well reproduces the electricity system behavior in 2016 in terms of electricity generation and cross-border trade. The article draws attention to the importance of validating electricity market models, and also highlights the need to question the completeness of input data and to check different data sources. We can confirm this too, as highlighted in Chapter 6 of the present paper.

Simones et al. [7] present a modelling approach to explore the impact of climate variability on the European electricity system. The modelling was made in the TIMES model environment, which is a detailed electricity system modelling tool, but does not have the same resolution as IAEA's Energy Scenarios Simulation Tool (ESST) [12] what we use in our study: in the models presented in Simones et al's paper each year is divided into 64 time slots, comprising the 4 seasons, 2 typical days (weekday and weekend) and 8 consecutive day periods. In contrary in our ESST model, each year under study is described fully in hourly resolution, covering all 8760 h of the given year. We believe that analyzing the impact of climate variability is of utmost importance for the future of electricity systems, but more detailed models with at least hourly resolution would give a much clearer picture on the functioning of the electricity system.

Lehtveer and Fridahl [8] have examined the role of Bioenergy with Carbon Capture and Storage (BECCS) in the 2050 s European electricity system by modelling it with the ELINEPOD model package. Their goal was to find the most cost-efficient energy mix – including the cost of new investments and operating costs – depending on the price of biomass and emission targets. Their study showed that if its price decreases, BECCS would be a suitable option for balancing variable renewables, especially in countries where the potential of variable renewables is low such as Bulgaria, Romania or the Netherlands. They have also made a survey which pointed out that preferences to invest in bio-based technologies are low in all countries. They have found that these types of studies are highly important by the preparation of energy policy decisions.

Langarita et al. [9] discuss the economic and environmental impacts of three possible development paths for the electricity sector in Spain, in line with the objectives of the European Union. The three development directions are: 1) Managing the currently low electricity trade with the rest of Europe, increasing integration into the European grid; 2) Improving sustainability, increasing the use of renewable energy sources, while reducing the use of fossil (mainly coal) energy sources. 3) Increasing the competitiveness of the Spanish electricity industry, by which the authors assumed an increase in the energy efficiency and productivity of the electricity sector. Each of the scenarios modelled in the study provides useful conclusions. The most significant change in carbon-dioxide emissions would be the introduction of renewables and phasing out of fossil-fuel based power generation. This is consistent with the 2030 and 2040 Spanish electricity mixes we have modelled, in which more than 80% of the electricity generated will come from carbon-neutral renewables. The analysis also finds that the expansion of cross-border capacities will help the penetration of renewables. The authors argue that making the economy more energy efficient would improve the situation of energy-intensive industries or power producers most but would not necessarily stimulate green growth.

Körmendi and Nagy [10] discuss the technological, administrative and institutional steps to be considered in order to implement the EU's 2011–2020 climate strategy, with a special focus on the use of renewable energy sources. They point out that energy supply data (including electricity data) need to be carefully collected and processed. They envisage a global institute of so-called energy security centres where this work could be done. In addition, the installation of simulation tools in

these centres would make it possible to obtain useful knowledge from the data collected in a very short time. This could be of great help in energy policy making. They also stress that climate change strategies need to think in the longer term, up to 2040 or 2050. The article confirms what we ourselves have concluded in the course of our work, namely that the data on electricity supply in Europe are not currently collected systematically enough and they are not cleared of any inconsistencies to a level that would allow them to be used directly for scientific studies. It is our view that systematic collection and provision of data would be necessary for detailed, comprehensive and consistent analysis.

Atsu et al. [11] discuss the situation of photovoltaic power generation in Hungary. The country is a relatively favorable area for solar energy utilization, with annual average daylight hours ranging from 1950 to 2150 h and horizontal ground surface radiation of around 1280 kWh/m². The widespread deployment of solar panels started later than in some European countries, but the last 3–4 years have seen a significant increase in installed PV capacities. The Atsu et al. article concludes that the supporting system is adequate, but there are some administrative and legal barriers to the further large-scale deployment of these systems. The 2017 production figures for the oldest solar PV system in Hungary, connected to the grid back in 2005 and still in operation today, has been examined, too.

Methods

In our current work, we set the objective to investigate the energy strategy of 19 continental European countries which have a well-developed and interconnected electricity grid. Based on currently available electricity data and strategies planning the future development of the economies and the shift in energy sources of the power plant systems, we wanted to summarize the possible European-wide changes and see their possible effects. A further objective was to investigate if besides the climate goals, security of electricity supply goals could be achieved by the strategies set in different countries. In our view, this wide range study could help the European Commission and the governments of the individual countries to identify the area where further discussions and coordination would be necessary.

To model the electricity supply of the selected 19 countries in continental Europe in year 2030 and 2040, we decided to use Energy Scenarios Simulation Tool [12] (ESST) developed by the International Atomic Energy Agency. The ESST is capable of modelling the annual generation data of the power plant system at hourly resolution, given a set power plant portfolio, annual electricity demand and the power system schedule for a reference year. The model is not able to model several countries at the same time, so in our present study the models of the different countries have been built one by one.

To build a model for a country for a given year the following data are required in ESST: annual electricity demand (GWh), primary energy mix of electricity generating units (MW), dispatch order of primary energy sources, hourly resolution data series from a reference year on electricity consumption and the hourly utilization factors of the particular weather-dependent energy sources (solar, wind and hydro). The reference year was 2019 in order to avoid any distortions on data caused by the economic crisis of COVID-19 pandemic. We did not define electricity exports or electricity imports for any of the countries in the modelling, as we wanted to know whether the individual countries would be able to meet their needs with their own resources and what their export/import potential would be. By modeling the natural gas based electricity production the evident constraints of EU's gas import were neglected.

In building the simulations for each country, we consistently followed the methodology of adopting the country's energy strategy for 2030 and 2040 in terms of the assumed annual electricity consumption and the primary energy mix of the foreseen power plant portfolio. The previously defined hourly data series were downloaded from the ENTSO-E database [4] and incorporated into the model. The individual

Table 1

The dispatch order defined in all the ESST models.

Place in the dispatch order	Name of the energy source
1.	Solar
2.	Wind
3.	Hydro
4.	Nuclear
5.	Geothermal
6.	Biomass
7.	Waste
8.	Gas
9.	Coal
10.	Oil

national energy strategy documents used as data source for the simulations are listed for the individual countries in Appendix A. The exact references of the strategy documents can be found in the bibliography.

After running the simulations, we obtained hourly-resolution data on electricity consumption, unserved energy, the production of each electricity generating units and their load factor.

The input data with hourly resolution from the ENTSO-E database were processed and entered into the model for the individual countries according to the methodology published by ENTSO-E [36], i.e., the consumer data series provided as input in the ESST are derived from the summation of the consumption data from the ENTSO-E database and the consumption data from the pumped hydro power plants. Since in ESST only one single hourly data series specific to hydropower plants can be entered in a given simulation and no pumped storage capacities can be defined separately, the hydropower data series input to ESST were calculated as the sum of the production of the “hydro run-of-river”, “hydro water reservoir” and “hydro pumped storage” plants. The situation is similar for wind power, for which it is not possible to provide separate hourly utilization factors for onshore and offshore wind power in ESST code. Thus, the wind power series provided as input in the ESST were calculated as the sum of onshore and offshore wind power production in each country.

In the ESST, aggregated data are used for energy sources, i.e., it is not possible to define power plant units with different installed capacities within a given energy source, but only to provide the total installed capacity and the annual utilization factor of the electricity generating units using the given energy source. A further modelling limitation is that the model cannot specify the speed of load changes of the power plants, and any resulting deviations should be considered as modelling inaccuracies.

The model also does not allow the definition of mandatory maintenance of power plant units. Therefore, maintenance does not appear at all in the model output, which is important to note because if maintenance of controllable plants was included, a significant amount of electricity generation potential would be lost from the electricity systems of each country, further complicating the continuous supply of electricity.

The model used here contains some (sometimes significant) approximations and is clearly not intended to provide system management instructions for a hypothetical year one or two decades from now. However, it is an excellent tool for analyzing the impact of each country's energy strategy and for assessing the potential and need for cooperation between countries. Despite the approximations mentioned above, the model is also suitable for high quality analyses of the future technical feasibility of electricity systems in different countries and of an integrated European electricity system.

Indeed, due to the emergence of weather-dependent energy sources in the electricity market, we believe that it is essential to increase the resolution of the electricity market simulations regularly used for energy strategy analyses to at least hourly resolution, thus providing the possibility to analyze the effects of hourly fluctuations of weather-dependent energy sources.

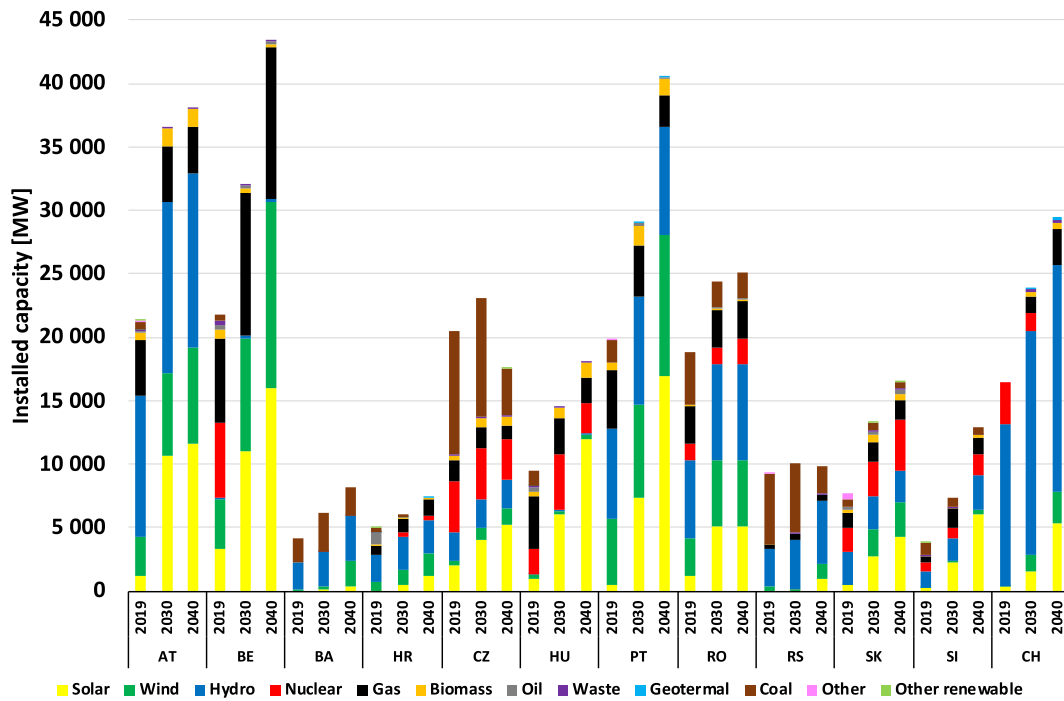


Fig. 1. Installed capacity (<50 000 MW in total) (data source [4,13–35]; own illustration).

For the different countries, a uniform dispatch order is defined and is presented in Table 1. Obviously, if for some reasons a particular energy source is not included in a given country, we have not defined that energy source in that model and the energy sources behind it in the dispatch order have moved one step forward.

The hourly resolution calculation logic of the model is as follows. Based on the predefined annual electricity demand of the year to be modelled, it proportionally increases or decreases the hourly values of the given hourly consumption dataset compared to the reference year, thus the model determines a demand for each hour. In the next step, the

hourly generation potential of weather-dependent energy producers (solar, wind and hydro) is estimated using the input data of the installed capacity and the hourly utilization factors of the reference year. The generation structure of each hour is finalized by taking into account the dispatch order. The model calculates for the energy source listed first in the dispatch order the production potential of that energy source in that hour (for weather-dependent energy sources this is done as explained above, for other energy sources it is equal to the installed capacity). The model determines whether this production potential is sufficient to meet the hourly consumption demand. If it is not sufficient, the model

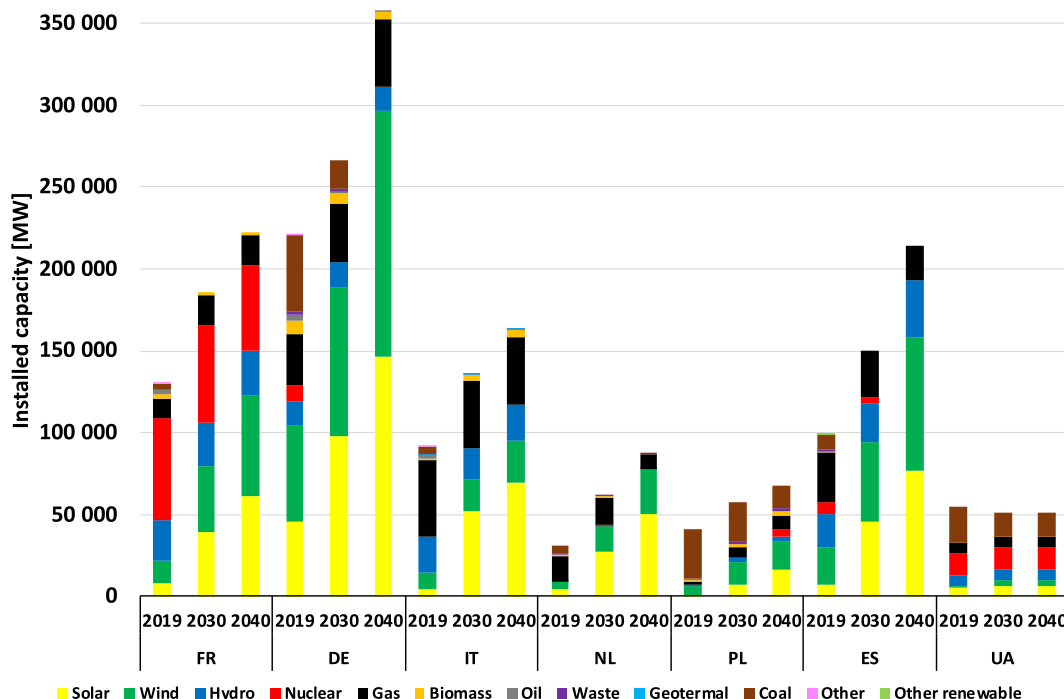


Fig. 2. Installed capacity (greater than 50 000 MW in total) (data source [4,13–35]; own illustration).

determines the production potential of the next energy source listed in the dispatch order until it can satisfy the total consumption demand for that hour. If the model has used the total production potential of all the energy carriers, but this is not yet sufficient to meet the consumption demand of that hour, then unserved electricity will appear in the system.

The data were processed and evaluated at both national and European level. The analyses at country level focused on the future potentially unserved electrical energy in the countries, the energy mix of electricity generation, the specific CO₂ emissions of the countries' electricity generation, and whether the share of electricity generated from carbon neutral energy sources (solar, wind, hydro, nuclear, geothermal, biomass, waste) in the countries reaches 90%. The potential curtailment of the different energy sources-based power plants was determined, too. The role of nuclear energy was also examined. The European-level assessment evaluates if the possible hourly unserved demand of a given country could be covered by curtailment of power plants theoretically still available in other countries in the given hour of the year. By summing up all the data calculated for the 19 continental European countries under investigation, we can evaluate if the actual energy strategies fulfil the European common objectives. We have to point out here that for the unlimited transport of electricity throughout these 19 countries, the "infinite" capacity transmission grid is physically not available. Also grid losses connected the long-range electricity transport are not taken into considerations in these calculations. The effects of these assumptions shall be subject of further studies.

Input data

As described above, the energy strategy documents summarized in Appendix A have been processed for the 19 countries under study to determine the electricity consumption and power plant portfolios planned for 2030 and 2040. A summary of the processed data is presented in this chapter, which serves as the basis for the simulations.

Capacity

Figs. 1 and 2 summarize the data found in the energy strategy documents for the current and planned future power plant portfolios of each country. Fig. 1 shows countries with installed capacity below 50,000 MW, while Fig. 2 summarizes the data for countries with larger power plant parks.

In both figures, the current trend is clearly visible: most countries are planning to develop solar and wind capacity to meet climate and CO₂ emission reductions goals, while a significant reduction in coal-fired capacities is planned. The only exception to these trends is Serbia in 2030, whereas in 2019 Serbia had 398 MW of wind capacity, but in 2030 only 51 MW of solar and 47 MW of wind capacity are expected in the selected scenario of the document [29].

In 2019, all the countries surveyed except Switzerland (18 countries in total) had some coal-fired capacity, with the largest coal-fired fleet in Germany (46,498 MW) and Poland (30,274 MW). Among these countries, it is important to highlight Czech Republic, Serbia, Ukraine and Poland, in which countries although the installed capacity of coal-fired power plants is expected to be decreasing, coal will be still a major contributor to the electricity generation capacity of the country in year 2030 and 2040.

In 2019, 12 countries had nuclear power plants in operation, and this could decrease to 11 by 2030 and to 10 by 2040, according to the countries' plans. While all the countries surveyed plan to phase out coal, the situation is not the same regarding nuclear power: there are countries that plan to phase out nuclear (Belgium, Switzerland, Germany and Spain), but there are also countries that plan to develop nuclear capacity. Poland is considered to be a nuclear newcomer in the near future. Figs. 1 and 2 also show a number of countries that are planning to maintain existing nuclear capacity in the long term or are planning to expand nuclear capacities: new build projects are planned e.g., in

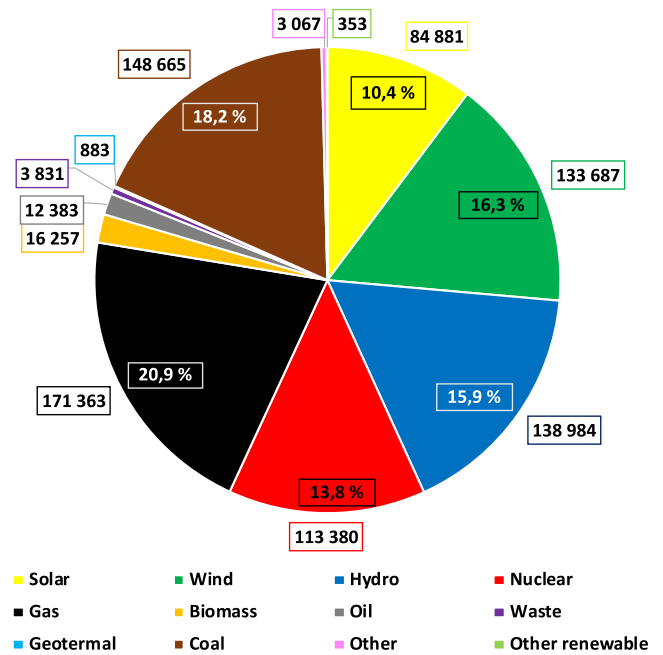


Fig. 3. Installed capacity in the EU by primary energy source (2019) (data source [4], own illustration).

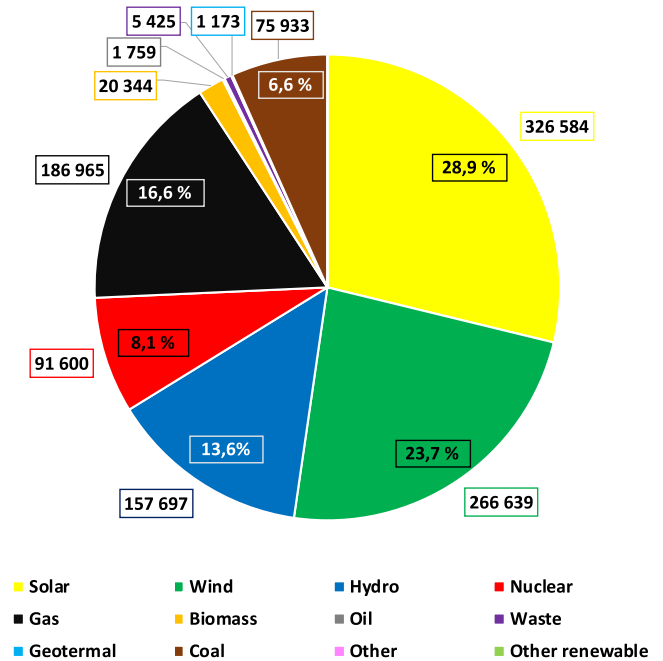


Fig. 4. Installed capacity in the EU by primary energy source (2030) (data source [13–35]; own illustration).

Hungary, Slovenia (together with Croatia), Czech Republic, Slovakia, and maintaining nuclear capacities in France, Ukraine, Romania. We assume that within the timeframe investigated in this study commercial fusion power will be not available.

It is also important to note from the data shown in Figs. 1 and 2 that there is no single country in 2030 or 2040 where the power fleet is all carbon neutral, namely all countries are planning to maintain or develop fossil capacity, including mainly natural gas based power plants.

The installed capacity data for the 19 countries surveyed are summarized in Figs. 3 to 6. The well-known energy policy trends can be clearly observed in quantitative terms: EU countries are committed to

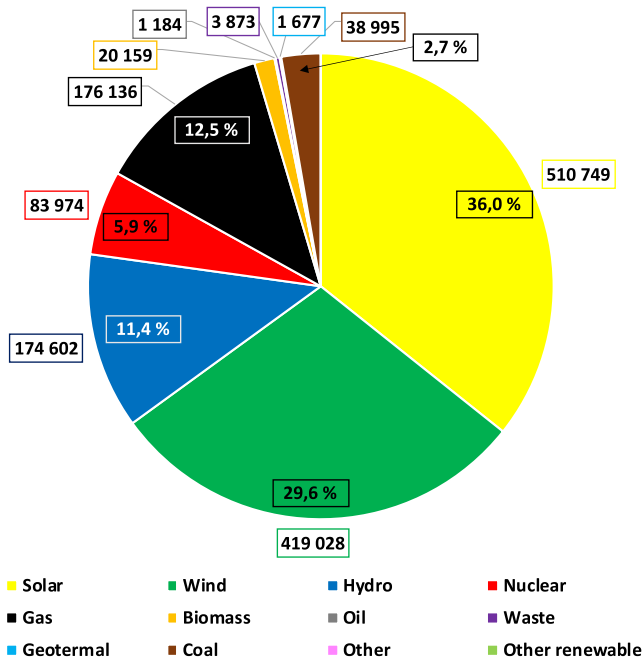


Fig. 5. Installed capacity in the EU by primary energy source (2040) (data source [13–35]; own illustration).

phasing out coal, while wind and solar power are prioritized in the plans for power plant developments. As Figs. 3, 4 and 5 show the share of coal in the power plant fleet in the 19 countries analyzed will decrease from 18.2% (149 GW installed capacity) in 2019 to 6.6% (74 GW) in 2030 and 2.7% (38 GW) in 2040, while the share of solar and wind installed capacity is assumed to increase from 26.7% in 2019 (85 GW solar, 134 GW wind) to 52.6% in 2030 (326 GW solar, 267 GW wind) and 65.6% in 2040 (508 GW solar, 418 GW wind). (Please see the development of the installed capacities of different primary energy based power plants

summarized in Fig. 6.)

It is also important to analyze the share of dispatchable capacities, i. e. nuclear, hydro, natural gas, biomass, oil, waste, geothermal and coal based power plants in the countries, as these plants ensure nowadays that our electricity system provides consumers with a continuous supply of electricity 24/7 over the whole year. The key role of these power plants is also reflected in their share in installed capacities in 2019, which was 73% (600 GW), but this figure is planned to fall to 47% (535 GW) in 2030 and 34% (485 GW) in 2040. It is important to highlight natural gas-fired power plants among the dispatchable power plants, as the data in Fig. 6 clearly show that their installed capacity does not decrease at all compared to 2019 (171 GW installed capacity in 2019) but increases compared to today's situation (187 GW in 2030, 176 GW in 2040), even though these capacities are also fossil-based. The data suggest that countries plan to have natural gas-fired power plants as the largest share of dispatchable plants in their electricity systems.

Consumption

After the analysis of installed capacities, we looked at electricity consumption data, i.e., how much annual electricity demand each country's energy strategy document expects for the next two decades. The actual electricity consumption of the countries under study in 2019 and the projected consumption of the energy strategies for 2030 and 2040 are summarized in Fig. 7. The data show that the energy strategies do not foresee a shift in power consumption: electricity consumption is expected to increase in almost all countries. Taking all the data of the 19 countries studied, we see that annual electricity consumption could increase from 2504 TWh in 2019 to 2716 TWh in year 2030 and to 2918 TWh in year 2040 according to the energy strategies of the individual countries.

From an energy policy perspective, very important data is shown in Fig. 8, where we compare each country's electricity consumption in 2019 with the foreseen changes whether it expects an increasing (in red in Fig. 8) or decreasing (in green in Fig. 8) trend in year 2030 and 2040. Fig. 8 shows that 15 of the 19 countries studied expect their electricity consumption to increase compared to 2019 levels. Among these 15

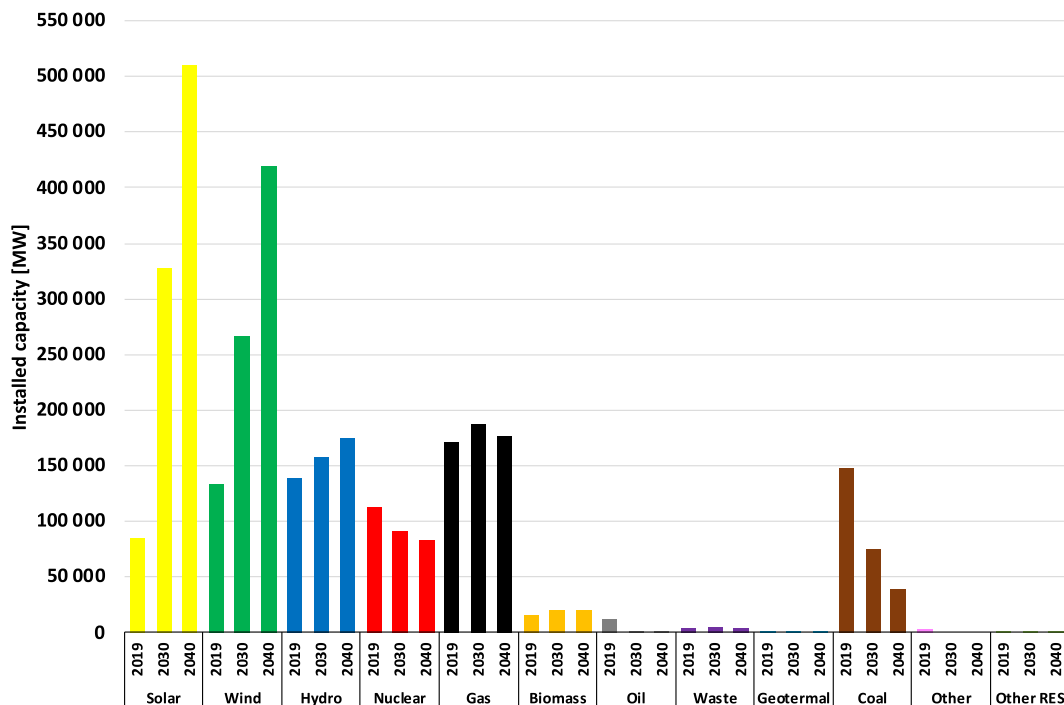


Fig. 6. Installed capacity in the EU by primary energy source (data source [4,13–35]; own illustration).

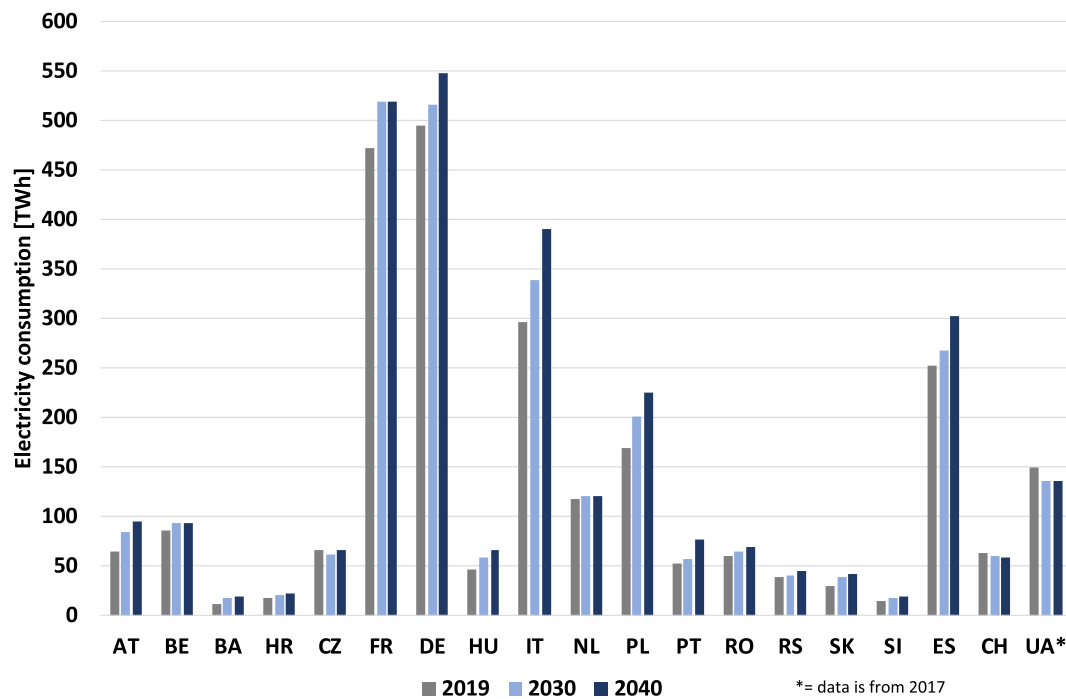


Fig. 7. Electricity consumption in 2019 and in the future (2030, 2040) in the studied countries (data source [4,13–35]; own illustration).

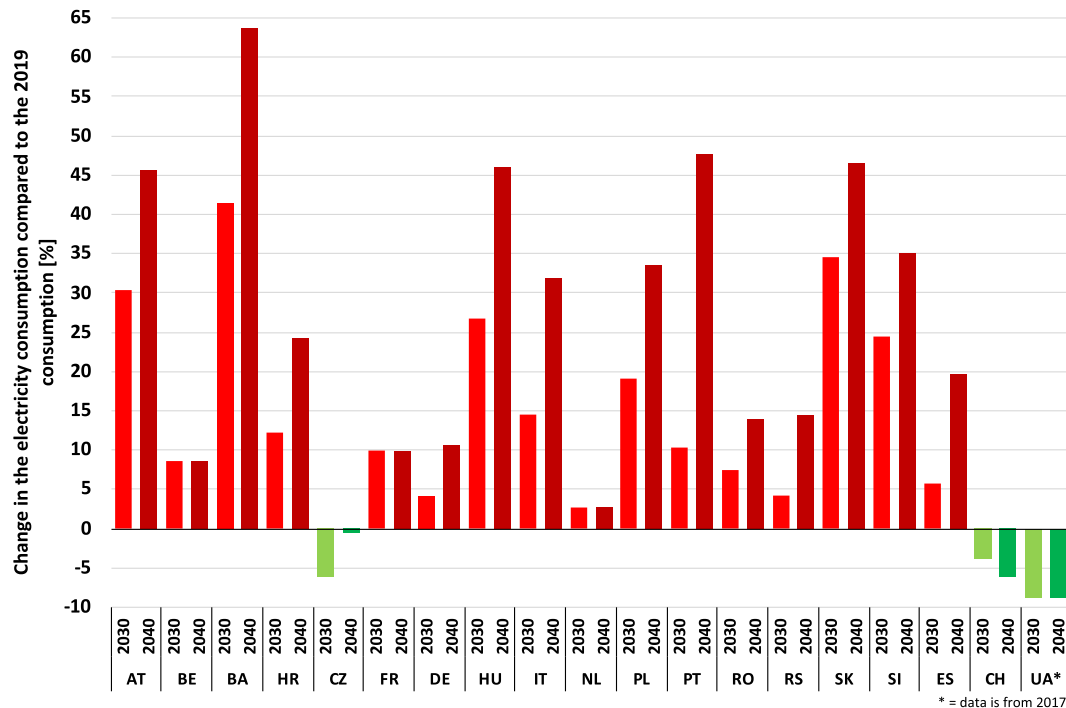


Fig. 8. Change in the electricity consumption compared to 2019 (data source [4,13–35]; own illustration).

countries, 8 (Austria, Bosnia and Herzegovina, Hungary, Italy, Poland, Portugal, Slovakia and Slovenia) are expected to consume more than 30% more electricity in 2040 compared to 2019, which means that in these countries, the electrification of the different sectors will definitely not keep pace with the increase in energy efficiency. Only the energy strategies of Switzerland and Ukraine foresee a permanent decrease in consumption, while the Czech Republic, although it foresees a 6% decrease by 2030, could return to 2019 levels by 2040.

Hourly data

Hourly resolution data, mostly downloaded from ENTSO-E's public database [4], played a key role in the analysis of electricity production and consumption in the 19 countries studied. The large number of countries and the large amount of data required a new visualization method for evaluation and comparison. Therefore, we developed and implemented a diagram type in the MATLAB programming environment that displays the values of a given technical parameter in an image

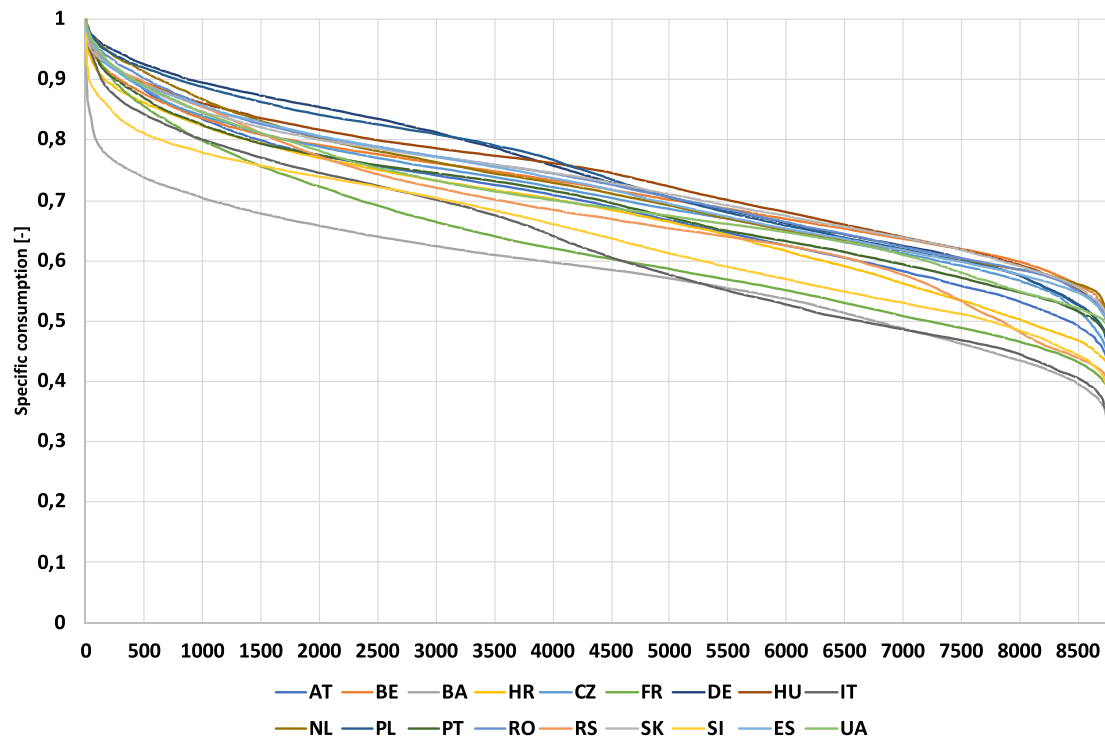


Fig. 9. Duration curve of specific consumption for all modelled countries based on 2019 data (data source [4], own illustration).

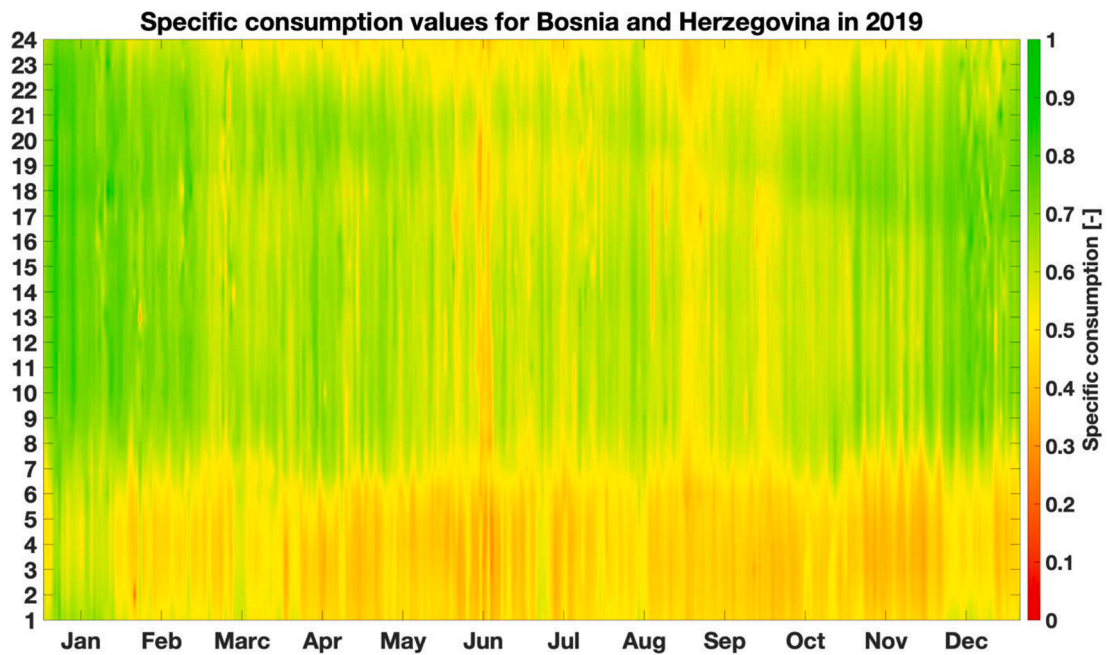


Fig. 10. Visualization of Bosnia and Herzegovina's hourly consumption values (data source [4], own illustration).

incorporating all 8760 h of the year. The diagram is a kind of *2D map of the year*, in which the variation of the value of a given technical parameter is visualized using a colour scale, with the days of the year represented moving from left to the right on the horizontal axis from 1 January to 31 December, and the hours of the day moving on the vertical axis from 1 to 24 h from the bottom to the top. Thus, in the 2D map of the year (see, for example, Fig. 10 and several times later), a day corresponds to the colours along a vertical line. These types of figures always show all 365 days of the year and the 24 h of each day, i.e. $365 \times 24 = 8760$ data points. In some figures, contour plots are used to

interpolate between the values (showing a pattern of the change of the given parameter over the year), while in other 2D map plots (see e.g. Fig. 25) the values are shown as discrete coloured rectangular areas. Sometimes we refer to this 2D maps of the year as *fishbone diagrams* because of the fishbone like pattern of solar PV production shown for example in Figs. 14–16.

Consumption

The ENTSO-E public database was used to assess the intra-year variation of electricity consumption data for the 19 countries in the

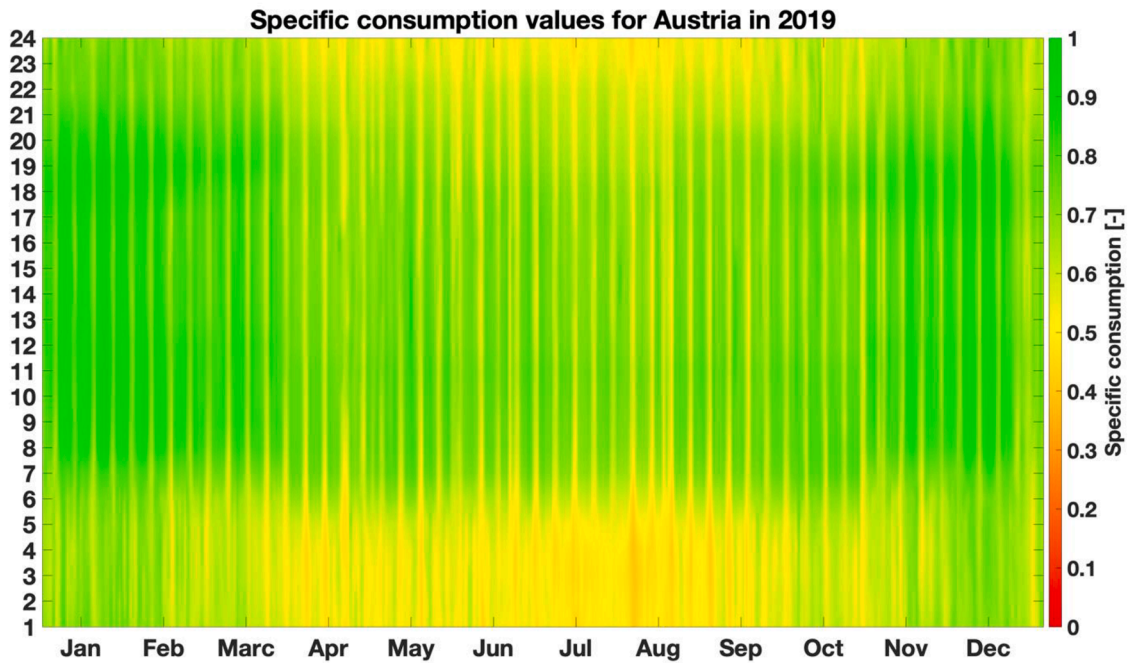


Fig. 11. Visualization of Austria's hourly consumption values (data source [4], own illustration).

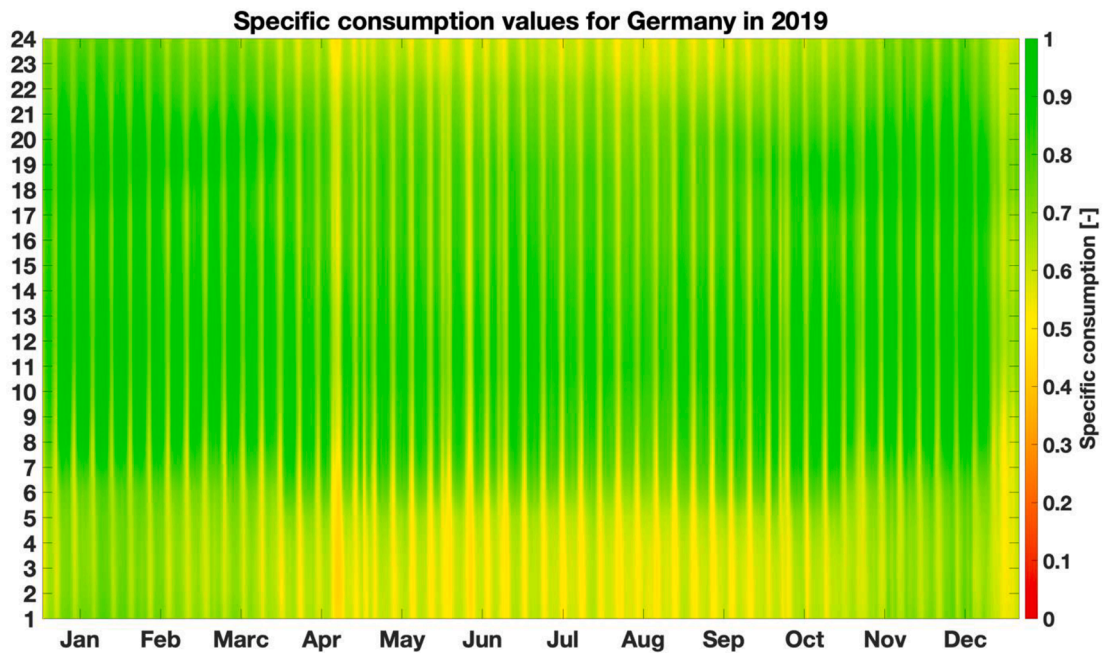


Fig. 12. Visualization of Germany's hourly consumption values (data source [4], own illustration).

year 2019. Using the annual peak demand of the country, specific consumption data were calculated, i.e. we determined the percentage of electricity demand compared to peak demand during 8760 h in 2019. The intra-annual evolution of the specific electricity consumption values was evaluated by comparing the data for each country and used to model the years 2030 and 2040: it was assumed that the intra-annual evolution of demand in the future would follow the same pattern on a relative scale as it did in 2019. This is obviously a modelling approximation, which introduces uncertainties in the calculation that need to be taken into account when assessing the results (please, see further details at the end of the paper.)

Fig. 9 shows the hourly specific consumption data for the countries

under study in the form of a duration diagram. In Figs. 10, 11 and 12 specific consumption data for Bosnia and Herzegovina, Austria and Germany are plotted on 2D maps. The reason for choosing these three countries is that Bosnia and Herzegovina shows the largest difference between the maximum and minimum load conditions, Austria shows a duration diagram close to the average of the countries studied, while Germany shows the highest duration curve with high load conditions.

Prior to the large-scale deployment of weather-dependent intermittent renewable electricity generation units, the consumption duration diagrams shown as example in Fig. 9 (supplemented with cost data for the different fuel type based power plant units) would have been sufficient to plan the amount of baseload, dispatchable and peak-load

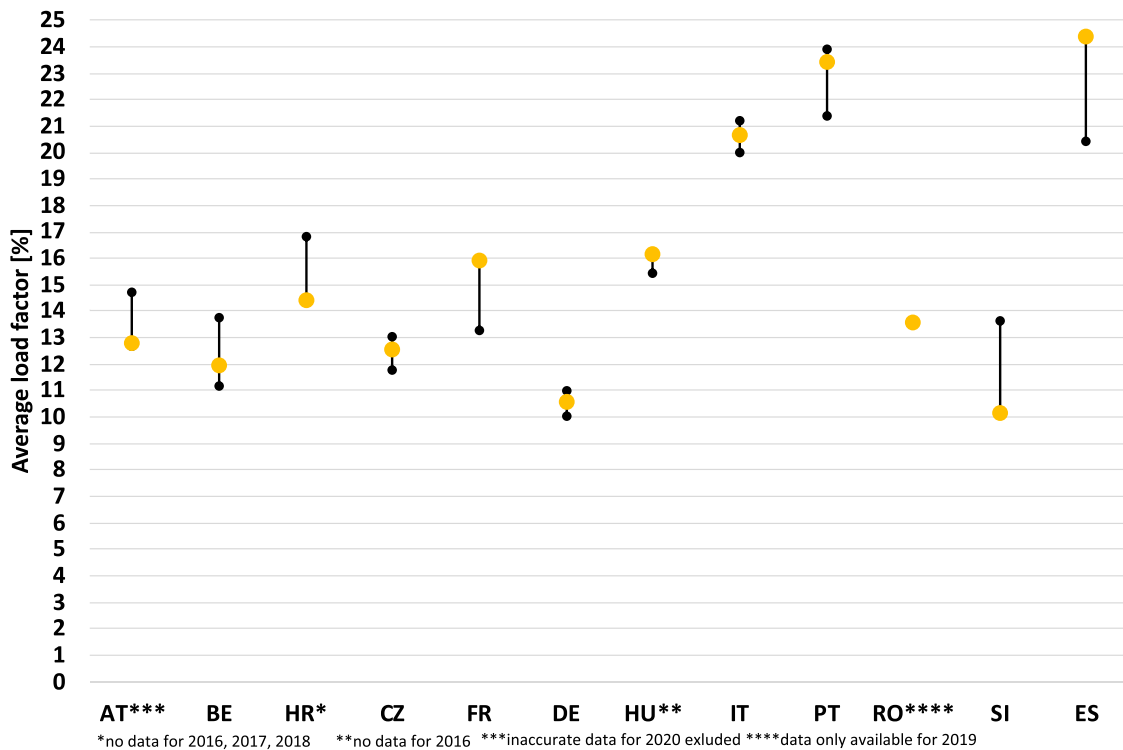


Fig. 13. Load factor of solar power plants for selected countries in years 2016–2020 (data source [4], own illustration).

capacities required to meet electricity demand in a given country in a cost-effective manner taking into consideration the security of supply requirements. Today, the situation has fundamentally changed with the high penetration of highly variable intermittent renewable generation. Therefore, nowadays it is not sufficient to design future electricity systems based only on annual balances, but rather to perform analyses with a much higher resolution than annual data. Based on the results presented in this paper we can highlight, that at least hourly resolution simulations are necessary to assess thoroughly the future behavior of the system and to make appropriate energy policy decisions.

We must recognize from the curves shown in Fig. 9 that for most of the analyzed European countries there is a strong need for baseload power supply based on the fact that at the 5500 h duration we can observe specific consumptions between 55% and 70%. For 14 from the 19 investigated countries at 8000 h duration the specific consumption is over 50%, meaning that over 8000 h in a year the load of the electricity system is over the 50% of the peak load. In order to comply with these electricity needs highly sophisticated, highly reliable electricity system with enough baseload capacities is required.

The data in Figs. 10, 11 and 12 highlight the importance of hourly resolution analyses by visualizing the hour-to-hour variation in specific consumption values. In the future electricity systems, electricity consumption will continue to vary from second to second, from hour to hour, and will need to be continuously balanced by power plant systems (technical means) that incorporate increasing amount of weather-dependent intermittent renewable energy sources. Fig. 10 shows data for Bosnia and Herzegovina, which has the lowest specific consumption values over the year 2019. The Fig. 10 shows that even here there is a demand for baseload electricity, as the lowest specific consumption value is 21%, i.e. system loads of this magnitude or above occur over the whole year. For Bosnia and Herzegovina, the system load at 8500 h duration is 40% of the peak demand, while 49% for Austria and 53% for Germany. This further underlines the high demand for baseload power.

The expansion of air conditioning is expected to increase this minimum specific system load in the future. Regarding the consumption data for Austria (Fig. 11) and Germany (Fig. 12), it is worth noting that the

difference between the maximum and minimum system load conditions is significantly smaller for these countries compared e.g., to Bosnia and Herzegovina and many other countries. This can be attributed on the one hand to the much more developed industry and on the other hand to the high penetration of air conditioning. It is worth noting that Germany's specific production data include only 3 yellow columns in Fig. 12, when specific consumption values did not enter the greener color scale for one or a few days. These are days when the system load does not exceed 70% for a single hour. These yellow ranges can be associated with major national religious holidays (Easter and Pentecost, Christmas and New Year's Eve), when it is common for a country's electricity consumption to be lower than usual. We can also remark that the equidistantly distributed thinner yellow stripes in Figs. 11 and 12 are the weekends.

Solar power

As shown in Fig. 6 in chapter 5.1, all the countries under study are planning significant developments in photovoltaic generation capacities. For each of the 19 countries, we examined how the hourly utilization factors of the existing PV parks evolved in 2019 and took into account these specific generation curves of the individual countries in the simulations. In this chapter, we present the processed data for six selected countries: in Fig. 14 we have plotted the specific utilization factors of the solar PV plants in Austria, Czech Republic, France, Germany, Hungary and Spain for 8760 h of the year 2019 in the form of the fishbone diagram mentioned earlier. Fig. 13 shows a summary of the annual solar utilization factors by country. Fig. 13 summarizes the annual solar utilization factors for the year 2019 by country, and the spread (maximum and minimum) of solar utilization factors for the countries in the period from 2016 until 2020. Fig. 13 does not include solar data for all 19 countries under study, as the ENTSO-E database is incomplete for several countries (these shortcomings are discussed in more detail in Chapter 6 and in Appendix B).

Fig. 13 shows that in 2019, the countries' overall average solar utilization factor varied between 10% (Slovenia) and 24% (Spain). When looking at the variation of the annual utilization factor over the period

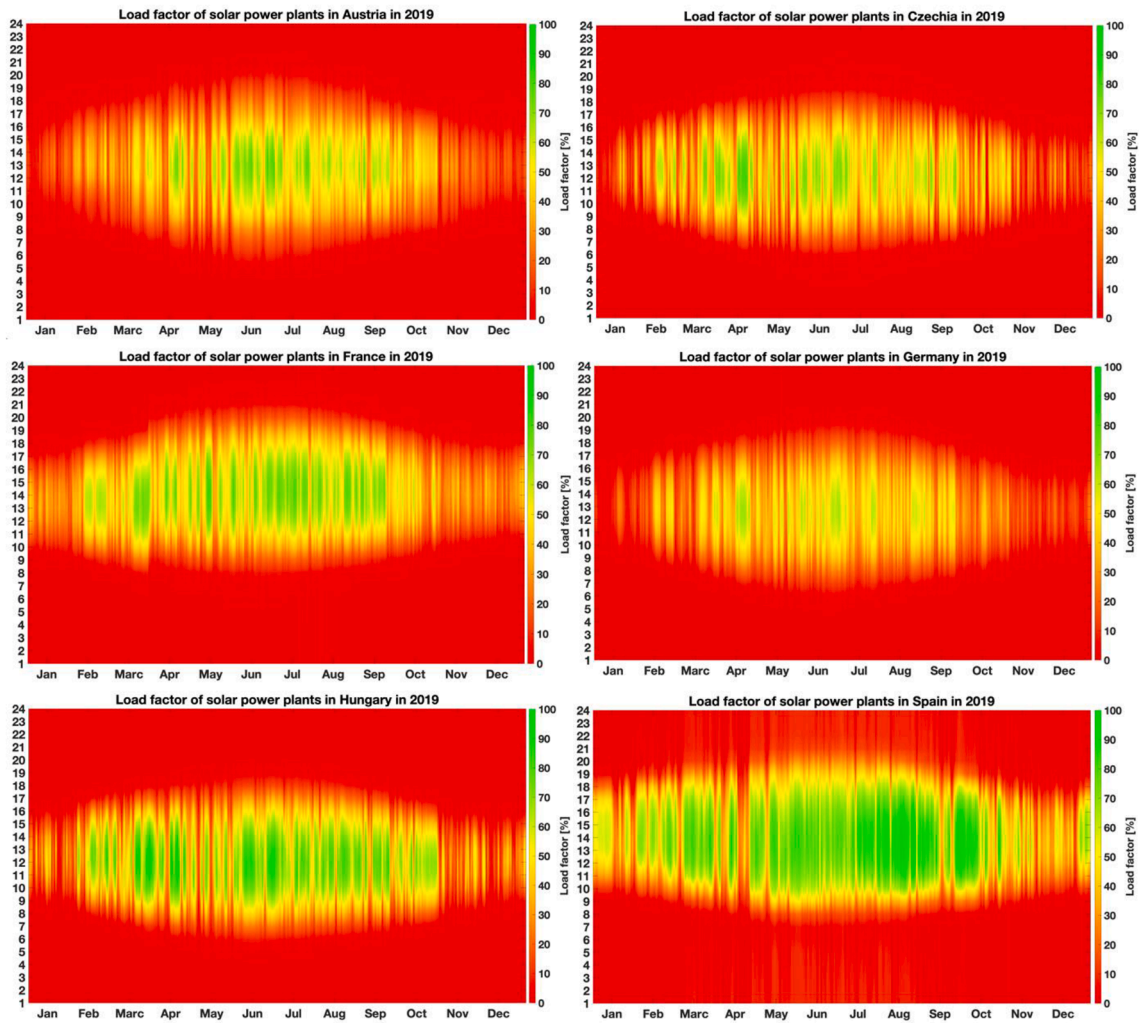


Fig. 14. Visualization of hourly solar power plant load factors for Austria (top left), Czech Republic (top right), France (middle left), Germany (middle right), Hungary (bottom left) and Spain (bottom right) in year 2019 (data source [4], own illustration).

2016–2020, a variation range between 1% and 4% can be observed across countries, with Austria being the most divergent country in this respect, with a total variability of 7%. The year 2019, which was used as the basis for the simulations, falls within the range in some countries (e. g. AT, BE, CZ, DE and IT); while in other countries, it falls at the maximum or minimum end of the spread. Therefore, the solar input data cannot be considered as conservative for the simulations, the effects of year-to-year variability of the solar data should be addressed later by estimating the uncertainties in the calculation.

Among the countries shown in Fig. 14, Germany's solar power plants perform the worst, as there are very few conditions in the central image of the right column of Fig. 14 where the utilization factor of German solar power plants is above 60% in a given hour. Furthermore, the German solar park has a very low production potential between October and February.

The situation is somewhat better in Austria and the Czech Republic, where there are already periods in the spring and summer when the solar power plants have a daytime load factor in the “green” range for several hours, i.e. above 60%. It is important to note, however, that Austria and the Czech Republic also have low solar load factors in the winter months.

As in Austria and the Czech Republic, France and Hungary can be compared in terms of solar potential, since, as shown in Fig. 14, the utilization factors of French and Hungarian solar power plants are higher than those of plants in Austria and the Czech Republic, but well

below Spanish values, which is the best placed country in Europe to utilize solar energy.

There are two different reasons behind the most favorable Spanish figures among the countries studied: on the one hand, Spain is one of the European countries with very favorable solar energy potential. As shown in Fig. 14, there are many periods during the day when the instantaneous solar power plant utilization factor is in the green range (greater than 60%), and these periods are not limited to one or two hours but form continuous periods (or bands in Fig. 14) from the end of January to November. In case of the other studied countries these favorable periods for solar energy are more typical from February until October.

However, in case of Spain, another important phenomenon can be observed in Fig. 14: solar infeed is also regularly observed at nights. This Spanish night-time solar energy production can be attributed to an approximately 2300 MW Concentrated Solar Power Plant capacity [37], which includes molten salt thermal energy storage systems, and are therefore able to generate electricity at night from the heat stored during the day. As can be seen from the Spanish data, this type of plant can significantly increase the flexibility of solar energy use and supports the operation of the electricity system, besides solar PV plants. In addition to this, it is important to point out, as it can be seen in Fig. 14, that although the utilization factor of solar plants is high in Spain, there are plenty of periods (not only at night and not only in winter, but also during the spring and summer daytime periods) when the production of solar plants in the country is negligible and they cannot contribute substantially to

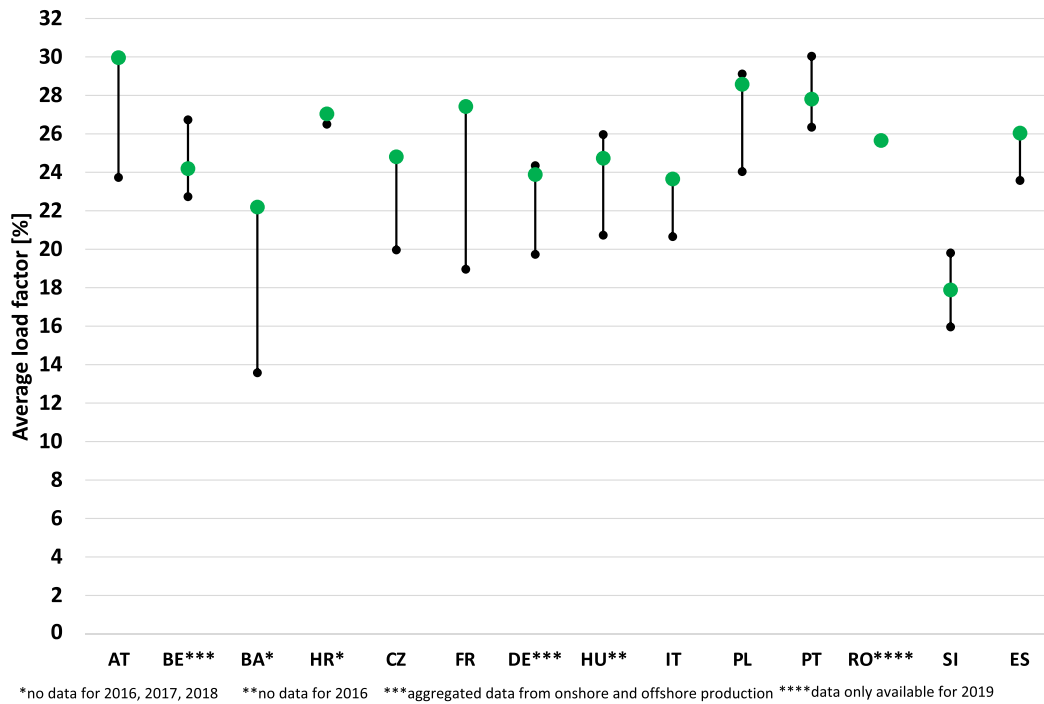


Fig. 15. Load factor of wind power plants for selected countries in years 2016–2020 (data source [4], own illustration).

the country's electricity supply. This must be kept in mind when designing a reliable and continuously operational electricity system with high security of supply requirements.

Wind power

Similar to solar PV production, we analyzed the hourly variation of wind-based electricity generation in 2019 for the 19 countries studied. We used here also data available in the ENTSO-E database. From the wind power generation data for 2019, we evaluated the load factor of the wind farms in each country and the change in wind power generation over time in order to use this data to forecast the expected operation of a future electricity system.

Fig. 15 summarizes the annual wind power utilization factors in 2019 for the 19 countries whose wind power data were available in the ENTSO-E database with a sufficiently high accuracy (see Chapter 6 and Appendix B for more information on the data errors in the ENTSO-E database). The figure also shows the spread of the annual wind power utilization factor for the period 2016–2020. The data for the 6 countries analyzed in more detail for wind power (Austria, Czech Republic, France, Germany, Hungary and Spain) are also presented in a “fishbone” diagram in Fig. 16.

Analyzing the data in Fig. 15, we can see that in 2019 the typical national wind energy load factor in the individual countries varied between 18% (Slovenia) and 28–30% (Austria, Portugal, Poland). If we look at the variation of the annual utilization factor over the period 2016–2020, we observe a range between 4% and 8% across countries. Contrary to the solar data presented in the previous subsection, for the wind data we can say that the data for the year 2019, which was used as the basis for the simulations, falls in the upper half of the range for most of the countries (10 out of 13 countries in Fig. 15), so the data used in the simulations for the wind utilization factor will be above the long-term average, and therefore the calculations will not be conservative from the point of view of security of supply requirements. The effects of year-to-year variability of the data in this respect will also be addressed by estimating the uncertainties in the calculation.

To compare the variability and temporal distribution of solar and wind power, it is worth comparing Fig. 16 with Fig. 14. While solar

energy is evidently available during the day and during the year mainly from spring to the end of autumn (of course taking into account the different geographical conditions of the countries), wind energy can be available independently of the time of day, but in the countries studied, wind energy input is negligible from the beginning of June until the end of September, but even outside these periods we see time periods when wind energy cannot contribute to meeting electricity demand nationally. It can also be seen from Fig. 16 that periods of high wind energy utilization are scattered throughout the year, as in every month of the year, there are periods when the wind energy feed-in is negligible compared to the installed capacity.

Looking at the diagrams in Fig. 16, there is an interesting period in March when the wind power generation potentials of the Czech Republic, Germany and France are very similar. On the one hand, this is positive, as each country has a higher share of renewables in electricity generation during this period. On the other hand, with the future increase in installed wind capacity, these system states could also pose a problem, since if neighbouring countries have high wind power inputs in the same period and wind power plants produce electricity in excess of their needs, it is possible that none of the countries could export the excess electricity, since there is no market nearby that could absorb it. Without industrial-scale electricity storage, the only way to maintain the stability of a country's electricity system would be to take wind power off the grid. From economic point of view, it is definitely deemed to be a not favorable solution.

Encountered difficulties

We encountered many complications when gathering the data needed to prepare the simulations. The sources of the problems were mainly the lack of data in the National Energy and Climate Plans or the incomplete or inconsistent nature of ENTSO-E data. These shortcomings have greatly complicated the preparatory work for the simulations and, unfortunately for Switzerland, have completely prevented the development of a future hourly resolution model of the electricity system. The main problems are listed in Appendix B.

Our experience shows that the data in the National Energy and

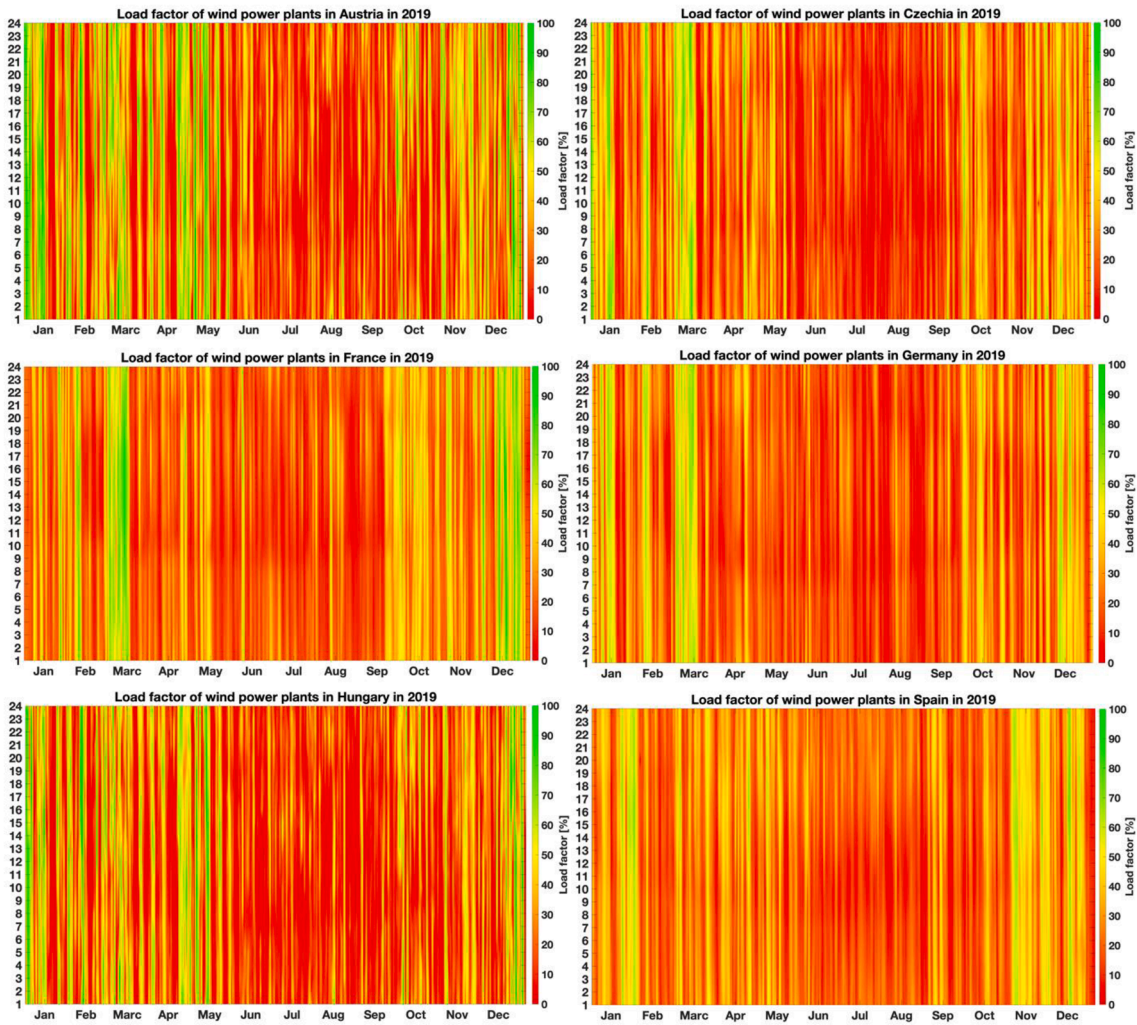


Fig. 16. Visualization of hourly wind power plant load factors for Austria (top left), Czech Republic (top right), France (middle left), Germany (middle right), Hungary (bottom left) and Spain (bottom right) in year 2019 (data source [4], own illustration).

Climate Plans and in the ENTSO-E database [4] are not sufficiently accurate to predict the implementation of the European Green Deal with the necessary precision. In order to provide the technical foundations for the European Green Deal and the technical analysis of future electricity systems, it will be critical to remedy the data gaps described in Appendix B so that experts can provide the most accurate analysis to assist decision-makers. As a result, a more sustainable, greener European electricity system could be achieved while maintaining a high level of security of supply. We believe that the refinement of data and energy strategies is essential for the proper analysis and implementation of such an ambitious and important plan.

Results of the analysis

In the work presented in this paper, our methodology was therefore as follows. Starting from the sources described in Chapter 4, we have compiled a summary of the current electricity supply situation in the 19 countries studied. We have identified the electricity consumption and power plant portfolios projected in official government energy strategies for 2030 and 2040. The data we synthesized and used for the simulations

are summarized in Chapter 5 of the paper. On the basis of these data, model calculations for each country were carried out using the International Atomic Energy Agency's ESST programme. The methods and assumptions of the calculations are described in Chapter 4. These hourly-resolution calculations, covering the years 2030 and 2040, show whether the power plant portfolios planned by each country could be able to meet projected future electricity demand, considering the hourly-resolution variation in demand over the year.

The simulation is also used to answer the question of whether, if a country's power fleet would not be able to meet current electricity demand at a given hour, the weather-dependent renewable energy sources available at the same time in the other countries under study could be able to cover the shortfall. This calculation does not take into account the fact that cross-border capacity between countries is in fact limited. We also do not take into account grid losses and the extent and technical characteristics of the primary, secondary and tertiary power reserves needed to keep the electricity system within the required stable technical conditions. The maintenance outages of the power plants are also neglected in the calculations. The use of the results of the hourly resolution simulations presented here can be very wide-ranging, both at

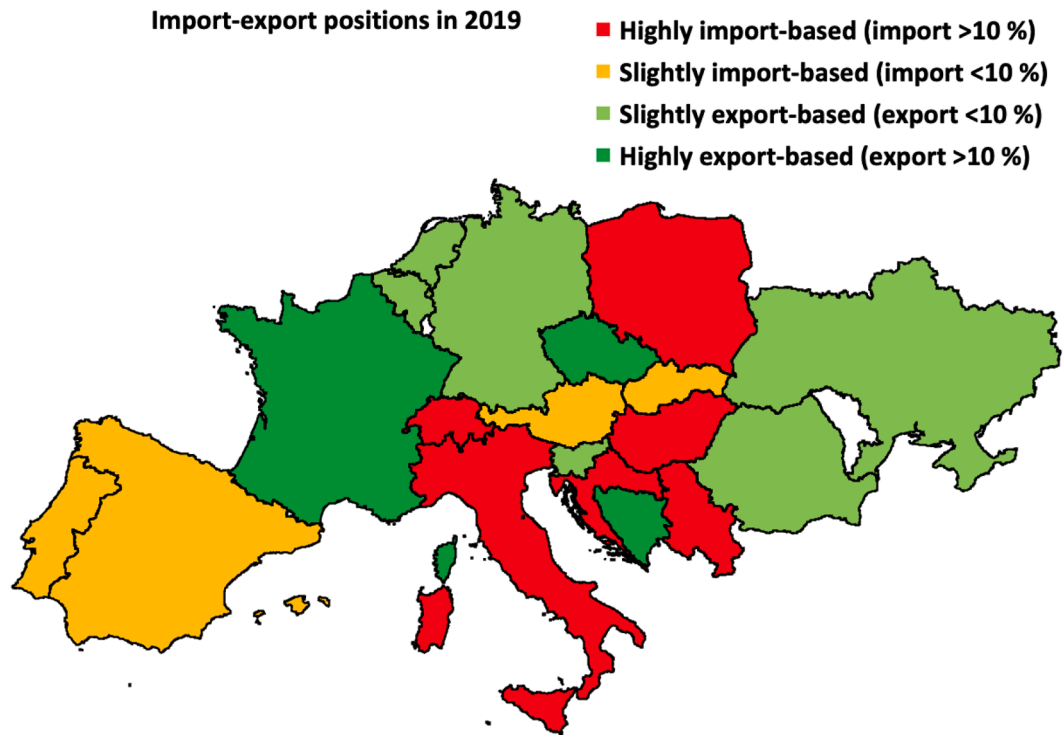


Fig. 17. Import-export positions in 2019 (data source [4], own illustration).

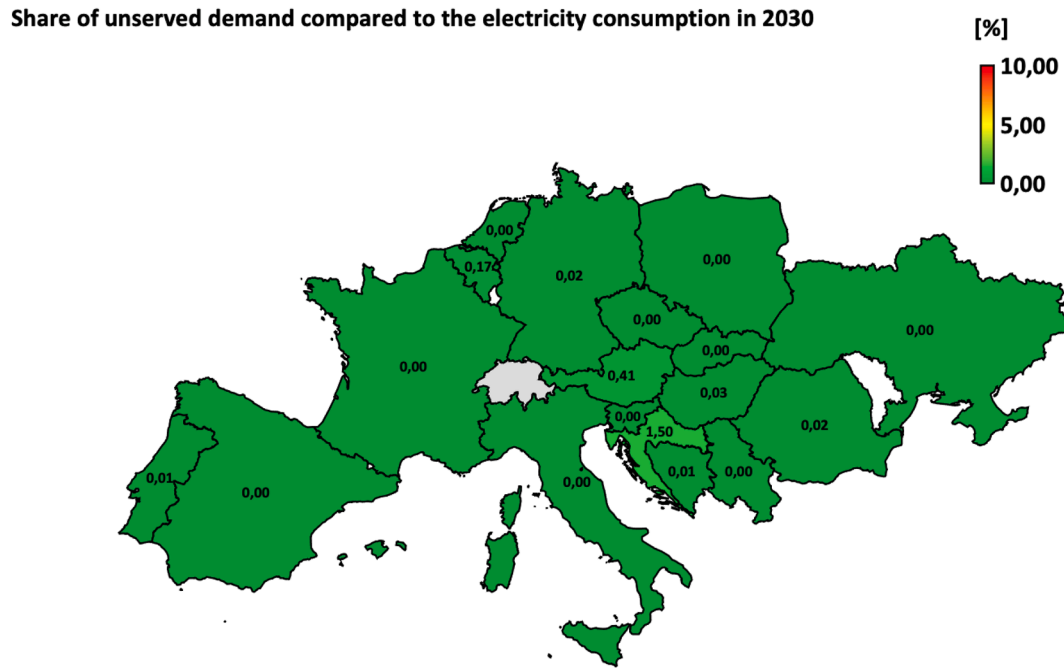


Fig. 18. Unserved demand in 2030.

national and regional level. In addition to verifying the adequacy of the power plant portfolios planned by individual governments, the calculations will also provide answers to the question of the extent to which the targets for reducing carbon dioxide emissions appear achievable and whether the level of carbon neutral generation will reach the level that countries have planned.

Unserved demand in the individual countries

Over the past 70 years in Europe, we have become accustomed to a continuous supply of electricity. The construction of power plants in the 1970 s and 1980 s in most of the countries under review has resulted in a power plant park and electricity network that, with significant reserve capacity and a high level of operation and maintenance, is able to meet

Share of unserved demand compared to the electricity consumption in 2040

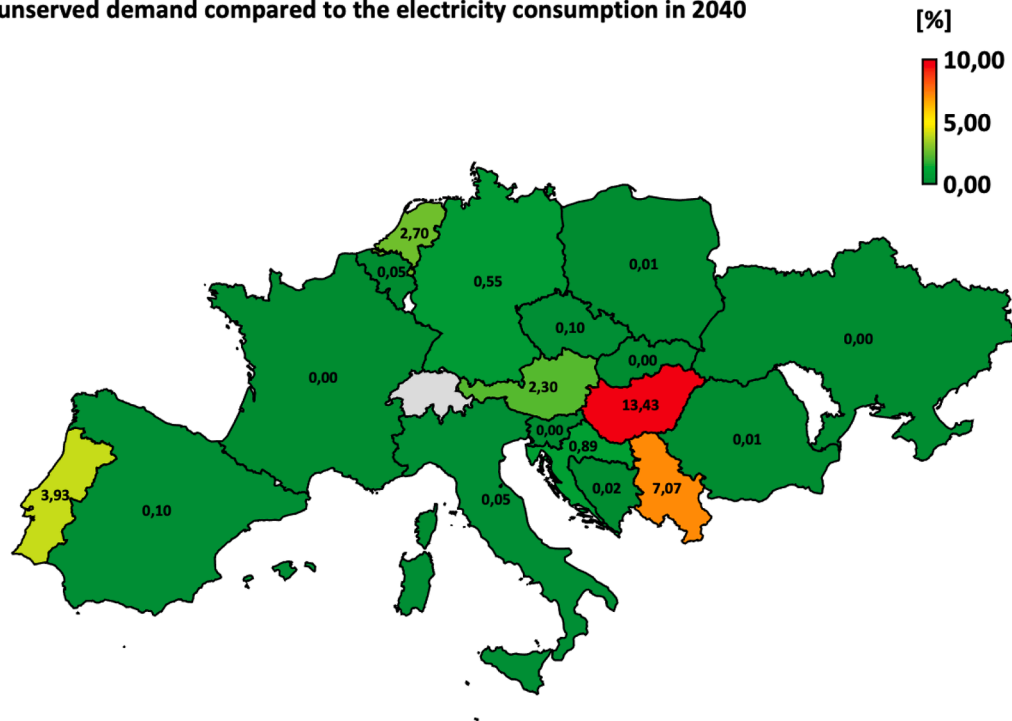


Fig. 19. Unserved demand in 2040.

the electricity needs of European consumers with a high level of reliability, 365 days a year, 24 h a day. However, with the large-scale expansion of weather-dependent energy sources and the retirement of dispatchable power plants, we believe that this situation could change if the system is not developed with the necessary caution. Calculation results supporting this statement are presented in this chapter.

First, we analyzed which of the 19 countries are in an export or import position, i.e. how the annual electricity import and export balances in each country evolved. In addition to the export and import position, we also assessed whether this was less or more than 10% of annual electricity consumption. The results are summarized in Fig. 17.

In Fig. 17, six countries fall into the red category, with electricity imports exceeding 10% of electricity consumption in 2019. Among these countries, Croatia (34.1 %) and Hungary (27.6 %) are worth highlighting as they have a very high import share, so it is particularly important to pay attention to whether the plans in these countries will result in a viable system in 2030 and 2040. Also of particular interest are the 3 countries in the dark green category (Bosnia and Herzegovina, Czech Republic and France). These countries are currently in a strong export position, the question is whether future development plans will change this.

Figs. 18 and 19 summarize the percentage of total annual electricity consumption in 2030 and 2040 that would not be met alone by the country's planned own power plant fleet. It should be underlined here that the ESST model used for the present studies describes countries individually and does not take into account the cross-border capacities between them. The results presented here highlight the countries which, with the power plant portfolios planned in their National Energy and Climate Plans, are not expected to be able to meet their electricity needs in 2030 and 2040. The graphs also provide indications of how the current export–import positions might change in the future.

Fig. 18 shows that the situation is relatively consolidated in 2030: although small amounts of unserved electricity demand appear in Portugal, Belgium, Germany, Austria, Hungary and Romania, only Croatia, which is currently still highly import-exposed, has unserved demand of more than 1% of the annual demand. Hungary does not show an unserved demand in 2030, given that it is planned to have 4,400 MW of nuclear capacity available by then, instead of 2,000 MW in 2019. It is worth noting that Germany exported a relatively smaller amount of electricity in 2019 (significant in absolute terms due to the size of the country, of course), but the 2030 figures show a small unserved demand, suggesting that Germany could move from its current net exporter position to a net importer position by 2030.

However, the situation is projected to substantially deteriorate by 2040 in the countries studied. It is worth comparing the change in colouring in Fig. 19 with Fig. 18, which clearly shows the countries that will be in a much worse position by 2040. Unserved demand is higher than 1% in Portugal, the Netherlands, Austria, Croatia, Serbia and Hungary. Hungary and Serbia have the highest share of unserved electricity due to the reduction of installed capacity of nuclear, coal and gas-fired power plants in the former and coal-fired power plants in the latter. A small share of <1% of unserved demand is foreseen for Spain, Belgium, Italy, the Czech Republic, Bosnia and Herzegovina, Poland and Romania. In 2040, there will be only three countries (Slovakia, Slovenia and Ukraine) where no unserved demand occurs in a single hour.

The calculation results summarized in Fig. 19 are particularly worrying because the official energy strategy of many countries (e.g. our country, Hungary) assumes that the electricity demand that cannot be met by domestic power plants will be covered by imports. But it is questionable whether, if only three of the 19 countries examined are left that are capable of self-supply, what guarantees are there that electricity will be available for import on the international market for those that are

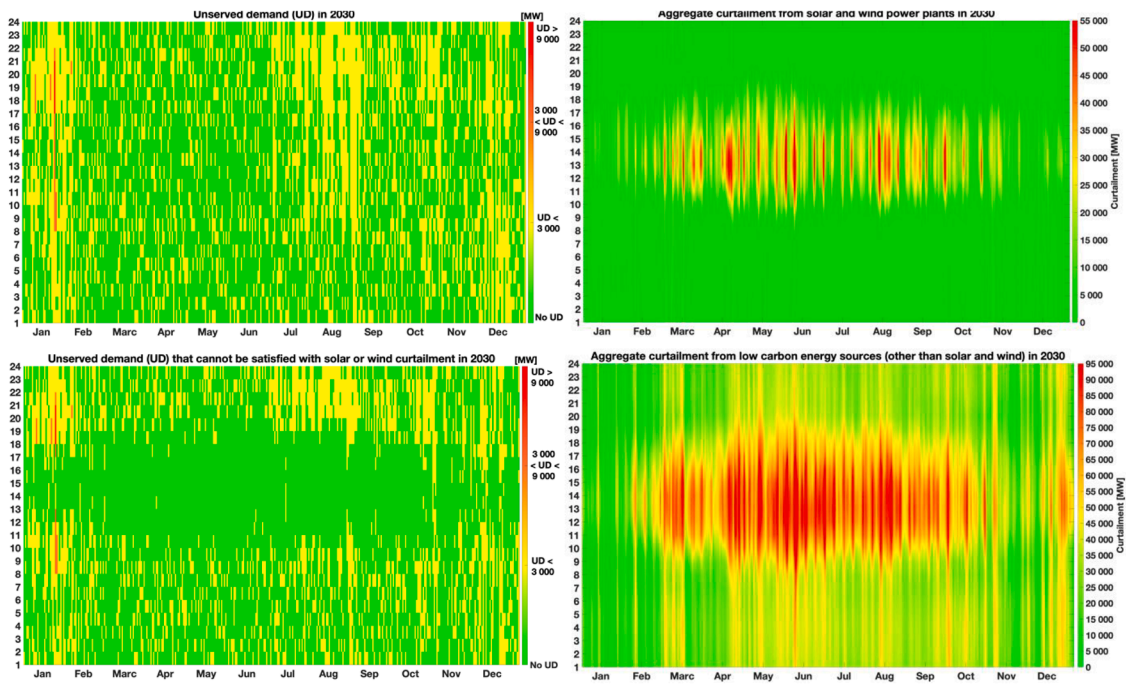


Fig. 20. Categorized unserved demand (top left), system-wide overproduction (curtailment) from solar and wind power plants (top right), unserved demand without solar and wind curtailment (bottom left) and system-wide overproduction from carbon free energy sources (bottom right) (except solar and wind) in 2030.

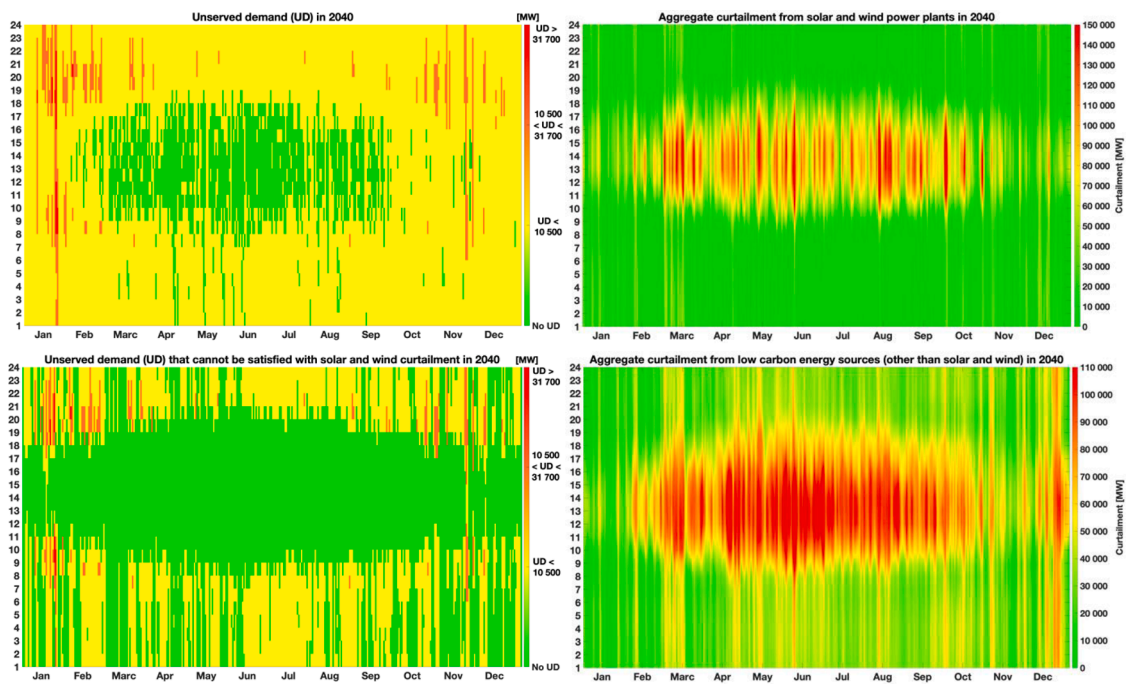


Fig. 21. Categorized unserved demand (top left), system-wide overproduction from solar and wind power plants (top right), unserved demand without solar and wind curtailment (bottom left) and system-wide overproduction from carbon free energy sources (bottom right) (except solar and wind) in 2040.

unable to supply themselves.

In our view, the energy strategies of many countries do not take sufficient account of external conditions and are therefore not feasible in their current form, thus do not guarantee the technical conditions for continuity of supply, including security of supply requirements. It

should also be stressed here that the calculations do not even take into account the requirements for the necessary level of primary, secondary and tertiary reserves, and are therefore not conservative. The incorporation of these aspects into the models would draw attention to even more technical problems.

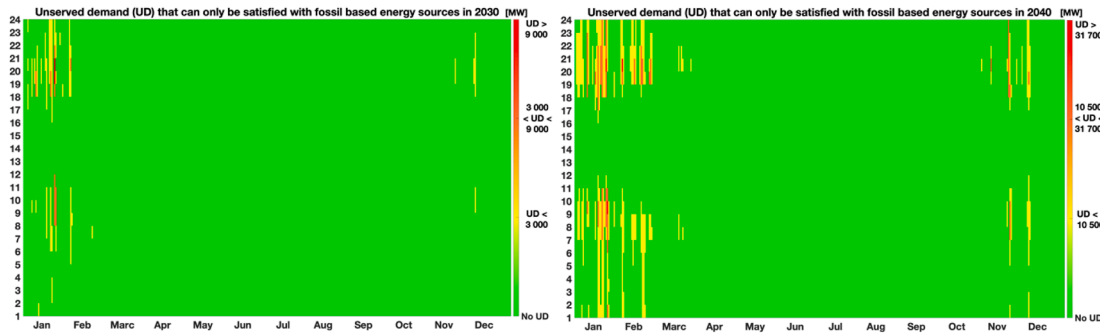


Fig. 22. Unserved demand which can only be satisfied with fossil-based electricity in 2030 (left) and in 2040 (right).

Unserved demand in a highly integrated grid

In the previous part of our study, we have shown that most of the countries under investigation are planning to replace their fossil capacity with solar and wind capacity. In some countries, these developments are such that the planned weather-dependent intermittent installed capacity would significantly exceed peak electricity demand. In this sub-section, we examine whether, if the unserved demand in each country is summarized on an hourly basis, it can be met by the excess electricity generation from solar, wind and other carbon neutral sources that is occurring in other European countries at that particular hour.

Unserved demand in 2030

Fig. 20 shows four related plots for which we have used the so-called “fishbone” illustration method presented earlier. In the top left corner, we have plotted the total unserved energy by hour for each country using four categories to colour the small rectangles representing each hour of the year. Green indicates the hours for which there was no unserved demand in any country. Yellow indicates hours where the total unserved demand was below 3000 MW. Orange indicates the system states with unserved demand between 3000 MW and 9000 MW while red indicates those above 9000 MW. The upper right graph shows the hours when in some countries it was necessary to decrease the power of solar and/or wind power plants artificially because their aggregated current output exceeded the electricity demand of the country in that hour. The bottom left of Fig. 20 shows the hours when the unserved electricity in countries cannot be covered by the excess solar and/or wind power in other countries in the same hour (curtailment). And the bottom right image summarizes the hours of the year and the MW of curtailment needed from other carbon neutral sources (hydro, nuclear, geothermal, biomass, waste) other than solar and wind. In Chapter 7.3.3, the categorized values of unserved electricity that can only be met by fossil energy are shown separately in Fig. 22.

Based on the results of our model calculations, in 2030, the modelled countries had a total of 0.78 TWh of unserved electricity with a maximum power demand of 11 942 MW. The upper left graph in Fig. 20 shows that this 0.78 TWh is scattered over the year. The highest values occur in the winter months, but the highest continuous period is in July–August.

On the other hand, in addition to the electricity that cannot be supplied by carbon neutral means at the level of the 18 modelled countries, there is a solar and wind overproduction (curtailment) of 40.76 TWh in 2030 in the countries studied, with a maximum of 73 208 MW. The top right graph of Fig. 25 shows the hourly distribution of this overproduction, which is mainly concentrated during the day (10 am – 5 pm). During the winter months, such system conditions are hardly visible.

It is not surprising that, assuming the arbitrary export of excess solar and wind energy production in each country to countries where the power system could not meet all demand at the time, this still leaves a total of 0.64 TWh of unsupplied energy in the 18 modelled countries. The data in the bottom left graph of Fig. 20 show that it is mainly during the hours without sunshine that unserved energy remains in the system. The export of surplus generation from other low carbon sources can already cover a large part of the unserved energy (0.49 TWh), but still leaves unserved electricity in the system (please see further discussion in Chapter 7.2.3. related to in Fig. 22).

Unserved demand in 2040

Fig. 21 shows the values of the unserved electricity in 2040, also in four connected diagrams. Based on our modelling results, the total unserved electricity in 2040 in the countries under study was 24.42 TWh with a maximum hourly value of 42 195 MW. (Note that this is a huge value, about six times the peak load in Hungary.) The top left graph in Fig. 21 shows that this 24.42 TWh is no longer intermittent in the course of the year but occurs almost continuously throughout the year except during the sunny hours of March–July. This means that the capacity planned in the national energy strategies for 2040 in the 18 countries modelled is not sufficient to ensure a continuous supply at that time. At the same time, in 2040, 220.48 TWh of surplus generation (curtailment) from solar and wind power will appear in the systems with a maximum of 205 557 MW. The surplus generation is about nine times the total amount of unserved electricity, but its distribution over time is not appropriate.

The diagram in the top right-hand corner of Fig. 21 shows the hourly distribution of this overgeneration which indicates that it is still mainly during sunny hours, but in 2040 there will be system states where wind farms will already show significant amounts of excess generation at night. If we consider that the overproduction in some countries can be exported and contribute to supplying consumers in other countries, we can see in the bottom left diagram of Fig. 21 that there is a lot of unserved demand at night and dawn: the amount of unserved demand is calculated to be around 13.83 TWh in 2040 for the whole system under study. Further details are given on the temporal distribution of unserved demand in Chapter 7.2.3. and in Fig. 22.

Large-scale electricity storage, a highly integrated electricity grid, significant interventions at the consumer side and a revised mix of generation capacities seem necessary to ensure the technical conditions for continuous supply of the consumers.

Main conclusions for unserved demand in 2030 and 2040

According to the calculations presented in subchapters 7.3.1 and 7.3.2, the unserved energy cannot be met by electricity generated from carbon neutral energy sources in 2030 or 2040.

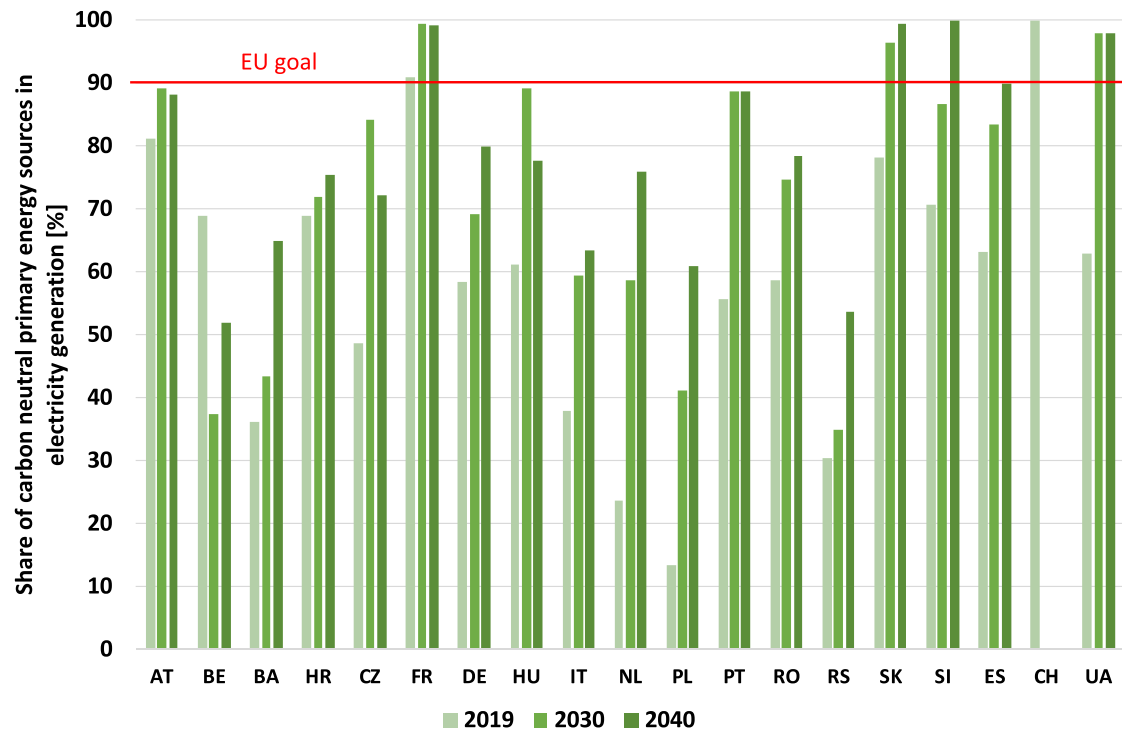


Fig. 23. Share of low carbon primary energy sources in the electricity generation (2019 data source [4], own illustration).

The temporal distribution of the unserved energy remaining in the system over the year is similar in 2030 and 2040, with these system states mainly appearing during the sunless hours of the winter months, as shown in Figs. 20 and 21. Although the temporal distribution of unserved electricity is similar, there is a significant difference between the total amount of unserved energy in 2030 and 2040: while 0.15 TWh of unserved energy remains in 2030, 2.7 TWh of unserved energy was

calculated for the year 2040 in the interconnected system of the 18 countries modelled. The distribution and magnitude of these values over the year are shown in Fig. 22. The problem is due to a reduction in the installed capacity of dispatchable power plants and the replacement of the reduced capacity with weather-dependent plants.

If the abovementioned unserved energy remaining in the system was to be produced by natural gas-fired power plants, we would have to

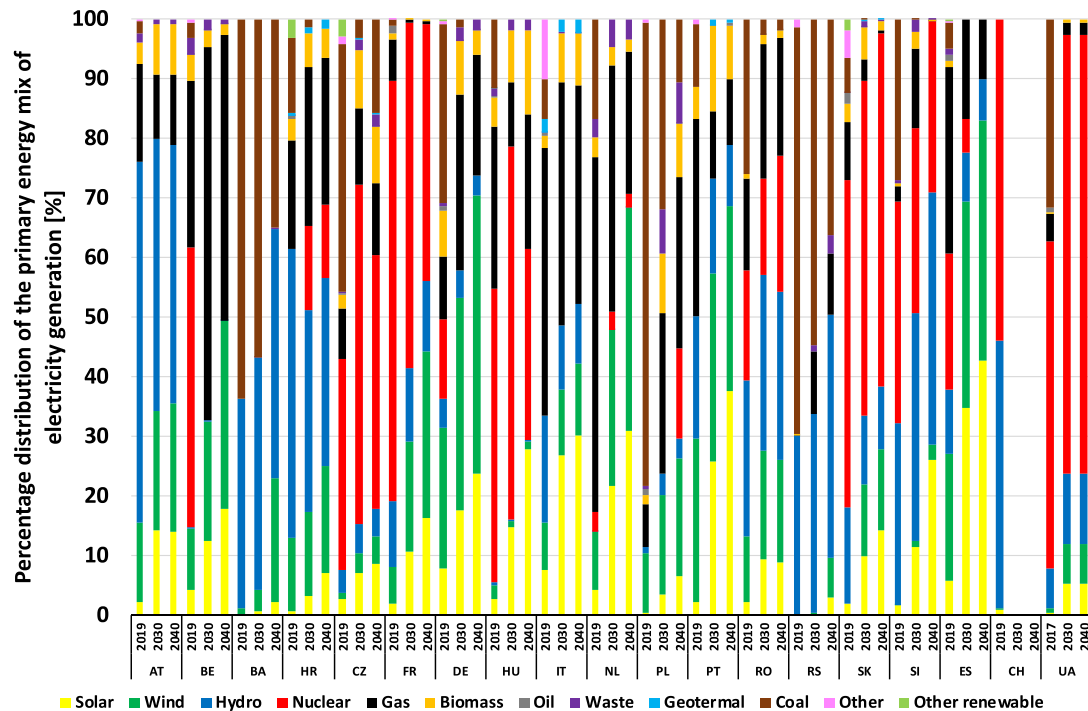


Fig. 24. The primary energy mix of electricity generation in 2019 (factual data) and in the years 2030, 2040 (simulation results) (2019 data source [4], own illustration).

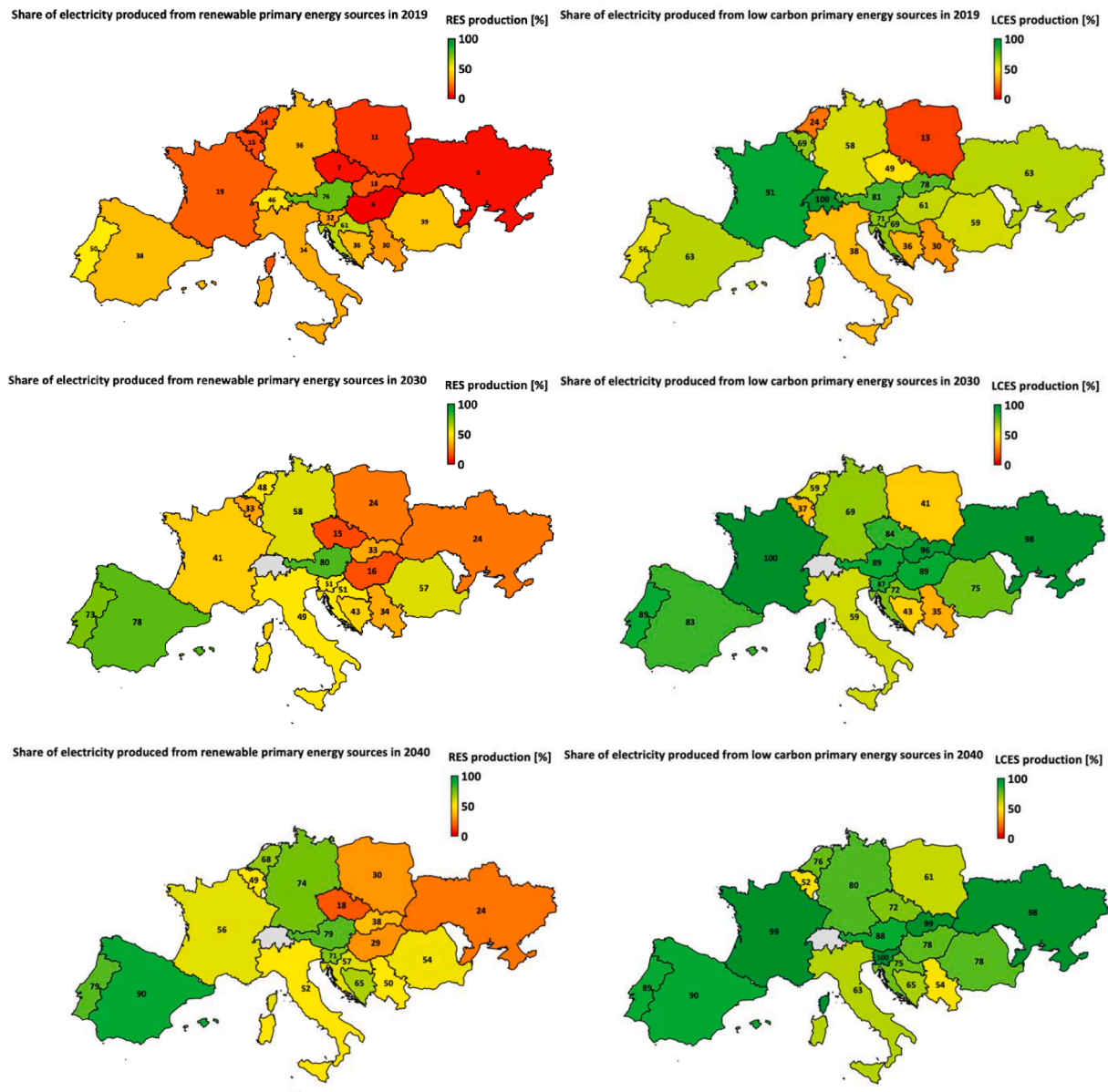


Fig. 25. Share of RES production in 2019 (top left), in 2030 (middle left), in 2040 (bottom left) and Share of LCES production in 2019 (top right), in 2030 (middle right), in 2040 (bottom right) (2019 data source [4], own illustration).

expect 54 387 tons of additional carbon dioxide emissions in 2030 and 984 483 tons in 2040, assuming 370 g/kWh specific CO₂-emissions [38] for natural gas fired power plants.

Regarding the temporal distribution of the problematic periods over the year, it has to be highlighted that based on the data showed in Fig. 22 the four months from November until February seem to be especially challenging.

The figures presented in subchapters 7.3.1 and 7.3.2 show that in both 2030 and 2040, the surplus of weather-dependent energy sources is much higher than the unserved energy. If electricity storage could be used to meet all the unserved energy with previously stored surplus generation from solar and wind power, the model calculations suggest that there would still be 40 TWh and 196 TWh of surplus electricity generated in 2030 and 2040, respectively. (To get a sense of the

magnitude, it is worth noting that the 196 TWh of electricity projected for 2040, generated on a weather-dependent basis and shown to be surplus, is four times the current annual electricity consumption in Hungary, so this is a very large amount.)

These figures clearly show that the solar and wind capacities of the National Energy and Climate Plans are not harmonized among the countries concerned, with the result that, if the energy strategies currently on the table were to be implemented, these plants will produce an extremely large amount of electricity that cannot be used. This is likely to create not only system operation problems but also significant additional costs. Of course, large, grid-scale electricity storage can provide a solution to this problem.

As a summary it can be stated that the main issues are the over-sized weather dependent power plant capacities listed in the national energy

strategy documents, while the development of other infrastructure elements would be also important and necessary to ensure continuous and secure supply. The appropriate design of those additional infrastructure element cannot be found in the National Energy and Climate Plans under study.

Carbon neutrality and the underlying energy sources

The key energy policy motivation behind the transformation of the energy system is to radically reduce the carbon dioxide emissions in our industrialized society. The European objective is to achieve a 90% share of electricity generated from carbon neutral energy sources in each country. This chapter shows how this share of carbon neutral electricity generation evolves for the 18 countries modelled. It also discusses the energy sources that can be used to meet these commitments.

Fig. 23 summarizes the share of carbon neutral energy sources in electricity generation for the years 2019, 2030 and 2040. The figure provides information not only on the feasibility of reaching the 90% carbon neutral target, but also provides a comparison across the countries studied.

There are only two countries in Fig. 23 that have already performed above the 90% target in 2019. These are France (90.9%) and Switzerland (100%), which have been able to achieve such a high share because of their large nuclear and hydropower capacities. (In case of Switzerland, it is worth noting that the country imports a significant amount of electricity, which allows it to avoid fossil fuels in its domestic production, while they still play a role in supply).

In 2030, France, Slovakia and Ukraine are above the 90% target. (Modelling Switzerland for 2030 was not possible due to the data unavailability issues mentioned earlier.) For all three countries, the large nuclear generation capacity and significant hydro power generation are the dominant factors. However, as can be seen in Fig. 24, France is already planning to have 10% solar and close to 20% wind-based generation in 2030, while Slovakia is planning to have 10% solar.

Although the situation for carbon-neutral electricity generation improves further by 2040, there are still only 4 countries out of the 18 modelled that meet the 90% target. By 2040, Slovenia, along with France, the Czech Republic and Ukraine, falls above the red line in Fig. 23, due to its plans to expand its nuclear generation capacity in the 2030 s.

It is important to highlight Austria, Portugal and Spain in Fig. 23, as these countries do not reach the 90% target, but are close to it. Austria and Portugal do not use nuclear power today, and Spain plans to phase out nuclear power by 2040. As summarized in Fig. 24, Austria plans to develop solar and wind power in addition to its existing large hydro capacity, and to replace dispatchable fossil capacities with biomass. Portugal and Spain are planning to exploit their outstanding solar and wind potential to replace fossil fuels, which currently play a dominant role in generation.

We can't overlook Belgium's data, which is the only country where the share of carbon neutral energy sources in domestic production is projected to decrease in 2030 (37%) and 2040 (52%) compared to 2019 (69%). This is clearly since the country's National Energy and Climate Plan targets the phase-out of nuclear power capacities by 2030, but this large amount of electricity from carbon neutral sources cannot be fully replaced by solar and wind power, so natural gas-fired power plants will play a higher role in 2030 and 2040 than they did in 2019.

A similar phenomenon can be observed between 2030 and 2040 in Hungary. Here the share of carbon neutral energy sources in generation will decrease from 89% in 2030 to 77.6% in 2040. The reason for this is that according to the actual plans, in 2030 s the existing Generation 2 nuclear units (that came on line in the 1980 s) and the new Generation

3 + nuclear units (which are currently under licensing) will still be in operation parallel, while by 2040 the old nuclear units will be already shut-down.

A summary of Figs. 23 and 24 shows that there are essentially three different pathways for European countries to achieve their carbon neutral electricity generation commitments:

- operating significant nuclear capacity alongside solar and wind capacity (see France, Slovakia, Slovenia, Hungary and Ukraine)
- hydropower is given a high role alongside solar and wind capacity (see Austria)
- the country has a very high solar and wind energy potential, complemented by hydropower and/or biomass (see Portugal and Spain).

Our analysis suggests that countries that cannot or do not want to take any of the above three pathways will fall far short of the 90% carbon neutral electricity generation target.

Summarizing the data for the 18 countries modelled, it can be seen that while the share of carbon neutral energy sources in electricity generation is 61.3% in 2019, it will rise to 74.9% by 2030, and further increase to 80.7% by 2040. For the modelled countries, this is very far from the European target of 90% carbon neutrality. This also means that the 18 modelled countries as a whole are very far from achieving the targets set by the European Commission in its 'fit for 55' plan, and these plans do not appear to be sufficient from a security of supply perspective, as summarized in chapter 7.2. In our view, solving the problems outlined here will require significant new efforts from governments preparing National Energy and Climate Plans.

Further geo- and energy policy conclusions of the calculations

Based on the results of the simulations, further geopolitical and energy policy conclusions can be drawn. In Fig. 25 the share of Renewable Energy Sources (RES) and Low Carbon Energy Sources (LCES) by year 2019, 2030 and 2040.

According to the 2019 data, the role of RES in Central European countries is smaller than in Germany, Italy or Spain, while France, Belgium and the Netherlands are not considered to be prominent in terms of current RES use. If other carbon-neutral technologies (nuclear, biomass) are added, the situation improves significantly in many countries, especially in the axis France, Switzerland, Austria, Slovakia, but also positively in Hungary, Romania and Ukraine.

A significant "greening" of the whole region is foreseen by 2030 and 2040, but while Western European countries focus mainly on RES capacity development, Central Europe aims to achieve its targets through a combination of RES and an increase in the role of nuclear and biomass. The maps in Figure 30 show that Germany cannot reach the 90% carbon neutrality target with its current energy strategy, while France, Spain and Portugal seem to be able to meet their objective. Belgium, the Netherlands, Italy, Poland, the Czech Republic and the Balkan countries are also far from the 90% target in 2040.

On the other hand, it has to be pointed out that the nuclear phase-out causes significant challenges in the affected countries. According to the simulations the actual Belgian nuclear production (43.5 TWh in year 2019) will be substituted mainly not by green energy sources but rather with natural gas: its current 25.7 TWh/year is assumed to increase to 58.4 TWh in year 2030 and change to 44.9 TWh in year 2040. In Germany this issue is even more pronounced: shutting down the German nuclear fleet will clear-away 71 TWh/year carbon free electricity while increasing carbon emitting natural gas production from 54.6 TWh/year to 153 TWh in year 2030 and 109 TWh in 2040.

The increasing role of natural gas is clearly seen also in the

simulation data for many other countries, e.g. in Austria, Croatia, Hungary, Italy, Poland, Romania and Serbia. (For more detailed data please see Table 3 in Appendix C.) The use of natural gas emits definitely less CO₂ than burning coal, but still natural gas is far away from being carbon neutral. The fact that the analyzed European countries rely heavily on gas imports poses additional constraints.

Also, the increasing role of biomass can be evidently seen among others in Austria, Czech Republic, Hungary, Italy, Poland and Portugal, while Germany plans to decrease the use of biomass in course of time.

Technical feasibility

After the presentation of the input data, simulation method and the results on RES and LCES development the question evidently arises, how the conventional power plants could perform and function within an electricity system with a high weather dependent power plant penetration. In this last chapter presenting the hourly resolution ESST simulation results, we discuss the share of each primary energy sources in the electricity supply and their capacity factors for the years 2019, 2030 and 2040. The annual production of the individual primary energy sources and the annual load factors for the year 2019 as factual data and for the years 2030, 2040 as results of the ESST simulations is summarized in Table 3 and Table 4, respectively (please see Table 3 and Table 4 in Appendix C).

By looking at Tables 3 and 4, we just invite the reader to assess the countries and energy sources in which he or she has a particular interest. Here we draw attention to some of the more significant or extreme data, processes or phenomenon.

First of all, it should be pointed out that the effect of coal phase-out is clearly visible in the tables. As a result of this major energy policy decision, coal-fired power generation in most countries will fall to zero by 2030. An exception is Poland, where the calculations show a need for 64 TWh of coal-fired power in 2030 and 24 TWh in 2040, but with a 31% and 20% utilization factor, respectively, which makes it economically challenging for these plants. In Serbia, 15 TWh/year of the current 23 TWh/year could remain by 2040.

The utilization factor of waste-fired power plants is high in most countries, but in Slovakia and Slovenia it drops below 10% by 2040, which does not seem economically feasible.

The utilization factor of gas-fired power plants in some countries (e.g. France, Slovakia, Slovenia, Ukraine) is very low, below 10%, which also raises economic issues and the question of the market viability of operating these plants.

The situation for nuclear power plants (NPPs) varies from country to country: while in most of the countries NPPs have high annual utilization factors of over 80% or even 90%, for some countries simulations show high utilization of planned nuclear capacity being challenging. This is the case in France, where nuclear plants' utilization could fall from over 70% today to below 60% by 2030 and below 50% by 2040. In Slovakia, the current level of over 90% is still typical for nuclear power plants in 2030, but the analysis shows a decrease to 72% by 2040. In Slovenia, the situation is similar, with the current 90% figure falling to 36% in 2040 if the developments are implemented as foreseen in the strategy. Spain and the Netherlands also show drastic reductions. As nuclear power plants are CO₂-free and low variable cost baseload generators, replacing them with flexible but fossil-based plants would in any case increase the greenhouse gas emissions of the European electricity system. Preserving the role of nuclear power plants in Europe's energy policy is key in meeting climate protection, sustainability and security of supply objectives.

Summary

In this article, we have collected information on the development pathways for the electricity sector in 19 continental European countries (Austria, Belgium, Bosnia and Herzegovina, Croatia, Czech Republic,

France, Germany, Hungary, Italy, Netherlands, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Switzerland and Ukraine). Considering projected consumption scenarios and planned power plant portfolios, hourly resolution simulation models have been developed and used to assess the expected electricity supply situation for year 2030 and 2040, using 2019 factual data as baseline.

Taking into account the predefined dispatch order of the power plants, simulations were used to calculate how the hourly electricity demand for 8760 h of the year can be covered. We also determined the number of system states where the capacity to supply the electricity needed in each country would not be sufficient, or where there would be an overgeneration of weather-dependent renewables. We have also determined the hourly and annual production data for all primary energy sources in each of the countries studied.

After the analysis of each country, and assuming quasi-infinite cross border capacities between all modelled countries, we examined whether the potential overgeneration of each country's renewable sources could be used to meet the electricity demand of another country during the same hour that could not be met from carbon neutral sources at home.

No grid losses were taken into account in the simulations. The primary, secondary and tertiary reserves necessary for the reliable operation of the electricity system are not taken into account in the models. The technical constraints on power plant load following are not considered, although these constraints are not taken into account in the energy strategies either. Similarly, the time required for maintenance and the schedule of maintenance of dispatchable power plants have not been modelled. These simplifications are not conservative approximations of the amount of capacity required, so taking them into account would in fact lead to even higher capacity requirements or more unserved electricity. This also means that the future electricity system will need more dispatchable capacity and more flexibility compared to the figures presented here.

In our view, meeting the European Commission's climate objectives is not possible under the boundary conditions of the countries' currently published National Energy and Climate Plans, considering also security of supply objectives. Another problem is that Member States do not seem to have taken into account in their plans the limits of the export-import potential of the interconnected European electricity system.

In compiling the input data for our models, we not only looked at the energy strategy documents of the countries under study, but also collected and processed a large amount of data from the ENTSO-E public database. In doing so, we found that there were many discrepancies, inaccuracies and erroneous data in the database collected and made publicly available by ENTSO-E. We are very grateful to the ENTSO-E experts for responding to our many enquiries and correcting many of the errors that have been detected. On the other hand, it would be necessary to push countries to provide more accurate data to ENTSO-E. In our view the future of the European electricity system is of such great importance that these databases should not have so many errors. Having more accurate data on the past system states could lead to more precise models and simulations for the future.

We found the case of Switzerland particularly problematic: Switzerland would need accurate, hourly-resolution data on its pumped storage power plants to be able to model the country in the same way as the other countries studied, but these data are not publicly available in the ENTSO-E database. It is noted that, due to the central location of Switzerland and its large pumped storage capacity, it would be key for modelling the whole European system to have at least hourly resolution data on charging and discharging of pumped storage hydro power plants (separated from run-of-river hydro power plants) transparently available for scientific investigations. Failing to do so will also significantly distort modelling at European level.

We found interesting the data from the Spanish concentrated solar power plant, which also produces solar energy at night. This is physically correct, as they produce electricity at night from thermal energy stored during the day, so the night solar feed-in is real, but for future

modeling purposes, it should be shown separately in the ENTSO-E database as energy from the discharge of the storage tanks. Otherwise, it cannot be well accounted for in the models.

The development of solar PV generators is intense these days. In many countries, their installed capacity is steadily increasing (month by month). In the modelling, the installed solar PV capacity for a given year will therefore not be accurate. A correction would be possible if these data were available for each country on a monthly basis. Accurate measurement would also be needed for electricity supply from solar PV plants and small household-scale roof-top solar plants. There is a need for smart metering across Europe so that the system operator has accurate data on all producers (including prosumers). This would also support modelling to a large extent, so that the uncertainties in calculations resulting from increasing solar PV penetration could be reduced in the future.

Based on the experience gained in building the models and evaluating the simulation results, we plan to continue our work to support the right decisions and to meet European energy, climate and security of supply objectives.

CRediT authorship contribution statement

Attila Aszódi: Conceptualization, Methodology, Investigation, Resources, Data curation, Writing – original draft, Supervision, Project

administration. **Bence Biró:** Conceptualization, Methodology, Software, Investigation, Resources, Data curation, Writing – original draft, Visualization. **László Adorján:** Software, Investigation, Resources, Writing – review & editing. **Ádám Csaba Dobos:** Software, Investigation, Resources, Writing – review & editing. **Gergely Illés:** Software, Investigation, Resources, Writing – review & editing. **Norbert Krisztián Tóth:** Software, Investigation, Resources, Writing – review & editing. **Dávid Zagyi:** Software, Investigation, Resources, Writing – review & editing. **Zalán Tas Zsiborás:** Software, Investigation, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. – Summary list of national energy strategy documents

Table 2

Table 2
The summary list of national energy strategy documents used as data sources to build the simulation models.

Country		Institution issuing the referenced energy policy document	Title of the energy policy document containing the data used	Year of publication	Ref.
Austria	AT	Federal Ministry of Sustainability and Tourism	Integrated National Energy and Climate Plan for Austria	2019	[13]
Belgium	BE	Coordination Committee for International Environmental Policy, National Climate Commission	Belgian Integrated National Energy and Climate Plan 2021–2030	2019	[14]
Bosnia and Herzegovina	BA	SEERMAP: South East Europe Electricity Roadmap	Country report: Bosnia and Herzegovina 2017	2017	[15]
Croatia	HR	Ministry of Environment and Energy	Integrated National Energy and Climate Plan for the Republic of Croatia for the period 2021–2030	2019	[16]
Czech Republic	CZ	Ministry of Industry and Trade, Ministry of the Environment	National Energy and Climate Plan of the Czech Republic	2019	[17]
		Czech Transmission System Operator	Assessment of generation adequacy of the CR electricity system until 2030	2017	[18]
France	FR	Government of France	Integrated National Energy and Climate Plan for France	2020	[19]
Germany	DE	Federal Government of Germany	Integrated National Energy and Climate Plan	2019	[20]
Hungary	HU	Ministry of Innovation and Technology	National Energy and Climate Plan	2020	[21]
Italy	IT	Ministry of Economic Development, Ministry of the Environment and protection of Natural Resources and the Sea, Ministry of Infrastructure and Transport	Integrated National Energy and Climate Plan	2019	[22]
		Cassa Depositi e Prestiti	The energy transition in Italy and the role of the gas and power sectors	2019	[23]
Netherlands	NL	Ministry of Economic Affairs and Climate Policy	Integrated National Energy and Climate Plan 2021–2030	2019	[24]
Poland	PL	Ministry of National Assets	The National Energy and Climate Plan for 2021–2030	2019	[25]
Portugal	PT	Ministry of Environment and Energy Transition	Roadmap for carbon neutrality 2050	2019	[26]
Romania	RO	Ministry of Economy, Energy and Business Environment	The 2021–2030 Integrated National Energy and Climate Plan	2020	[27]
Serbia	RS	SEERMAP: South East Europe Electricity Roadmap	Country report: Serbia 2017	2017	[28]
Slovakia	SK	Ministry of Economy	Integrated National Energy and Climate Plan for 2021 to 2030	2019	[29]
		Donato de Rosa, The World Bank: Macroeconomics, Trade and Investment Global Practice	A Low-Carbon Growth Study for Slovakia: Implementing the EU 2030 Climate and Energy Policy Framework	2019	[30]
Slovenia	SI	Republic of Slovenia	Integrated National Energy and Climate Plan of the Republic of Slovenia	2020	[31]
Spain	ES	Ministry for Ecological Transition and Demographic Challenge	Integrated National Energy and Climate Plan 2021–2030	2020	[32]
		Ministry for Ecological Transition and Demographic Challenge	Estrategia de Descarbonización a Largo Plazo 2050 - Anexos	2020	[33]
Switzerland	CH	Federal Department of the Environment, Transport, Energy and Communications	The energy perspectives for Switzerland until 2050	2012	[34]
Ukraine	UA	KPMG International	Renewables in Ukraine	2019	[35]

Appendix B. – List of the main difficulties encountered during the data collection and model set-up

Belgium, France and the Netherlands

- The countries' National Energy and Climate Plans [14,19,24] did not provide projected future electricity consumption, only primary energy consumption, without details of how much of this would be used for electricity consumption. Since we did not have annual electricity consumption data for 2030 and 2040 for these countries, we assumed that electricity consumption would increase by 2030 compared to 2019 at the rate predicted by the countries' National Energy and Climate Plans [14,19,24] for primary energy resources between 2019 and 2030.
- In the National Energy and Climate Plans [14,19,24], none of the countries (BE, FR, NL) had a numerically given power plant portfolio for 2040, only for 2030. Thus, the installed capacity based on each energy source in the 2040 power plant portfolio was generated by interpolation using 2019 and 2030 values, except for nuclear power plant capacities, where we used other sources [39,40].

Belgium

- The National Energy and Climate Plan [14] did not quantify pumped storage capacity, even though the country had 1 300 MW of such capacity in 2019. Thus, in the hourly input data, only the consumption of pumped storage plants has been included in the country's consumption data series as described in Chapter 4, but the hydroelectric power generation does not include the production potential of pumped storage plants, only that of run-of-river plants. Approximately 200 MW of run-of-river hydro capacity included in the plan [14] was considered as hydropower capacity in the model set-up.

Bosnia and Herzegovina

- On 20.12.2019, between 18:00 and 19:00, the wind power generation (90 MW in ENTSO-E data at that hour) exceeds the installed wind power capacity (87 MW nominal). This discrepancy would be a problem for the hourly specific input data of the wind farms, as this would lead to a system state where the instantaneous utilization factor of the wind farms would be above 100 %, which is in principle not possible. These data were corrected by ENTSO-E in response to our enquiry.
- The data of 15.06.2019 23:00–0:00 are completely missing from ENTSO-E's dataset [4]. ENTSO-E has sent a correction of these data upon our request.
- Several hours had zero or very low (some 10 MW) system loads in 2019. These have been replaced with estimated expected electricity consumption values based on data from adjacent hours.
- The hourly specific input data for solar PV were taken from the solar PV data for Croatia, as the installed capacity of solar PV in Bosnia and Herzegovina in 2019 was 0 MW, and the expected production of solar PV capacities to be installed in the future was estimated based on this.

Croatia

- The expected annual electricity consumption in 2030 was not included in the Croatian National Energy and Climate Plan [16], only the share of renewable energy sources in electricity production that Croatia would like to achieve and the amount of electricity that each

renewable energy source would produce in 2030. Thus, Croatia's electricity consumption in 2030 was estimated. Electricity consumption in 2040 was calculated based on the growth between 2019 and 2030.

- The necessary input data for the simulations were downloaded from the ENTSO-E database [4] in April 2021. Based on the data at that time, the utilization factor for solar plants in Croatia was found to be low (around 8%), but we accepted this data. In September 2021, while summarizing the simulations, we discovered that the ENTSO-E database [4] had been updated with Croatian solar generation data, which now showed a higher annual utilization factor (around 14%). Due to the data update, the simulations for Croatia had to be repeated, and the simulations for Bosnia and Serbia had to be updated, as these simulations were based on the Croatian data.

Hungary

- Unlike the other countries, we not only had the installed capacity of solar power plants in 2019, but also a monthly breakdown of this data from MAVIR [41] between January 2019 and December 2019. This was key because the installed capacity of solar power plants in Hungary increased from 423.37 MW in January 2019 to 936.15 MW in December 2019, meaning that it has more than doubled within one year. If we had divided the total production data of 8760 h by the installed capacity in December 2019 to get specific production data, we would have obtained a very inaccurate data set for most of the year. Thus, for solar power plants in Hungary, the hourly input data were generated in such a way that the installed capacity changed every month. This allowed more accurate modelling compared to several other countries studied. This modelling approach would have been useful also for other countries, however, the necessary data were not available for other countries.
- We did not find a detailed planned power plant portfolio for 2030 in the country's National Energy and Climate Plan [21], so the 2030 data was derived by interpolating between 2019 and 2040 data. The exception to the interpolation was nuclear power capacity, since, as indicated in the plan, in 2030, existing nuclear power plants (2 000 MW) and two new nuclear power units under preparation currently (2 400 MW) will operate in parallel in Hungary.

Italy

- The country's National Energy and Climate Plan [22] only had data until 2030, the input data for 2040 were taken from the study [23], from which data for the decentralized (DEC) scenario were used.
- According to ENTSO-E data [4], the installed capacity of solar PV plants in Italy in 2019 was 4717 MW. If this installed capacity was used to calculate specific hourly production data, several values were obtained where the utilization factor of Italian solar PV plants was higher than 100% in 2019, which is in principle not possible. This is due to the fact that the installed capacity of solar plants does not include the capacity of small plants (<1 MW), but their production is included in the production data series. To overcome this error, we have identified the maximum of the production dataset and taken this as the installed capacity of solar plants in 2019 and used this to produce hourly resolution specific production input values.

Netherlands

- Hourly renewable production data were incomplete in the ENTSO-E datasets [4], as hydro generation was a constant zero and solar generation was very low, mostly zero (their productions was given

typically in winter). Thus, for the Dutch simulations, the hourly specific utilization factor data of the Belgian hydro and solar plants were used.

Poland

- ENTSO-E data series [4] do not include electricity generated by solar PV power plants. To solve this problem, the German hourly specific solar PV data were used to build the Polish model.
- There were also shortcomings in the pumped storage capacities. The 2019 ENTSO-E dataset [4] does not contain consumption values for the pumped storage hydro capacities, only production data, so neither consumption nor production of pumped storage capacities were taken into account in the construction of the consumption and hydroelectric production hourly data of the Polish model.

Portugal

- Only data for 2030 were available in the National Energy and Climate Plan [42], so the models were based on the so called “Yellow Jersey scenario” of the National Long-Term Strategy [26].
- For Portugal, the maximum solar generation in 2019 was 517 MW, which is higher than the 2019 installed solar capacity (324 MW) in the ENTSO-E database [4], resulting in a utilization factor higher than 100%, which is not viable. To resolve this, we took the installed capacity of Portuguese solar plants in 2019 as 517 MW and used this capacity to form the specific hourly input data series, which was then used to build the Portuguese model.

Romania

- In the ENTSO-E data series [4], production by energy source cannot be displayed for 2019 because Romania has switched from hourly to quarterly resolution data. The 2019 data for the simulation was retrieved via API [43]. Additionally, one summer hour’s production data was missing, which was replaced in the model with the average of the hours before and after the hour in question.

Serbia

- In the case of Serbia, an interesting phenomenon is that they theoretically have 398 MW of wind power capacity, but in the ENTSO-E production data series [4] these are not reported, only a “N/A” error message can be found by the wind production hourly data.
- Like in case of Bosnia and Herzegovina, Serbia did not have any solar capacity in 2019, so naturally there is no hourly solar production data in the ENTSO-E database [4] for the country. To overcome these problems, both solar and wind hourly specific data for Croatia were used to build the Serbian model.

Slovakia

- In the ENTSO-E data series [4] containing the production data of Slovak solar power plants, there are several occasions when night production appears, which are comparable to day production and therefore difficult to be filtered. For example, between 08.08.2019 and 09.08.2019, 140 MW of night production is shown. This is the most extreme value we found, but besides this we found values between 1 and 140 MW of night-time solar generation, which is not physically possible.
- The hourly data for wind power generation are not suitable for producing accurate specific hourly data due to the very small

installed capacity. To eliminate these errors, the Hungarian 2019 specific hourly data for Slovakia were used for both solar PV and wind power.

Slovenia

- The ENTSO-E database [4] on Slovenia’s electricity production by energy carrier is lacking many hourly data (several fields marked with “N/A” are in the database). The missing data have been replaced either by the same hourly data of the previous day or by the average of the surrounding hourly data.
- The output of solar and wind power plants for a given hour exceeds their installed capacity on several occasions. This problem was solved by reducing the data with a value higher than the installed capacity to the maximum value corresponding to the installed capacity.
- No detailed information on the future power plant portfolio was provided in the National Energy and Climate Plan [31], only a bar chart of the electricity generated from the given fuel type. From this bar chart, the installed capacity of the energy carriers was constructed using the typical utilization factor of the power plant using that energy carrier.
- Electricity consumption in 2040 was not specified in the National Energy and Climate Plan [31], so the expected increase in electricity consumption between 2030 and 2040 was assumed to be the same as between 2019 and 2030.
- The National Energy and Climate Plan [31] included the energy source “synthetic and hydrogen”. The values for this energy source were included in the ESST models under the biomass energy source.

Spain

- Data for 2030 are taken from the “Target Scenario” presented in the National Energy and Climate Plan [32] for 2030 and data for 2040 are taken from the ELP scenario in [33].
- In [33], no detailed power plant portfolio was reported for 2040, only ratios. A linear extrapolation using these ratios and data of installed capacity value in year 2030 was used to obtain the installed capacities defined in the model for 2040.
- The assumed electricity consumption in 2030 is equal to the sum of the consumption assumed in the National Energy and Climate Plan [32] and the consumption of the planned pumped storage power plants.
- Electricity consumption in 2040 has also been determined proportionally from the 2030 value based on the ELP scenario of [33].

Switzerland

- The consumption (electricity used for filling up) of pumped storage hydro capacities for Switzerland is not available in the ENTSO-E database [4], so their consumption could not be included in the consumption input data set. Simulations were performed, however, since the installed capacity of pumped storage plants in Switzerland and the system load of the country are of a comparable magnitude, the consumption data set defined in the model did not represent the consumption data observed in reality. The problems described above introduced so much error into the simulations that the results were considered invalid and are not presented in this paper. Accurate, hourly resolution data for Switzerland’s pumped storage hydro-power plants would be needed to model the country in a similar way to the other countries studied. It is noted that due to Switzerland’s central position and its large pumped storage hydro capacity, it

would be key for the modelling of the whole European system to have all their data available in a transparent way.

Ukraine

- No data other than system load was available for Ukraine on the ENTSO-E platform [4], so the actual capacities were taken from the Statista [44] database.
- Wind and solar are treated as one category in the country's National Energy and Climate Plan [35], therefore the capacity ratio was taken as in the year 2017.

- No data on the hourly profile of renewable production was available, so for Ukraine we used the specific production curves of Romania.
- In Ukraine, we have also included the capacity of Moldova in the generation capacity.
- Within the country, between the systems of Ukraine and Moldova, as well as the transfer capacities between the two electricity grid systems within Ukraine were not taken into account.

Appendix C. – Summary tables of simulation results

Table 3

Yearly electricity production [TWh/year] based on different primary energy sources by country for year 2019 (factual data), 2030 and 2040 (as results of hourly resolution simulations) (2019 data Source [4]).

Country	Year	Solar	Wind	Hydro	Nuclear	Gas	Biomass	Oil	Waste	Geo-thermal	Coal
Austria	2019	1,3	8,0	36,5	0,0	9,9	2,2	0,0	0,9	0,0	1,3
	2030	12,0	16,9	38,6	0,0	9,2	7,2	0,0	0,6	0,0	0,0
	2040	13,0	19,9	40,3	0,0	10,9	7,9	0,0	0,7	0,0	0,0
Belgium	2019	4,0	9,6	0,2	43,5	25,7	4,1	0,0	2,5	0,0	2,5
	2030	11,5	18,8	0,2	0,0	58,4	2,6	0,1	1,7	0,0	0,0
	2040	16,6	29,4	0,2	0,0	44,9	1,6	0,0	0,8	0,0	0,0
Bosnia and Herzegovina	2019	0,0	0,2	5,4	0,0	0,0	0,0	0,0	0,0	0,0	9,7
	2030	0,1	0,6	6,6	0,0	0,0	0,0	0,0	0,0	0,0	9,6
	2040	0,4	4,1	8,2	0,0	0,0	0,0	0,0	0,1	0,0	6,9
Croatia	2019	0,1	1,5	5,8	0,0	2,2	0,4	0,0	0,0	0,1	1,5
	2030	0,6	2,8	6,7	2,8	5,3	1,1	0,0	0,0	0,2	0,3
	2040	1,6	4,0	7,0	2,8	5,5	1,1	0,0	0,0	0,4	0,0
Czech Republic	2019	2,3	0,7	3,1	28,6	6,8	2,0	0,1	0,2	0,0	33,6
	2030	4,4	2,1	3,1	35,3	8,0	6,1	0,0	1,2	0,2	1,9
	2040	5,7	2,9	3,1	28,0	7,8	6,4	0,0	1,3	0,1	10,4
France	2019	11,4	34,6	62,1	399,0	38,2	6,3	6,5	0,0	0,0	6,5
	2030	55,1	96,1	64,5	301,4	2,3	0,6	0,0	0,0	0,0	0,0
	2040	85,1	145,4	61,6	223,1	3,8	1,1	0,0	0,0	0,0	0,0
Germany	2019	41,9	123,8	26,2	71,0	54,6	41,0	4,0	3,5	0,0	159,1
	2030	90,2	183,9	24,1	0,0	153,0	46,5	0,0	12,0	0,0	6,3
	2040	129,0	255,5	18,3	0,0	109,2	23,3	0,2	9,6	0,0	0,0
Hungary	2019	0,9	0,7	0,2	16,3	9,0	1,7	0,0	0,4	0,0	3,9
	2030	8,5	0,7	0,2	36,2	6,2	5,0	0,0	1,0	0,0	0,0
	2040	16,1	0,7	0,2	18,5	12,9	8,2	0,0	1,1	0,0	0,0
Italy	2019	19,1	19,9	45,8	0,0	113,6	5,1	1,0	0,3	5,7	17,1
	2030	91,0	37,8	36,6	0,0	137,7	28,1	0,0	1,0	7,3	0,0
	2040	117,8	47,4	39,0	0,0	142,9	34,0	0,0	0,9	8,8	0,0
Netherlands	2019	5,2	11,5	0,1	3,9	71,2	3,7	0,0	3,8	0,0	20,0
	2030	26,1	31,4	0,0	3,7	49,6	3,5	0,0	5,6	0,0	0,0
	2040	36,1	43,7	0,0	2,6	28,1	2,4	0,0	3,9	0,0	0,0
Poland	2019	0,7	14,6	1,5	0,0	10,6	2,1	1,6	0,6	0,0	114,0
	2030	6,7	33,6	7,6	0,0	54,2	19,9	0,0	15,0	0,0	64,2
	2040	14,9	44,5	7,6	34,1	64,7	20,5	0,0	15,7	0,0	23,8
Portugal	2019	1,1	13,4	10,1	0,0	16,1	2,7	0,0	0,0	0,0	5,2
	2030	14,9	18,1	9,2	0,0	6,5	8,3	0,0	0,0	0,6	0,0
	2040	27,9	23,1	7,6	0,0	8,2	6,6	0,2	0,0	0,5	0,0
Romania	2019	1,4	6,7	15,7	11,3	9,3	0,4	0,0	0,0	0,0	15,7
	2030	6,0	11,8	19,1	10,3	14,7	1,0	0,0	0,0	0,0	1,6
	2040	6,0	11,8	19,2	15,7	13,5	1,0	0,0	0,0	0,0	1,2
Serbia	2019	0,0	0,0	10,2	0,0	0,0	0,1	0,0	0,0	0,0	23,2
	2030	0,1	0,1	13,7	0,0	4,3	0,0	0,0	0,4	0,0	22,4
	2040	1,2	2,8	17,0	0,0	4,3	0,0	0,0	1,3	0,0	15,1
Slovakia	2019	0,5	0,0	4,5	15,3	2,7	0,8	0,5	0,0	0,0	1,6
	2030	3,9	4,7	4,5	21,9	1,4	2,1	0,0	0,4	0,1	0,0
	2040	6,1	5,8	4,5	25,2	0,2	0,6	0,0	0,1	0,0	0,0
Slovenia	2019	0,2	0,0	4,5	5,5	0,4	0,1	0,0	0,1	0,0	4,0
	2030	2	0,2	6,7	5,5	2,4	0,5	0,0	0,4	0,0	0,0
	2040	5,0	0,5	8,1	5,5	0,0	0,0	0,0	0,0	0,0	0,0
Spain	2019	14,4	52,4	26,7	56,0	77,1	2,9	2,2	2,5	0,0	11,1
	2030	93,0	92,5	22,4	15,0	44,6	0,0	0,0	0,0	0,0	0,0
	2040	129,0	122,4	20,3	0,0	30,8	0,0	0,0	0,0	0,0	0,0
Ukraine	2017	0,7	1,0	10,5	85,6	7,4	0,3	1,3	0,0	0,0	49,3
	2030	7,2	9,0	16,1	100,6	2,8	0,7	0,0	0,0	0,0	0,0
	2040	7,2	9,0	16,1	100,6	2,8	0,7	0,0	0,0	0,0	0,0

Table 4

Load factors of different primary energy sources by country for year 2019 (factual data), 2030 and 2040 (as results of hourly resolution simulations) (2019 data Source [4]).

Country	Year	Solar	Wind	Hydro	Nuclear	Gas	Biomass	Oil	Waste	Geo-thermal	Coal
Austria	2019	12,8	30,0	37,4		25,3	49,8		66,7		23,9
	2030	12,8	29,8	32,9		23,6	59,8		49,1		
	2040	12,8	29,8	33,6		34,2	65,6		56,6		
Belgium	2019	12,0	24,2	9,8	83,8	44,2	66,3	1,0	77,6		61,4
	2030	12,0	24,1	9,8		59,0	99,1	2,9	99,3		
	2040	11,9	22,8	9,1		42,7	89,0	1,0	89,7		
Bosnia and Herzegovina	2019		22,4	28,5							59,1
	2030	14,4	22,4	28,4					99,9		36,0
	2040	14,4	22,4	27,9					84,5		35,2
Croatia	2019	14,4	27,1	30,6		33,4	67,7	0,6	5,7	78,8	51,3
	2030	14,4	27,1	30,2	93,1	58,0	87,0			89,3	15,1
	2040	14,4	27,1	29,9	90,5	48,5	82,9			85,9	
Czech Republic	2019	12,5	24,8	15,5	80,8	48,6	55,7		21,2		39,7
	2030	12,5	24,8	15,5	99,8	56,7	93,6		85,6		2,4
	2040	12,5	24,8	15,5	99,9	89,8	98,1		96,3		33,1
France	2019	15,9	27,4	29,2	72,2	36,5	37,5	22,6			18,6
	2030	15,9	27,4	27,6	58,0	1,4	6,2				
	2040	15,9	26,8	26,3	48,8	2,3	7,6				
Germany	2019	10,6	23,9	20,3	85,2	19,7	60,4	10,4	23,8		39,1
	2030	10,5	23,1	18,1		48,2	85,3	0,5	81,2		4,2
	2040	10,1	19,4	13,8		30,5	62,4	5,3			
Hungary	2019	16,2	24,8	42,1	92,4	24,9	54,7	1,2	77,1	39,1	37,8
	2030	16,2	24,8	41,2	93,9	24,4	71,9		79,9		
	2040	15,3	23,6	38,2	88,1	73,7	81,2		83,7		
Italy	2019	20,7	23,7	23,7		28,0	38,0	7,6	29,4	74,7	40,1
	2030	20,0	22,4	21,8		38,4	85,2		83,0	87,8	
	2040	19,3	21,3	20,4		39,8	79,7		77,9	82,0	
Netherlands	2019		21,0	91,0		52,2	87,1		57,2		49,3
	2030	11,0	22,4	8,9	86,5	33,3	83,1		84,8		
	2040	8,2	18,2	6,4	60,4	37,8	55,7		58,1		
Poland	2019		28,6	29,5		50,8	27,8	44,0			43,0
	2030	10,6	28,6	29,5		98,6	100,0		100,0		31,3
	2040	10,6	28,6	29,5	99,8	83,3	99,0		97,9		19,8
Portugal	2019	23,4	29,9	16,0		40,0	51,1				33,7
	2030	23,3	28,0	12,3		18,7	59,0	0,2		69,9	
	2040	18,8	23,6	10,2		39,1	54,1	26,6		58,4	
Romania	2019	13,6	25,7	29,2	99,1	35,1	42,7				43,4
	2030	13,6	25,7	28,7	90,6	56,8	83,0	0,9			9,4
	2040	13,6	25,7	28,9	90,6	51,9	79,7	0,5			7,2
Serbia	2019		39,4			0,7	44,5				47,2
	2030	14,4	27,1	39,4		100,0			100,0		47,3
	2040	14,4	27,1	39,4		99,8			100,0		82,5
Slovakia	2019		20,2	90,3		26,6	43,7	23,5			34,4
	2030	16,2	24,8	20,2	90,7	9,9	47,3		32,4		0,3
	2040	16,2	24,7	20,1	72,6	1,8	13,2		8,3		
Slovenia	2019	10,2	17,9	41,9	90,4	8,3	60,1		21,0		49,5
	2030	10,2	17,9	41,9	87,4	17,3	67,2		61,8		
	2040	9,4	16,5	34,2	36,0	0,2	2,9		1,5		
Spain	2019	24,4	26,0	15,0	89,8	29,1	65,7	34,7	53,5		13,2
	2030	23,2	21,7	10,6	56,1	17,8					
	2040	19,2	17,2	6,6		17,0					
Ukraine	2017										
	2030	13,6	25,7	29,2	83,0	5,3	22,3				
	2040	13,6	25,7	29,2	83,0	5,3	22,3				

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