Paris Agreement Compatible Scenarios for Energy Infrastructure

Renewables Grid Initiative

Hitachi Energy

Modellers' Exchange Workshop

Accelerating full decarbonisation:
Resource optimisation in energy infrastructure planning

Workshop Summary Report

May 2022

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

Joint publishers:

Renewables Grid Initiative e.V.
Manfred-von-Richthofen-Straße 4
12101 Berlin
Germany

Hitachi Energy
Affolternstrasse 44
8050 Zürich
Switzerland

Co-authors:

Léa Hayez, Andrzej Ceglarz, Alexandros Fakas Kakouris, Antonella Battaglini – Renewables Grid Initiative

Meijun Chen, Alexandre Oudalov, Hei Kern Leong, Jochen Kreusel, Katarina Knesovic, Anser Shakoor – Hitachi Energy

Special thanks to Charlotte Mueller for help in editing this report.

Contact:

Léa Hayez: lea@renewables-grid.eu

Publishing date: May 2022

DISCLAIMER

The results from the Paris Agreement Compatible (PAC) scenario published by CAN Europe and EEB in open-source format in June 2020 have been used in the analysis presented at this workshop as an exogeneous data point coming as input for the calculations in the model. The modelling exercise presented at this workshop is, therefore, independent to the PAC scenario and its results are the sole responsibility of the authors and the respective organisations they represent.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

FOREWORD

Climate change is accelerating and causing more frequent and severe weather and climate extremes. Last year many European countries experienced devastating flash floods, prolonged droughts, tornadoes, and uncontrollable wildfires. Despite this, Europe continues to consume large amounts of fossil fuels – in 2021 CO_2 emissions *increased* compared to 2020[1] and current EU actions are still not sufficient to meet the 2030 decarbonisation target[2].

Moreover, Russia's invasion of Ukraine has shown that dependence on fossil fuels jeopardises the security of energy supply and contributes to the financing of military actions. This makes decarbonisation of the energy system even more urgent alongside addressing the numerous uncertainties related to this shift. To respond to this urgency and progress with a fair and coherent energy transition, the development and use of ambitious decarbonised scenarios for planning the energy system is of paramount importance.

The PAC Scenario, released in 2020, sets up a clear and ambitious decarbonisation pathway, reflected in the following objectives: (1) at least 65% reduction in greenhouse gas emissions by 2030; (2) net-zero greenhouse gas emissions by 2040, and (3) 100% renewables in Europe by 2040 in all sectors[3].

The PAC scenario, representing the voice of the European civil society organisations and developed under the guidance of Climate Action Network (CAN) Europe and European Environmental Bureau (EEB), shows that through energy efficiency gains, energy saving potentials and a massive build-up of renewable energy sources, a deep and rapid decarbonisation is possible. Open questions remain regarding infrastructural needs and technological solutions to complete this decarbonisation pathway while also optimising available resources.

This question was a starting point that in 2021 brought Renewables Grid Initiative (RGI) and Hitachi Energy together to better understand the infrastructural challenges and opportunities related to a decarbonised energy system. Months of discussions between both partners, several bilateral consultations with European stakeholders, and a number of modelling runs carried out by Hitachi Energy eventually yielded preliminary modelling results which we aimed to discuss with other energy system modellers, strategists and planning experts.

To that end, at the beginning of February 2022 RGI and Hitachi Energy co-organised an online Modellers' Exchange Workshop ''Accelerating full decarbonisation: Resource optimisation in energy infrastructure planning'' that brought together more than thirty participants from across Europe and beyond. This report summarises the outcome of this workshop. It introduces the optimal

[1] IEA. 2022. Global Energy Review: CO2 Emissions in 2021 – Analysis - IEA. https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2

[2] Climate Action Tracker (2022): https://climateactiontracker.org/countries/eu/

[3] The PAC scenario projects that final energy demand halves between 2015 and 2050.

capacity expansion planning model developed by Hitachi Energy, presents the main initial findings and gives an overview of the discussions held with the invited guests.

We believe that this is just a beginning of a very exciting journey that will not only allow us to address many questions and uncertainties related to an accelerated decarbonisation, resource optimisation, and increased security of the European energy system, but will hopefully grow into a broader collaborative endeavour. We are therefore happy to receive further feedback from the readers of this report and look forward to participating in deeper and targeted conversations in the upcoming months.

1. INTRODUCTION

Modelling decarbonisation pathways is a difficult but necessary exercise, allowing us to understand the infrastructural implications of a decarbonised energy system and consider the related resource optimisation options. The modelling collaboration between RGI and Hitachi Energy aimed to quantify grid infrastructure needs to achieve the political objectives outlined in the PAC scenario. More specifically, modelling the current European energy system and using electricity and hydrogen demand of the PAC scenario as input data allowed us to determine optimal investment decisions for infrastructure development.

Carrying out modelling runs allowed us to evaluate the technological and economic feasibility of the PAC scenario, while considering different spatial and time constraints, such as: limited land and maritime areas for variable renewable energy sources development; limited capacity of underground caverns for seasonal storage of green gases; and, infrastructure permitting and construction time delays. Nevertheless, each modelling exercise requires finding a balance between model complexity and reality concordance, while coping with the uncertainty of future trends and events. This implies that assumptions must be taken to simplify reality and the results must then be interpreted accordingly.

The Modellers' Exchange Workshop co-organised by RGI and Hitachi Energy in February 2022 served exactly this purpose. The main objective of this event was to present and discuss main findings and features of the modelling carried out. To that end, we invited a group[4] of prominent energy system modellers, strategists and planning experts representing industries, NGOs, international organisations, and academia. We facilitated discussions to share their experiences and best practices as well as to discuss the assumptions taken. This, in turn, improved the quality of ongoing and future analysis. We believe that such facilitated conversations can further enhance energy modelling community exchanges dedicated to decarbonisation pathways as well as related implications in the EU energy and climate community. Finally, the collected feedback was important to determine next steps for the modelling exercise.

The entire workshop took place as an online event to enable the participation of stakeholders in different geographical locations. It was divided into two main plenary sessions (opening and closing), two sessions with four thematic parallel breakout groups and a break. Each breakout session was moderated to extract as much information as possible – these findings can be found in the following pages. Table 1 details the workshop agenda, including the thematic scope of the parallel breakout sessions.

[4] A complete participants' list can be found at the end of this report.

Table 1: The structure of the Modellers' Exchange Workshop: "Accelerating full decarbonisation: Resource optimisation in energy infrastructure planning"

09:30 – 10:05	Opening plenary session	
10:05 – 11:05	**Parallel breakout sessions – round I**	Energy system expansion modelling: methods, assumptions, and tools
		Evolution of energy demand and renewable generation profiles in Europe
		Projections of future energy technology trends
		Environmental, resource availability, supply chain, financial and other constraints
11:05 – 11:25	Coffee break	
11:25 – 12:30	**Parallel breakout sessions – round II**	Energy system expansion modelling: methods, assumptions, and tools
		Evolution of energy demand and renewable generation profiles in Europe
		Projections of future energy technology trends
		Environmental, resource availability, supply chain, financial and other constraints
12:30 – 13:00	Closing plenary session	

Section 2 of this report outlines a description of the optimisation model applied for this analysis. It also presents the preliminary results in terms of energy infrastructure development at the EU level. Section 3 summarises the discussions facilitated during the parallel breakout sessions. Section 4 provides a conclusion on the findings and the feedback collected from stakeholders. It also reflects on the next steps related to this modelling exercise. The final pages of this report include a list of the participants, suggestions of further reading and the annexed detailed input data of the presented results.

2. IMPLEMENTED MODELLING APPROACH

2.1 DECARBONISATION PATHWAYS AND ENERGY SCENARIOS

Many recent energy scenarios provide frameworks to explore future energy perspectives leading to full decarbonisation[5]. With this in mind, CAN Europe and EEB published the PAC scenario in 2020, which is based on multiple exchanges with civil society organisations carried out throughout the PAC project.

The key assumptions included in the PAC scenario are aligned with the Paris Agreement's goal to limit global warming to 1.5°C degree by the middle of the current century. The PAC scenario outlines a trajectory with at least 65% greenhouse gas emission reductions by 2030, as well as net-zero greenhouse gas emissions and a fully renewable energy supply by 2040.

RGI together with Hitachi Energy decided to take the political objectives of the PAC scenario as a starting point and develop a spatial and temporal trajectory with a higher granularity than the original PAC scenario — which reflected annual trends presented for the entire European Union. By adopting the chronological development of electricity demand and electrification trend of the original PAC scenario, the multi-zonal, multi-periodic optimisation model used by Hitachi Energy[6] [7] delivers a detailed picture about the pathway that Europe could take towards full decarbonisation. This includes, among others, when and where to invest in a type of energy generation, storage or transport technologies.

Although the scenario applied for this analysis shares some characteristics with the PAC scenario in terms of total demand value and greenhouse gas emission targets, it includes several deviations from the original PAC scenario assumptions, namely:

- Taking energy storage and cross-border energy transfer (electricity transmission and hydrogen pipeline transport) into account;
- Breaking down the total demand value into sector- and country-specific demand values;
- Including countries that are in Europe but not part of EU, such as UK, Norway, Switzerland and some Balkan countries (Bosnia and Herzegovina, and Montenegro);
- Adjusting the demand data according to actual energy generation and consumption data of year 2019 such as the one provided by ENTSO-E Transparency Platform.

[5] See for example: the scenarios of TYNDP 2020 and 2022 and SolarPower Europe

[6] Knezovic, K., Marinakis, A., Evrenosoglu, C.Y., Oudalov, A. (2021) "Role of grid and bulk storage in the integration of variable renewable energy resources: Framework for optimal operation-driven multi-period infrastructure planning", *Energy*, 226 [online]. Available at: https://doi.org/10.1016/j.energy.2021.120378

[7] Pereira, P. (2020) "Expansion planning for electrical and hydrogen assets in the context of a scenario with high shares of variable renewables", Master thesis, Eindhoven University of Technology.

These changes were made in order to combine information from different sources to improve data reliability and achieve a more holistic picture of the European energy transition.

2.2 CONFIGURATION OF THE APPLIED MODEL

For the purpose of this analysis, Hitachi Energy configured and applied the optimal capacity expansion planning model, which serves a long-term technology-focused analysis. The model aims to give a benchmark of required technology capacity under given demand and price development conditions. Since this model is a high-level European-wide tool, it does not specifically model the transmission and distribution network within each country, but rather models only cross-border high voltage interconnectors.

As shown in Figure 1, the applied model focuses on the the long-term energy analysis and related infrastructure landscape. Market mechanisms could be further explored based on this present long-term analysis to bring real-world operation into the picture. On the foundation of short-term analysis, more detailed technical analysis on electrical system stability could be performed. However, both market mechanisms and further detailed technical analyses are outside the scope of the model configuration guiding this study.

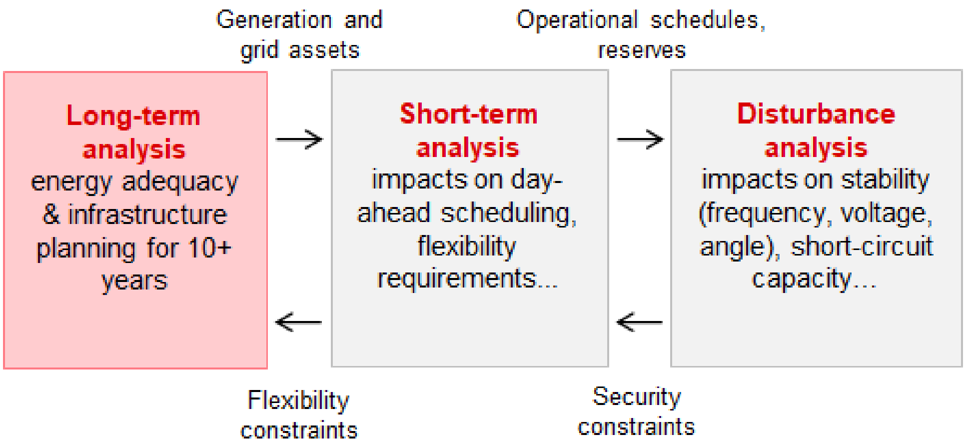

Figure 1: Focus of the applied optimisation model in the energy system modelling landscape

2.2.1 Objective function

The modelling tool has been calibrated to estimate the infrastructural needs and the cost thereof for reaching the emission target of carbon neutrality in Europe by 2040. The optimisation problem is formulated as a linear optimisation problem, in which the objective is to minimise the cost, including investment and operational costs of the whole system, within a single optimisation period. Residual costs are excluded to avoid overestimating the cost of new capacity investments compared to established capacities.

2.2.2 Spatial and temporal resolution

The applied optimisation model includes 75 geographical zones, of which 30 are European countries. The remaining zones are offshore wind sites within European maritime areas. The temporal resolution of the model has been adjusted according to the available computational power: hourly step, daily step and weekly step are used to sample hours within a year in order to reduce the number of variables. For the results presented at the workshop, the investment decision step was set to be 5 years (4 steps in total until 2040) and the data sample period was set as each second hour, each third day, and each fourth week. Supply must meet demand at every sampled hour and at each decision step.

2.2.3 Technology mix

The technologies included in the model are categorised into electricity-related and hydrogen-related infrastructure, at the generation, storage and transport levels, as summarised in Table 2.
The newly invested capacity of the technologies included are all decision variables, except run-of-river, fossil generation, nuclear, and steam methane reforming (SMR) with and without Carbon Capture and Storage (CCS). These variables are to be determined by the optimisation algorithm.

Table 2: High-level technology mix included in the modelling

	Electricity		Hydrogen	
	Fossil-based	**Non-fossil-based**	**Fossil-based**	**Non-fossil-based**
Generation	Coal Gas Oil	Nuclear Reservoir and run-of-river hydro Solar PV On-shore and off-shore wind Gas-to-Power (fuel cell, H2 compatible gas turbine)	SMR SMR + CCS	Water electrolysis
Storage	Pumped-hydro Li-Ion battery		Salt cavern	
Transport	High voltage cross-border transmission (overhead lines, underground and submarine cables)		Hydrogen high-pressure pipeline	

2.3 INPUT DATA USED FOR THE ANALYSIS

The model was fed with data from reliable and publicly available sources, such as from the PAC scenario, ENTSO-E Transparency Platform, EC JRC ENSPRESO, Eurostat and renewable.ninja, as well as studies and reports published by other organisations. A sample of the specific input numbers used can be found in the appendix at the end of this publication. Due to the size of the input file, only the crucial parts have been included. Further input data can be provided upon request.

2.3.1 Demand profile

The total EU electricity demand per year was extracted from the PAC scenario data and applied by maintaining the same percentage of electrification for all countries in each time step. The annual country-specific profiles are synthesised via a bottom-up process which considers the proportion of energy consumption within a certain country and the proportion of a certain sector (such as transport) in the total energy demand. The approach for defining the hourly demand profiles is as follows: each individual sectors is granulated into subsectors and then individual demands are summed up to create the total demand profiles. The obtained electricity total demand quantity is similar to those from the PAC scenario, with slight deviations due to the adjustments listed in Section 2.1.
The current hydrogen demand is taken from Hydrogen Europe[8]. The shape of hydrogen demand throughout the year is assumed to be flat due to lack of data and projection of possible hydrogen utilisation patterns.

2.3.2 Renewable generation profile

The wind and solar hourly profiles and capacity factors are taken from the 2019 generation profile available on the renewables.ninja online database. The profiles are assumed not to change throughout the decision steps. Hydro inflow numbers are taken from the ENTSO-E Transparency Platform.

2.3.3 Technology cost, parameters, and existing capacity

The chronological investment and operational cost of different technologies and performances (e.g., efficiency, lifetime, ramping, emissions) are given by internal sources as well as the combined consideration of several publicly available sources (see section 7.2). The numbers are taken in the middle of the range of collected data while the minimum and maximum levels are used in sensitivity analysis (see Section Appendix). The current (beginning of simulation period) generation, energy storage, cross-border, and off-shore wind connection capacities as well as electricity demand are from the ENTSO-E Transparency Platform.

2.4 ASSUMPTIONS AND KEY CONSTRAINTS INCLUDED IN THE MODELLING

The model assumes electricity and hydrogen are balanced temporarily and spatially. The balance condition is illustrated schematically in Figure 2. The electricity and hydrogen systems are coupled through Power-to-Gas (P2G) and

[8] Fuel Cells and Hydrogen 2 Joint Undertaking. (2019) "Hydrogen Roadmap Europe". Available at: https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf

Gas-to-Power (G2P) technologies, and both should be balanced in each zone and at each simulation step (hourly).

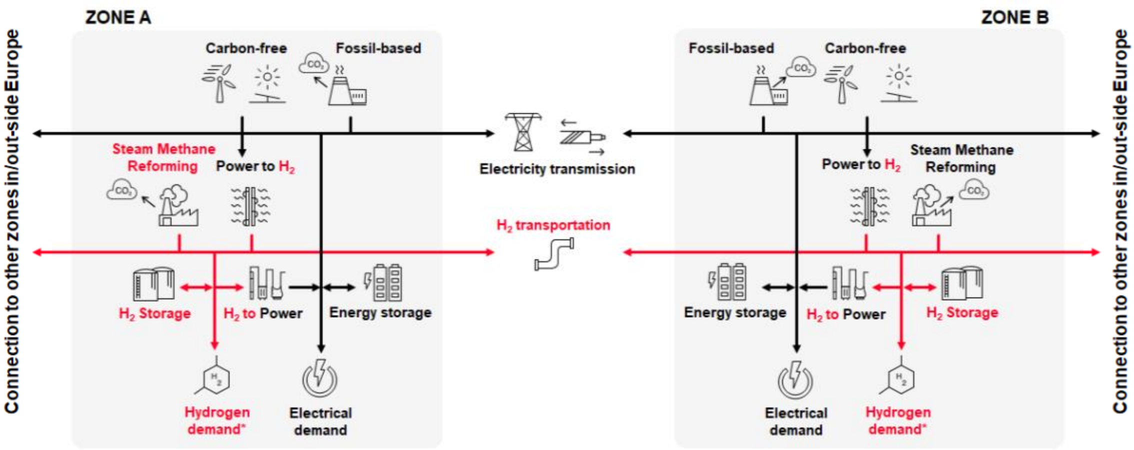

Figure 2: Coupling of electricity and hydrogen networks

Regarding the inequality constraints, the model includes:

– Technology-specific constraints, such as ramping rates of generation units;

– Infrastructure capacity growth is limited per each decision step considering the growth rate of the past and is region independent. For technologies with low/zero installed capacity in 2020 the initial investment limit is set at 2 GW;

– Maximum chronological CO_2 emission cap is set according to the PAC scenario targets.

Other model parameters given to steer the simulation behaviour:

– Cost of imports of electricity and hydrogen is set to a very high value to force model towards self-sufficiency by developing local resources in Europe;

– Renewable generation curtailment penalty is set at 50 €/MWh to simulate real-world conditions and avoid massive curtailment;

– Discount rate is set at 3 % for all technologies and countries.

2.5 OUTPUT STRUCTURE

The output of the model includes the following:

– Investment volume (capacity, cost) in each technology per zone and between zones at each investment simulation step;
– The operational information of each type of technology in each zone at each sampled hour (for example, the solar generation of Germany in the first hour of the first investment step).

2.6 PRELIMINARY RESULTS

This section presents and discusses the preliminary results of the modelling carried out. These results will be a subject to revision upon completion of modelling and simulation work.

2.6.1 Installed capacity

The decarbonisation of the European energy supply by 2040 requires a fast growth of all clean technologies (a substantial amount of variable renewable generation as well as electrical hydrogen production capacity) within the next 15 years. Figure 3 illustrates the required new installed capacity per technology.

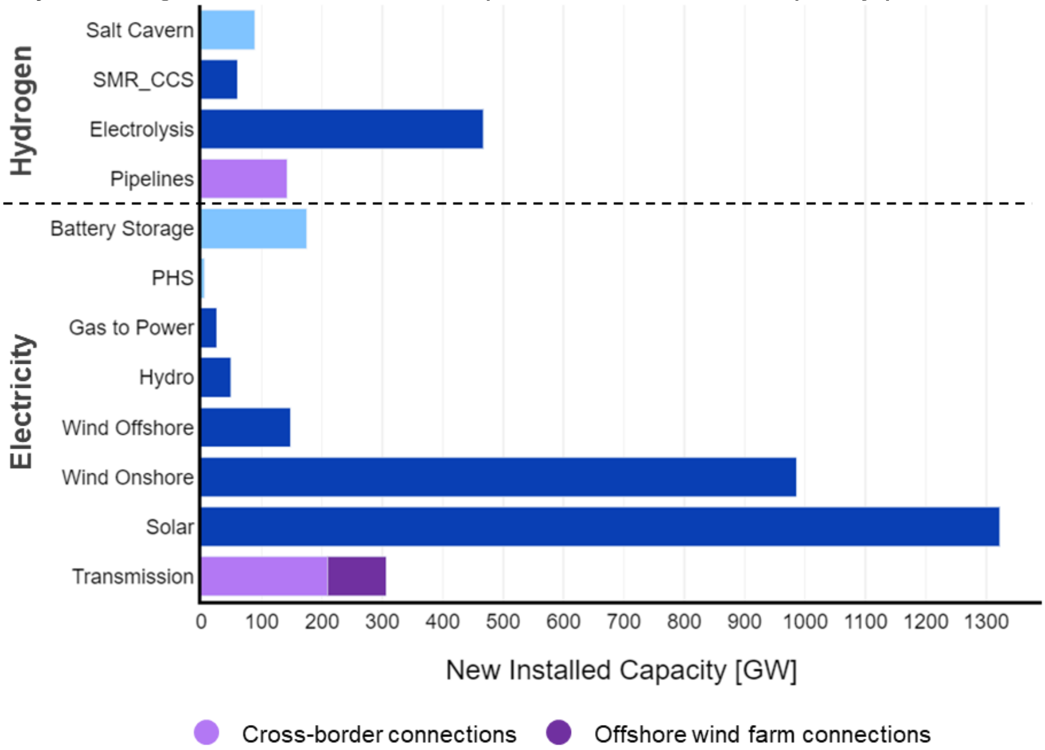

Figure 3: New installed capacity per technology in Europe by 2040, in GW

Figure 4 details the chronological yearly capacity deployment of selected technologies in selected countries. The upscaling of wind and solar saturates after 2035 — in part due to the limited available land for these technologies at certain locations and partly due to the sufficiency in generation capacity and saturation in electrification of demand.

A certain addition of energy storage volume, especially lithium-ion batteries and underground hydrogen storage in salt caverns, is needed to improve the utilisation of variable renewable energies (VREs) generation and bridge the temporal mismatch between supply and demand. Electrolyser and salt cavern growth is limited by the model assumption that newly invested capacity in one step is constrained to be lower than two times the installed capacity at the previous step. Additional transmission and hydrogen pipelines are also built to connect supply and demand.

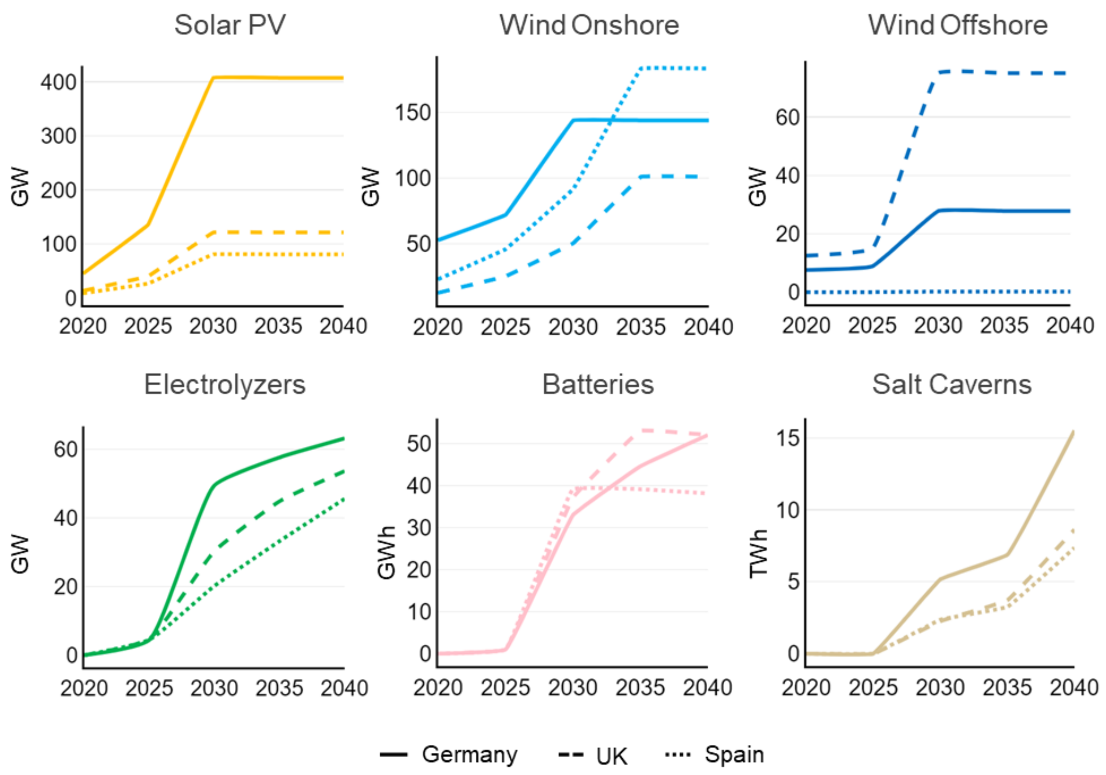

Figure 4: The chronological capacity deployment of several technologies in Germany, UK and Spain, in GW

2.6.2 Operation profiles and energy supply-demand balance

Figure 5 shows the chronological development of energy demand and the overtake of renewables in electricity generation. Fossil fuels phase out is driven by the CO_2 emission cap defined by the input data while nuclear generation capacity is phased out according to the PAC scenario targets. Wind production is constrained by the capacity addition limit. The area between the red and the black dashed lines corresponds to the electricity demand by electrolysers for green hydrogen production, which is growing constantly and is forecast to eventually comprise of more than one fourth of total electricity demand. The area between the red dashed line and the total generation capacity represents the grid and storage losses.

Figure 6 presents the energy generation mix differences in four selected countries: France, Norway, Spain and the United Kingdom. These countries reflect different legacy capacity volumes and geographical conditions. For example, massive hydro capacity in Norway and nuclear capacity in France require these countries to employ different approaches to reaching their emission goals. The profiles of electricity power exchange with other countries depend on the optimal capacity development of the country in question as well as those of neighbouring countries.

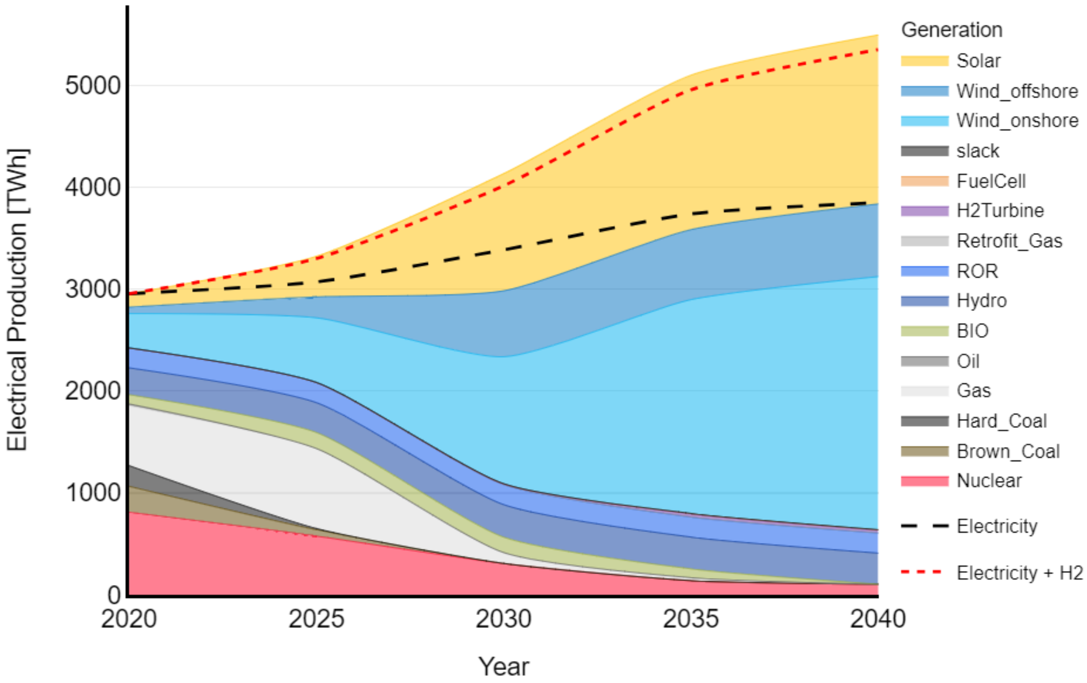

Figure 5: European electricity generation mix, in TWh

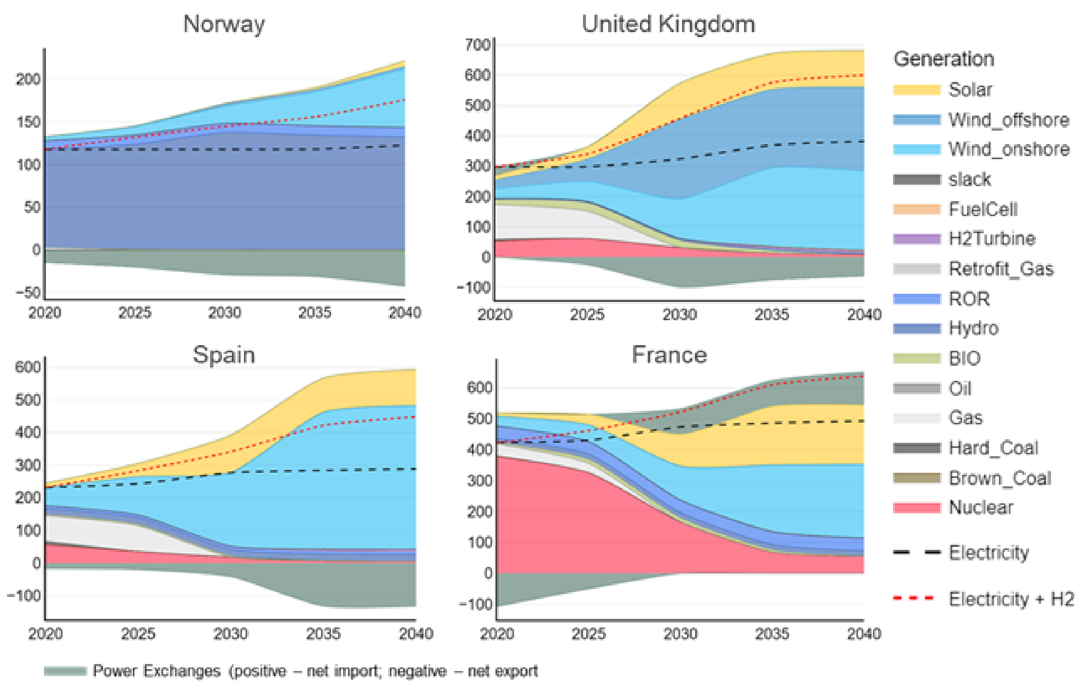

Figure 6: Development of the electricity generation mix in Norway, the UK, Spain and France, in TWh

With the rapid growth of hydrogen demand, its generation composition is changing significantly. Figure 7 illustrates this change from exclusively SMR production ("grey" hydrogen) in 2020 to the electrolysis production ("green" hydrogen) in 2040 under the carbon emission constraint. "Blue" hydrogen, produced through a method based on SMR combined with CCS, is used in the intermediate period to cover hydrogen demand, since electrolysis scale-up is limited by the model assumption of limited electrolysis scaling speed. As in the case of the electricity production mix, hydrogen production above the dashed red line representing the total hydrogen demand is due to pipeline and storage losses.

The same countries as in case of the electricity generation mix, shown in Figure 8, also demonstrate different patterns with regard to hydrogen exchange and technology deployment speed. Some countries, such as Norway or the United Kingdom, are net exporter while others, such as France, are net hydrogen importers. A detailed development trajectory needs to be understood in the context of neighbouring countries and sector coupling.

The production of solar power in summer is generally much larger than in winter while wind production in winter is generally bigger than in summer, as shown in Figure 9. Curtailment of wind and solar production also sees a larger amount in summer. During both seasons, pumped hydro and battery storage are acting as intra-day short-term balancing technologies for electricity. Generally, electrolysis is highly correlated with solar power; in winter when solar power is rather limited, salt cavern storage is discharged to satisfy the static hydrogen demand, which is stored during excessive solar times in summer (seasonal storage). As indicated above and in figures below, the hourly and seasonal profiles of the four countries vary substantially.

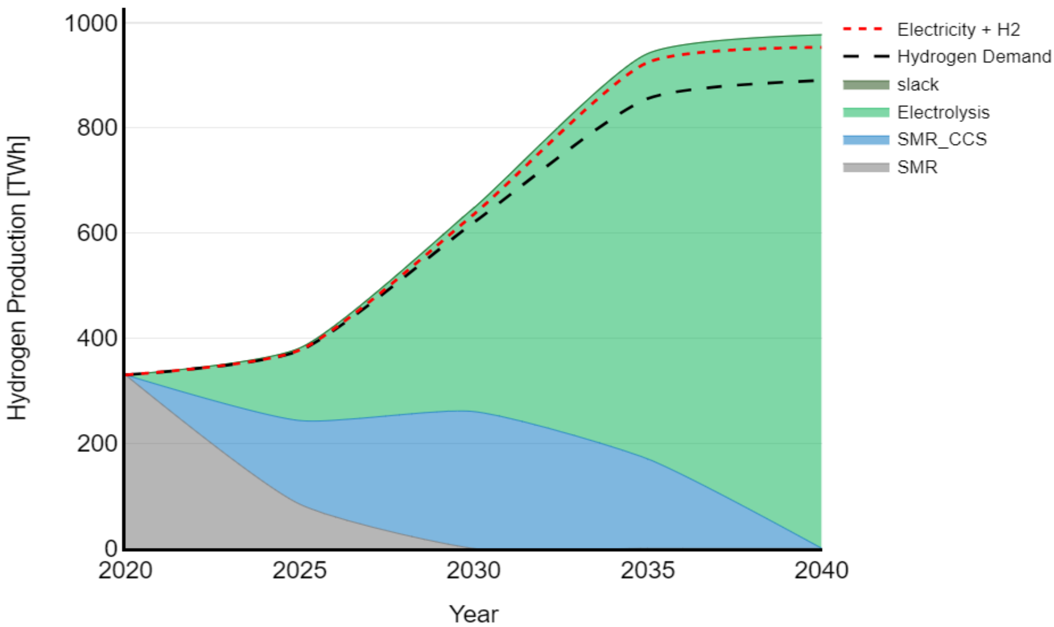

Figure 7: European hydrogen generation mix, in TWh

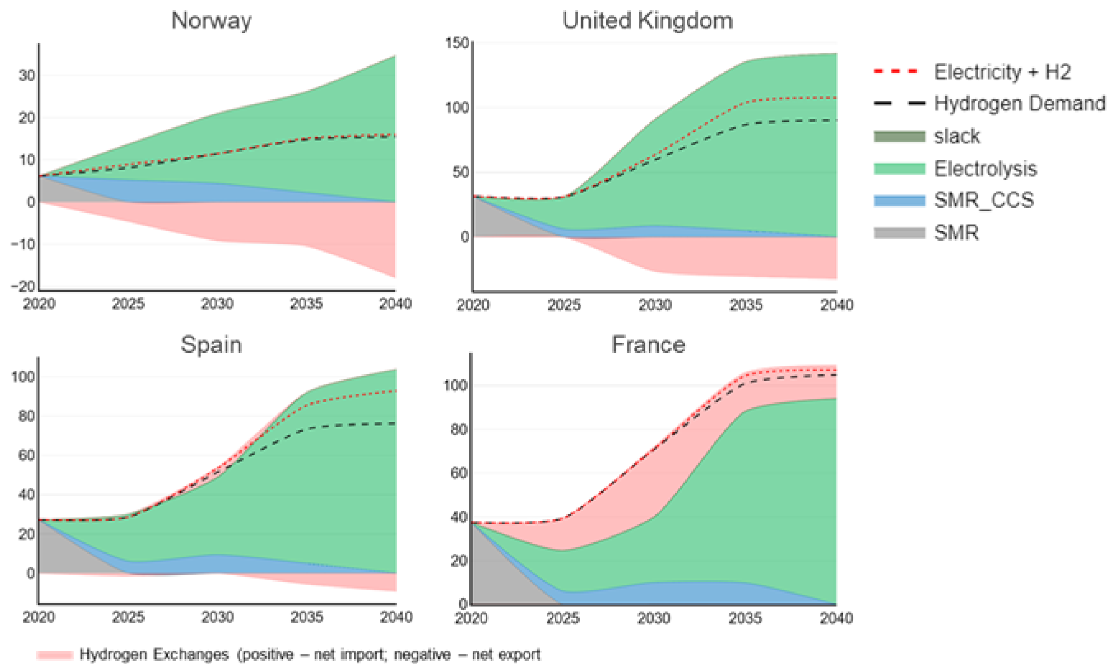

Figure 8: Development of the hydrogen generation mix in Norway, the UK, Spain and France, in TWh

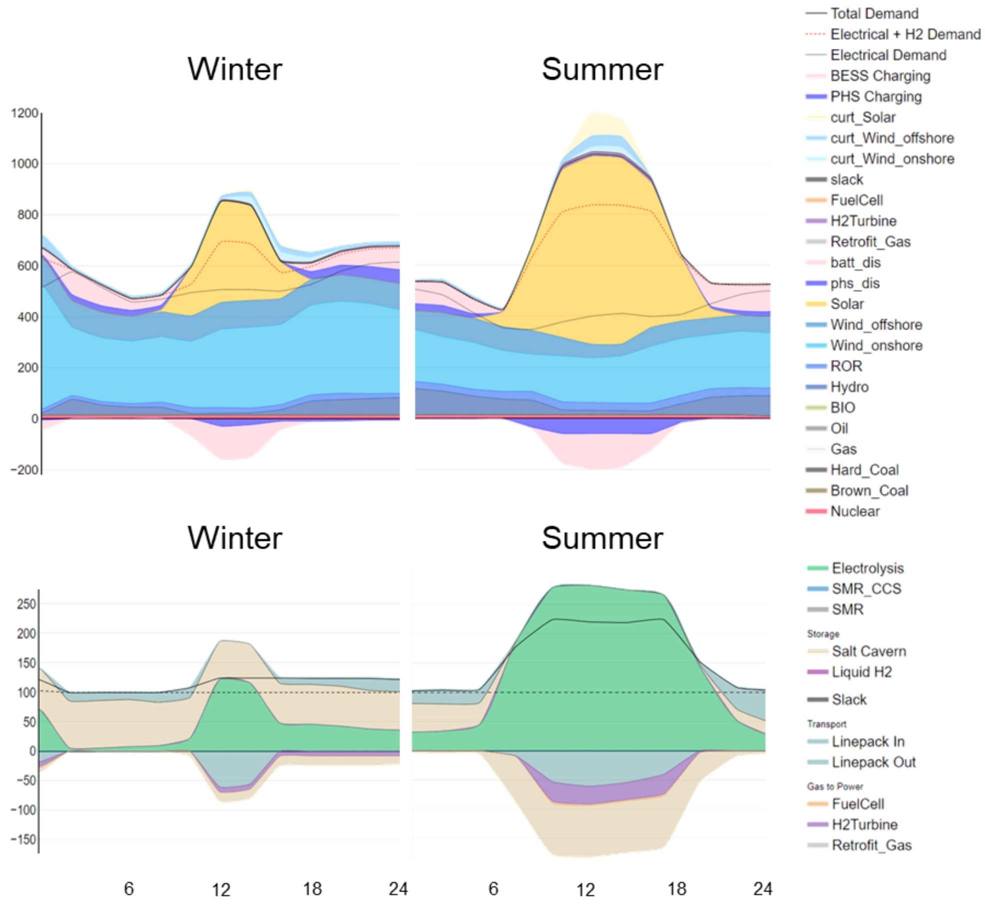

Figure 9: European electricity and hydrogen balance of a typical winter and summer day, in GW

The modelling results showed that there is a difference in daily operations of hydrogen and power exchanges in different countries (in that case: in Norway and France), as shown in Figure 10. There is one similarity, namely that in both countries the optimal hydrogen production takes place during peak loads in summer, whereas in winter, barely any additional hydrogen would be produced. Due to the difference in capacity mix, there are significant variations in the main generation technology that drives hydrogen production, and the country's role as net importer or exporter. For example, in France the main hydrogen generation technology is solar, whereas in Norway it is hydro and onshore wind.

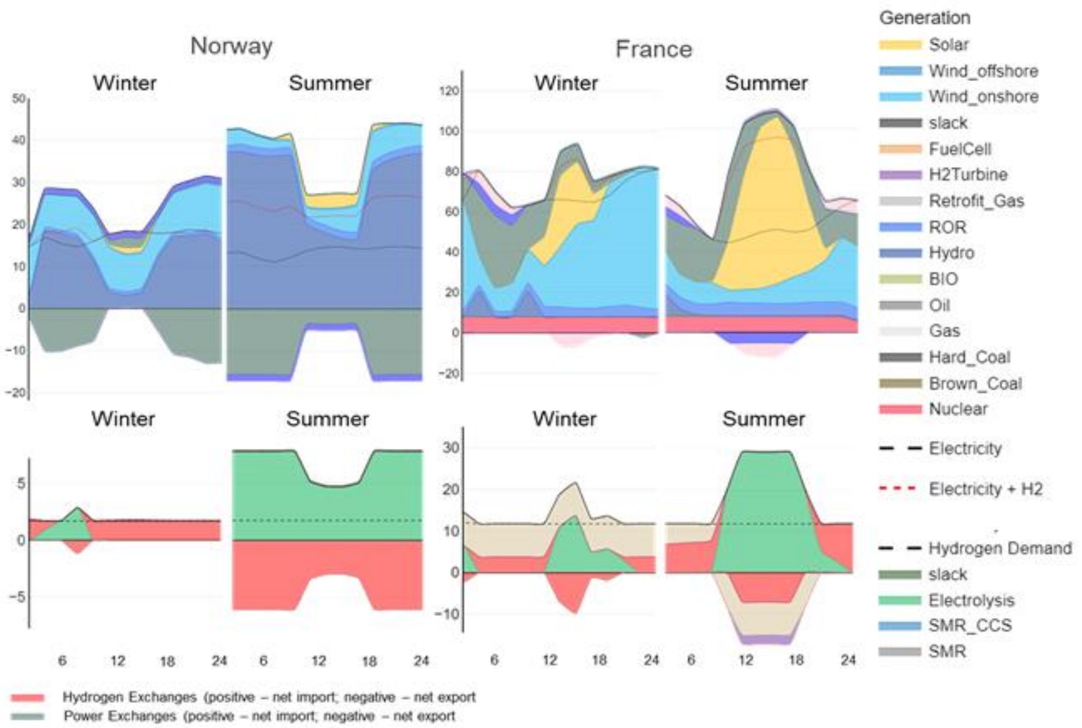

Figure 10: Electricity and hydrogen balance of a typical winter and summer day of Norway and France, in GW

The modelling results showed a complex view of the energy balance of European countries (net importer or net exporter), the generation mix of the main countries, and the transmission or pipeline capacity between countries (see Figure 11). These results indicate that the connections between Spain and France as well as Germany and Austria are the backbones of the transmission system, while the North Sea offshore zones of Germany and the UK are playing a major role in electricity production. The relatively even sizes of pipelines throughout Europe are due to the investment constraint posed by model assumptions.

The main reason for the large transmission capacity between Germany and Austria is the higher onshore wind capacity in Austria, according to the input data. The model makes the decision to build more onshore wind in Austria and use cross-border transmission to meet the large electricity demand in Germany.

The feasibility of this arrangement can be further examined and certain constraints may be enforced according to the real-world situation.
We can also observe a development of an offshore meshed grid in the North Sea area, where multiple offshore wind zones are interconnected to optimise the simultaneous transmission of offshore wind and power exchanges between continental Europe, Scandinavia, the UK and Ireland.

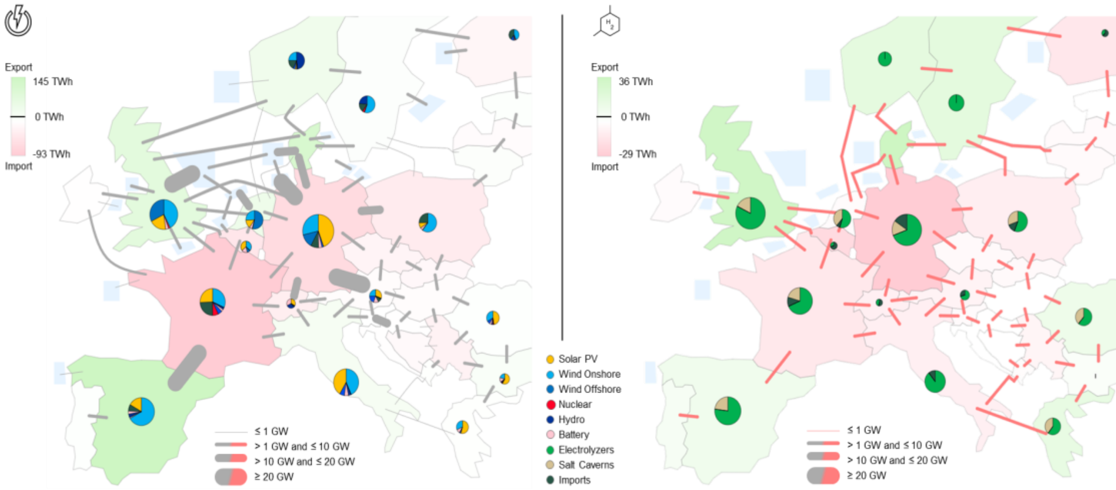

Figure 11: European electricity and hydrogen balance of main nodes and transport capacity, in GW

2.6.3 Financial aspects and sensitivity analysis

The investment cost composition of the simulation case showed that the installation of renewable generation accounts for more than half of the capital investment, while storage is the second-largest section of investment. This relationship is visualised in Figure 12 below. Please note that the specific numbers showing total system investment costs have not been presented deliberately – the figure indicates the increase of costs only in relative terms, reflecting the results of sensitivity analysis.

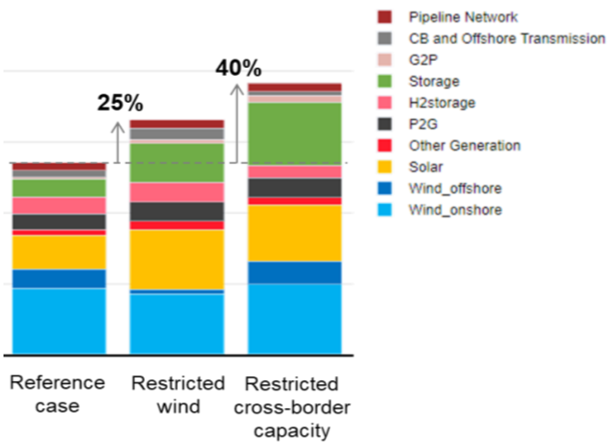

Figure 12: European total system investment cost comparison

In the case where a more restricted wind potential was applied (extracted from the JRC ENSPRESO database), simulating the limited wind construction capacity, the investment in offshore zones shrinks while solar investment expands. Electrical storage and transmission investment also expands due to the intra-day fluctuated production of solar power. Moreover, because of the changed onshore wind potential value, its investment is geographically redistributed and requires more investment in cross-border transmission. Under such a scenario, the total investment cost increases around 25 % compared to the reference case, indicating that sufficient wind potential is a favourable condition for a lower cost energy transition.

If no new investments in cross-border interconnection capacity are allowed in the simulation, solar investment would also increase significantly and electricity storage investments would almost triple. That leads to a 40 % increase in total investment costs and a lower energy utilisation rate, since each zone modelled in non-peak times would need to curtail the excess amount of generated electricity. This means that cross-border interconnections can serve to enhance the penetration of renewable energies and their development is important for the total system cost reduction.

These cost figures include neither inter-zonal transmission grid investments — since we model each zone as a “copper plate”— nor distribution grid investments. These investments may account for a significantly higher value compared to a sum of high voltage cross-border capacities and offshore wind connections.

3. BREAKOUT SESSION SUMMARIES

The following pages summarise the discussions carried out in the different thematic workshop's breakout sessions.

3.1 SESSION 1: ENERGY SYSTEM EXPANSION MODELLING: METHODS, ASSUMPTIONS, AND TOOLS

Facilitated by: Katarina Knezovic (Hitachi Energy) & Hei Kern Leong (Hitachi Energy)

The first breakout session focused on modelling techniques and software tools applied for long-term energy system capacity expansion planning studies. Among the energy modelling community there is a consensus that the future modelling tools should be able to simulate large-scale multi-energy vector systems as a multi-zonal, multi-period optimisation problem in hourly resolution. However, these requirements, together with numerous constraints, result in a large mathematical problem and often require high performance computing to solve it in a reasonable time frame. This session addressed numerous questions related to the abovementioned aspects, which are divided into three sub-topics: approaches to improve problem tractability; data sampling; and, modelling of energy carrier dynamics. Additionally, the workshop participants pointed out several adjacent issues.

3.1.1 Approaches to improve problem tractability

The large size optimisation problem is an issue that most modellers participating in the workshop face. Many of the workshop participants employ the use of server clusters, but solving the optimisation problem can still take up to one week, depending on its size. To improve tractability, or problem complexity, the participants proposed several solutions. However, there is no ideal solution and all had specific trade-offs.

One suggested approach was to model the problem optimisation myopically. This means that the optimal solution is found only for one investment step, and further used as input to the next investment step. While this approach offers significant advantages in terms of computation time, it was noted it can lead to substantial differences to the decision outcome. For example, one participant noticed that the application of a myopic approach often led to results that included stranded assets. Another mentioned method was the myopic approach while stepping backwards, i.e., starting the first simulation on the last investment step, then moving stepwise to a present day.

Some participants mentioned the system of systems approach, where the optimisation was split into sub-systems as opposed to splitting up on the time axis. The main drawback of this approach is that it might not be able to include certain system synergies that would otherwise be included if solved in a monolithic way.

The workshop participants agreed that by employing spatial aggregation it is not possible to model certain synergies and bottlenecks present at the lower levels of aggregation.

The experts mentioned mathematical decomposition as another method applied in their work. An example of mathematical decomposition is the Bender's decomposition. According to them, mathematical decomposition introduces significant communication overhead to the optimisation problem. While the problems could be split up into smaller pieces to be solved in parallel, the requirement for information to be shared between the sub problems might negate the advantage of splitting up the problem.

3.1.2 Data sampling

The workshop participants confirmed that creating representative data as an input to the optimiser is an important factor to get good quality output. While they shared the opinion that representative climatic conditions are a very important input vector, they noticed that simulating a large set of climatic conditions can significantly increase the computational burden. As a solution, machine learning clustered algorithms can be employed to determine or create representative years (used as time series input data). For system robustness studies, extreme cold periods with low wind were mentioned as particularly important inputs. In turn, for average representative investment studies, average years are more suitable as input.

Some of the experts attending the workshop mentioned that on a lower time resolution they use representative days within the year, which dramatically reduces computational complexity. However, reduction in this manner tends to neglect storage technologies that are seasonal in nature.

3.1.3 Modelling of energy carrier dynamics

Since electricity demand for green hydrogen production will massively affect the electricity sector, the experts agreed that the modelling of hydrogen pipelines is of high importance. In that context, they acknowledged the salience of modelling the dynamic behaviour of hydrogen pipelines, considering the slower time constants for hydrogen transport when compared to electricity. Therefore, including the appropriate time delay of hydrogen transport is very important and relevant to accurately model the relationship between the electrical and hydrogen networks.

However, including detailed physical constraints into the optimisation can lead to substantial increases in computational requirements. Therefore, participants currently use simpler approximations in their work such as a steady state approximation.

3.1.4 Adjacent discussion points

During the discussion, a few adjacent points of importance were raised.

First, participants voiced the importance of spatial resolution, as considering local climatic conditions could exhibit complementarity between climatic zones. For instance, one region's high demand period might coincide with another region's strong wind period.

Second, on the electric grid front, one of the participants found that 100 to 200 nodes with 3 hourly sampling was able to give a good representation of grid restrictions within Europe. Another attendee shared the experience that the division of node by electricity markets can also be helpful towards providing a representative grid model.

Third, in terms of wind power, one of the participants mentioned that modelling separate areas of offshore zones is important as these areas can have large variation in climatic patterns.

Fourth, the workshop participants referred several times to the bottom-up approach in creating time series data, particularly in the generation of demand data, such as: heating, electricity, and hydrogen demand. According to them, temperature changes resulting from the changing climate are of particular importance among the factors that will affect demand.

3.2 SESSION 2: EVOLUTION OF THE ENERGY DEMAND AND RENEWABLE GENERATION PROFILES IN EUROPE

Facilitated by: Anser Shakoor (Hitachi Energy) & Meijun Chen (Hitachi Energy)

This session was dedicated to the future changes in European energy demand and the variable renewable energies (mainly wind and solar) generation profile, which are key input data for energy system modelling. Static demand and VREs generation profiles do not represent reality: statistic shows that VREs generation, and consequently net demand (the demand volume subtracted by VREs generation), could reach up to 10% inter-year variability[9]. This can pose substantial challenges for demand coverage and requires a modelling method that takes into account many uncertainties and provides good guidance for real-world activity. On the generation side, climate change may also impact weather conditions in the long-term, resulting in an overall increase of wind and solar capacity factors and redistribution of high-output hours throughout the year.

3.2.1 Energy demand profiles

Participants first discussed the factors that influence demand trends, such as: the speed and scale of electrification; energy efficiency; behavioural changes; and, demand side technology developments.

[9] ENTSOE. (2019). Mid-term Adequacy Forecast 2019 Edition. Available at: https://www.entsoe.eu/outlooks/midterm/previous-maf-versions/

Different studies or databases, such as Ten Year Network Development Plans (TYNDP) [10] or the JRC Data Catalogue [11], show an increasing rate of electrification but a decreasing trend in the final energy consumption. This is mainly due to the increase in electrification and energy efficiency, as also outlined in the PAC scenario. Electrification is expected to be significant: as much as a two times electricity generation increase is expected from 2015 to 2050, according to the PAC Scenario.

As one of the participants of this session noted, if one takes an optimistic view in the building sector, the renovation rate for buildings is expected to increase from the current 1 % to 3 % in 2050. New heating solutions and appliances, such as heat pumps, are expected to replace inefficient fossil heating systems and contribute to large savings in heating energy consumption. More efficient household appliances and behavioural changes may both contribute to demand reduction.

Regarding the transport sector, a different expert joining this session mentioned that while the electrification of domestic transport is growing rapidly, it remains a challenge to ensure sufficient renewable generation of the infeed electricity as well as to produce renewable fuel for aviation, shipping, and heavy trucks. The scalability of hydrogen still has various uncertainties. Green hydrogen (hydrogen generated with exclusively renewable sources) is currently facing economic difficulty, but political support is envisioned according to documentation from the European Commission.

The stakeholders in this session mentioned that direct electrification can effectively contribute to decarbonisation of industry. It can, for example, be deployed in production processes such as electrochemical production or heating of iron. For the processes that are more difficult to electrify, such as the production of cement, investment in electrolysers may be stimulated to replace carbon with hydrogen, or, in some cases, Carbon Capture and Storage (CCS) could be utilised to control carbon emission levels.

One of the experts pointed out that technological breakthrough could allow an acceleration with deep electrification, while at the same time enhanced energy efficiency would largely reduce the energy demand. The participants voiced that the discussion over the EU's 2030 energy efficiency targets (at the time of this workshop still under decision), embodies an important policy opportunity window to establish efficiency trajectories of technology development.

The participating stakeholders mentioned diverse topics regarding the effect of indirect behavioural change on future demand profiles. First, the full

---

[10] TYNDP. (April 2022) *Scenario Report* [online]. Available at: https://2022.entsos-tyndp-scenarios.eu/wp-content/uploads/2022/04/TYNDP2022_Joint_Scenario_Full-Report-April-2022.pdf [Accessed 21 April 2022].

[11] Data.jrc.ec.europa.eu. (2022). Joint Research Centre Data Catalogue - ENSPRESO - an open data, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials - European Commission. [online] Available at: https://data.jrc.ec.europa.eu/collection/id-00138 [Accessed 22 April 2022].

implementation of demand sufficiency, involving a societal mindset change, would bring the energy system considerably closer towards lower emission targets. Second, the overproduction of some technological solutions contributing to decarbonisation (i.e., electric vehicles) could cause auxiliary negative environmental effects. In that case, the stakeholders praised the incentives leading to behavioural change, such as use of public transportation. Third, as observed during the COVID-19 pandemic, external shocks could result in paradigmatic demand changes which the energy system should be prepared to face.

3.2.2 Integrating climate effects into modelling and infrastructure resilience

Similarly to the first session, the participants of Session 2 emphasised the importance of considering how climate change effects could be represented as specific constraints or formulations in energy system modelling. They recalled some studies showing that changing the infrastructure design to a large extent can help avoid re-building costs. Extreme weather events are another factor which can put an additional pressure on infrastructural resilience and efficiency. Regarding the year-to-year fluctuation in energy demand and the VREs supply, the experts noticed that long-term storage is a key bridging factor that can cover the gap between years and reduce the required generation infrastructure size. As reflected on during the session, in Europe hydro reservoirs in the Nordic region could serve this purpose, but their availability varies up to 20% between years. Hydrogen stored in underground caverns may play a role in seasonal storage, but more investigations and research are needed to understand the compatibility of converting existing caverns used for natural gas to store hydrogen.

Lastly, the participants of this session pointed out that the investments in research, new renewable generation capacity, and in other forms of new technologies are gradually being guided by the consideration of climate change related uncertainty – climate change has started representing a factor to consider while calculating the investment risk. In that sense, climate change effects can accelerate the development of promising technologies and projects (e.g., flood-resistant power substations), which can lead to lower technology costs for a wider deployment.

3.3 SESSION 3: PROJECTIONS OF FUTURE ENERGY TECHNOLOGY TRENDS

Facilitated by: Alexandre Oudalov (Hitachi Energy) & Léa Hayez (RGI)

During the last decade, unprecedented cost reduction and the increase of new energy technology performance were observed. These technologies range from the supply side to the demand side, via transmission and distribution networks, and include both hardware and digital solutions. Against this backdrop, the third thematic session focused on key modelling assumptions of future technology trends in terms of cost and performance, which are decisive parameters in the model.

3.3.1 Future technology trends

The participants of this session pointed out that following the concept of learning curves (as observed for lithium-ion batteries and solar PV), it could be expected that other technologies (such as heat-pumps, hydrogen-related technologies, or new types of renewables) will follow similar trends in terms of cost reduction and performance increase (e.g., conversion efficiency, storage losses, lifetime). For robust modelling, such cost reduction should be considered for the relevant technologies even if the current prices do not reflect it yet. At the same time, as the experts attending this session noticed, it should be expected that a world of scarcity would imply higher raw material costs. This would lead to higher technology costs if the European recycling industry does not experience a breakthrough in delivering materials required for a technology built-up.

The participants of this session mentioned that the performance trends of each technology should ideally include evolution in efficiency, lifetime, and dynamics. Regarding the technology costs, the participants agreed that the model should distinguish the CAPEX from the OPEX, and include the grid connection costs as part of CAPEX. Some technologies may require more precise cost allocation, like hybrid offshore projects (i.e., offshore wind farms connected to more than one offshore zone). The experts voiced a need to consider a regional sensitivity to costs, when deemed relevant and if data is available. This aspect was considered important, as it would reflect existing asymmetries in Europe due to cost of labor, terrain complexity, and local logistic processes.

During the session, the participants raised specific questions about the carbon footprint of technologies. The participants expressed a need for modelling future decarbonised energy systems which include the carbon footprint of the technology in its total life cycle (in addition to the operational CO2 cost already built-in into the model). This would be a preventive consideration with regard to the Carbon Border Adjustment Mechanism (CBAM) currently under design at the EU level and the CBAM‘s expected effects in the near future.

Finally, the participants remarked that the available cost projections mostly assume enough political and geostrategic stability in the world to enable trade and large cost variation. At the time of this workshop, fossil fuel and raw material supplies uncertainties were perceived to remain stable. Nevertheless, these should be kept in mind when analysing the modelling results. In that context, the participating stakeholders mentioned probabilistic assessments as a powerful tool to help in the decision-making processes under uncertain conditions.

3.3.2 Adjacent discussion points

While the time constraints did not allow deep dives into all aspects related to the projections of future energy technology trends, the session's attendees brought up relevant adjacent discussion points.

First, they considered the role of local distribution networks as a high potential lever for enabling the energy transition – also in terms of land availability. The currently modelled energy network, as presented to the participants, considers only nodes representing states and transmission lines between these nodes. Adding another layer into the optimisation programme would enable the consideration of the distribution system and smaller scale investments. In this way, small-scale infrastructure market would be co-optimised with a larger scale grid extension (that usually has a lower Levelized Cost of Electricity, LCOE).

Moreover, the participants recommended further sensitivity studies to verify the relevance of cost and performance parameters and analyse the impact on the overall results thereof. This would lead to robust results concerning the investment in infrastructure development.

Finally, the participants briefly mentioned the salience of market design assumptions as well as the use of smart grids and digital solutions to improve asset management. They also pointed out the importance of transparency about model assumptions, which can lead to higher trust and legitimacy regarding the modelling results.

3.4 SESSION 4: ENVIRONMENTAL, RESOURCE AVAILABILITY, SUPPLY CHAIN, FINANCIAL AND OTHER CONSTRAINTS

Facilitated by: Jochen Kreusel (Hitachi Energy) & Alexandros Fakas Kakouris (RGI)

The fourth thematic session was dedicated to constraints that could reduce the technical potential of energy transition infrastructure and how these should be reflected in modelling. While traditional inputs such as demand, technological limitations and energy balance are already part of the energy system modelling, the participants agreed that modelling the transformation of an entire energy system would require a recognition of further, non-conventional constraints. These include: environmental constraints, resource availability, supply chain and financial restrictions.

For this purpose, stakeholders highlighted the need to identify a holistic set of questions, encompassing technical, environmental, and societal aspects, that could provide guidance towards the emission reduction goals. Completing this task would not only allow the constraints to be defined and crystalised, but would also guide their proper inclusion in modelling activities. This would require improved data availability, that, for example, could potentially feed the models with operational solutions minimising the environmental impacts (e.g., cease operation of wind turbines during bird migration periods). This can be achieved only through an open dialogue between various stakeholders on assumptions, methodologies and transparent actions.

The participants of this session noted that prioritising a thorough planning of the energy system which includes a reflection over scarcity trends (visible already in the current decade) could prevent highly inefficient, ad hoc solutions. Among the non-conventional restrictions that should be considered in modelling activities, they listed: biodiversity protection, raw material availability and water and land use/occupation. Deepening the environmental constraints would add a further layer of complexity, as environmental factors and models pose their own limitations and constraints. On that front, the participating stakeholders raised concerns about a possible need for the evaluation of these limitations, considering their high diversity. The participants mentioned that currently existing models can present the consequences of selected trade-offs, offering possible and physically consistent solutions alongside a rough cost estimation. They also agreed on the fact that interlinkages between parallel crises (i.e., climate and biodiversity) and related constraints necessitate joint responses and measures.

Furthermore, the participant discussion revealed a concern over the limited workforce availability as a cross-cutting restriction that can affect the entire decarbonisation trajectory – including the transition of different sectors and construction capacity. This is because the energy transition necessitates a significant infrastructure deployment with a related skilled workforce. This holds true especially for the building sector. The replacement of fossil fuel boilers with more efficient (and carbon-free) heat pumps requires a significant number of skilled workers. In that context, the invited stakeholders pointed out a need to explore the compatibility of existing and new infrastructure while considering the limited capacity of the existing workforce. In line with this, some participants supported a near optimal solution approach, the benefits of which would outweigh the slight cost increase. They also valued an orderly “what if” analysis of the transition, focusing on the demand side.

Ultimately, the stakeholders agreed on the need to acknowledge the global perspective of the energy transition, given the variety of pathways to climate neutrality. The recognition that energy transition is not taking place in isolation is a crucial precondition for a sustainable decarbonisation of our economies. It relates to the fact that political decisions at the European level can cause environmental, social, and economic impacts on a global scale and vice versa.

4. CONCLUSIONS AND OUTLOOK

Energy system modelling is fundamental to understand different decarbonisation pathways and their related infrastructure needs. The online workshop “Accelerating full decarbonisation: Resource optimisation in energy infrastructure planning” gathered stakeholders who deal with these questions on a daily basis: energy system modellers, strategists, and planning experts. The interest in this event from numerous stakeholders confirmed the salience and relevance of modelling ambitious energy scenarios, such as the PAC scenario.

During the workshop we presented the results of modelling carried out by Hitachi Energy and reflected on the findings and underlying assumptions with stakeholders in four thematic breakout sessions. The workshop’s objectives were achieved in the following ways:

First and foremost, the interaction with stakeholders allowed feedback to be collected, which will improve the modelling itself and increase the quality of future analysis. More specifically, a short survey carried out at the end of the workshop showed that stakeholders prioritise: (a) consideration of climatic extremes and variations, the inclusion of environmental and spatial constraints, and the identification of resource scarcity; (b) a need to study the effect of recycled materials on future costs, the cost sensitivity to spatial zones, and the carbon footprint of each technology; and (c) the importance of modelling interplayed transmission and distribution scale planning, smart system operation, and the demand pattern. The participants also suggested other topics of interest to be included in the model, for instance, the modelling of digital solutions that could improve asset management or the implementation of constraints related to environmental and biodiversity protection. The aforementioned topics are either under ongoing investigation or will be considered in the later development of Hitachi Energy’s modelling work.

At the time of publishing this Workshop Summary Report first steps to address some of the expressed needs and improve the ongoing analysis have been undertaken. The overview of future features to be included in modelling is summarised in Table 3.

Table 3: Future features

Future feature	Motivation and feature description
Technology supply chain constraint	Considering the case study analysed, assuming an unlimited infrastructure capacity growth per each investment decision step for all technologies at all locations is probably both uncertain and unrealistic. This determinant shall be investigated based on the economic and technology development of various countries, their policy goals as well as historical capacity growth. Another approach to include the new capacity growth constraint would be to combine it with budgetary constraints. Different approaches could also be discussed, in particular the inclusion of non-conventional constraints with regard to biodiversity, raw material availability and land/water occupation.
Time and space resolution	The time step currently adopted for the modelling process has been suited to the current computational power, however, it is not the most suitable sampling method. In order to increase the model robustness and to take more reasonable assumptions for long and short-term storage options, more representative time resolution shall be investigated and selected for further studies. The spatial division of the nodes is based on the territorial areas of different countries. In result, some nodes represent a significantly larger geographical area than the other. Other approaches shall be investigated – for instance, splitting larger countries into small zones that have similar weather conditions, while respecting the electricity system integrity.
Effects of climatic conditions and climate change	The modelling results have been generated with the assumption that the renewable generation profiles remain static as the number in year 2019. This is not fully representing reality, since the renewable generation capacity factor can vary from year to year, and the shape of hourly profile also contains high uncertainty. Additionally, the inclusion of variable weather and long-term climate change effects reflected in the renewable generation (or other input data, such as demand) would enable system modelling with a higher robustness level.
Technology development trend	As the cost projection of technologies can evolve quickly, the input data shall be refined to reflect the newest development (e.g. cost of green hydrogen).
Carbon footprint	Applying the life-cycle assessment (LCA) of technologies may be a better way to represent the process towards net-zero in 2050. Coupling the current optimisation model with LCA will require a more complex commissioning and decommissioning schedule module.

Secondly, we believe that by facilitating this workshop and inviting stakeholders who represented different organisations across the energy and wider economic sectors, we simulated a fruitful multilateral knowledge exchange. These stakeholders elevated the quality of our work by sharing differentiated perspectives, experiences, and best practices.

Finally, based on rich feedback collected from the invited stakeholders, we were able to prioritise the avenues of further exploration, reflect on the specific modelling features, and come to the decision of continuing conversations with external experts. In this context, we will organise focused deep-dive discussions targeting selected stakeholders to further discuss specific assumptions, such as those relating to the demand side model.

The insights collected at the workshop on the model's preliminary results, alongside future feedback from deep dives, will provide a solid ground for further techno-economic analysis. At the same time, we are aware of changing external conditions and the need to adjust our work to shifting reality (e.g. reshaping the import paths, energy consumption curtailment). Russia's invasion of Ukraine shows, on the one hand, that global stability can be easily threatened and, in thus increase the uncertainties related to energy infrastructure planning — such as in resource and material supply chains. Consequently, this can lead to inefficient use of global resources and much higher costs. On the other hand, this crisis makes us think about the short- and mid-term consequences for the European energy system (e.g. for the demand side) and how our work can contribute to further discussions. We remain open to any feedback that would allow us to progress on that front and advance forward in building an optimised European energy system based on renewables.

5. ACKNOWLEDGEMENTS AND LIST OF PARTICIPANTS

We would like to thank all participating stakeholders for dedicating their time and providing us with important input during the workshop. We are grateful to everyone involved from RGI and Hitachi Energy for their commitment in organising this workshop.

Table 4: List of participants and organisations

Participants	Organisations
Rüdiger Barth	Amprion, Germany
Stephanie Bätjer	Renewables Grid Initiative, Germany
Antonella Battaglini	Renewables Grid Initiative, Germany
Tobias Bossman	Artelys, France
Tom Brown	TU Berlin, Germany
Andrzej Ceglarz	Renewables Grid Initiative, Germany
Modassar Chaudry	Cardiff University, UK
Meijun Chen	Hitachi Energy, Switzerland
Damon Coates	Elia, Belgium
Ricardo Coelho	University of Lisboa, Portugal
Sean Collins	IRENA
Matteo De Felice	Joint Research Centre of the European Commission
Alexandros Fakas Kakouris	Renewables Grid Initiative, Germany
Tim Felling	Amprion, Germany
Léa Hayez	Renewables Grid Initiative, Germany
Kevin Johnson	Nordic Energy Research Council
Katarina Knesovic	Hitachi Energy, Switzerland
Ivan Komusanac	WindEurope
Jochen Kreusel	Hitachi Energy, Switzerland
Olivier Lebois	RTE, France
Hei Kern Leong	Hitachi Energy, Switzerland
Cristina Madrid López	University of Barcelona, Spain
Vincent Minier	Schneider Electric, France
Robbie Morrison	Openmod-initiative
Jörg Mühlenhoff	Climate Action Network Europe (CAN Europe), Belgium
Alexandre Oudalov	Hitachi Energy, Switzerland
Maud Perilleux	Elia, Belgium
Stefan Reschwamm	Renewables Grid Initiative, Germany
Anser Shakoor	Hitachi Energy, Switzerland
Elisabeth Zeyen	TU Berlin, Germany
Policy Officers	European Environmental Bureau (EEB), Belgium
Head of Department	Fraunhofer ISE, Germany
Chief Expert	Instrat Foundation, Poland
Research Associate	KU Leuven, Belgium

6. FURTHER READING SUGGESTIONS

- Artelys. (2020) “What energy infrastructure to support 1.5°C scenarios? – Final report” [online]. Available at: https://www.artelys.com/wp-content/uploads/2020/11/Artelys-2050EnergyInfrastructureNeeds.pdf [Accessed 2 February 2022].

- Morrison, R. (2018) “Energy system modeling: Public transparency, scientific reproducibility, and open development”, *Energy Strategy Reviews*, 20, pp.49-63 [online]. Available at: https://doi.org/10.1016/j.esr.2017.12.010 [Accessed 2 February 2022].

- Oudalov, A. (2021) “Infrastructure needs of an optimized European energy system”. EMP-E online conference [online]. Available at: https://emp-e-2021.b2match.io/page-4451 [Accessed 21 April 2022].

- PAC-Scenarios.eu. (2022) *Scenario Development*. [online] Available at: https://www.pac-scenarios.eu/scenario-development.html?L= [Accessed 21 April 2022].

- Pfeifer, A., Herc, L., Batas Bjelić, I. and Duić, N. (2021) “Flexibility index and decreasing the costs in energy systems with high share of renewable energy”, *Energy Conversion and Management*, 240, p.114258 [online]. Available at: https://www.sciencedirect.com/science/article/pii/S0196890421004349 [Accessed 2 February 2022].

- TYNDP. (2022) *Scenarios* [online]. Available at: https://tyndp.entsoe.eu/scenarios/ [Accessed 21 April 2022].

- Zeyen, E., Victoria, M., Brown, T. (2020) “PAC scenarios with PyPSA-Eur-Sec – 4th PAC scenario workshop” [online]. Available at: https://www.pac-scenarios.eu/fileadmin/user_upload/KIT_Aarhus_University_PAC_scenarios_with_PyPSA-Eur-Sec_15oct20.pdf [Accessed 2 February 2022].

- Knezovic, K., Marinakis, A., Evrenosoglu, C.Y., Oudalov, A. (2021) “Role of grid and bulk storage in the integration of variable renewable energy resources: Framework for optimal operation-driven multi-period infrastructure planning”, *Energy*, 226 [online]. Available at: https://doi.org/10.1016/j.energy.2021.120378

7. APPENDIX

7.1 INPUT DATA TABLES

Table 5: Cost input data and characteristics of generation and storage technologies

	Power Cost (€ / MW)	Energy Cost (€ / MWh)	Fixed O&M (€ / MW)	Variable O&M (€ / MWh)	Efficiency	Lifetime (years)
Solar PV	560,000 ~ 300,000	\	14,000	0	\	25
Wind Onshore	1,258,000 ~ 1,105,000	\	31,450	0.1	\	25
Wind Offshore	2,428,450 ~ 1,592,050	\	60,711	0.2	\	25
Hydro	2,208,000	\	44,160	12.75	0.9	80
Run of River	3,059,020	\	61,180	21.25	0.9	80
Battery	92,000 ~ 75,000	315,138 ~ 190,000	2,760	5.82	0.93 (in), 0.93 (out)	15
Pumped Hydro Storage	1,659,193 ~ 1,518,558	17,850 ~ 5,000	33,184	6.87	0.86 (in), 0.75 (out)	80
SMR_CCS	1,269,475 ~ 1,088,000	\	38,084	3.9	0.75	20
Electrolysis	594,649 ~ 267,097	\	17,839	1.2	0.65	20
H2 Turbine	1,100,000 ~ 880,000	\	23,357	2.86	0.5	40
Fuel Cell	1,076,667 ~ 850,000	\	56,100	1.04	0.5	15
Salt Cavern	625 ~ 375	3,000 ~ 2,000	\	\	0.98 (in), 0.98 (out)	40

Table 6: Transmission and hydrogen pipeline specific data

	Fixed Cost (€ / MW)	Variable Cost (€ / MW / km)	End Station Loss (%)	Variable Loss (% of installed capacity per 1000 km)	Lifetime (years)	Fixed Maintenance Cost (% of CAPEX)
Overhead line	40,000	400	0.4	7	60	3.5
Underground cable	121,000	500	1.5	3	60	3.5
Undersea cable	181,500	2,100	1.5	3	60	5.25
Land pipeline	76,500	1,000	\	2.4	50	\
Undersea pipeline	114,750	1,500	\	2.4	50	\

Table 7: Fuel price data range of technologies (in function of the zone)

Fuel Type	Fuel Price (€ / GJ)	Heat Rate (MJ / MW)
Hard Coal	1.56 ~ 3.08	10,000
Brown Coal	1.56 ~ 3.25	10,000
Uranium	1.275	11,000
Natural Gas	3.54 ~ 6.83	7,500
Oil	9.11 ~ 10.09	12,000
SMR	4.01	3,600
SMR_CCS	4.01	3,600

Table 8: CO2 price

CO2 Price (€ / t)	25

Table 9: Ramping and emission data of generation technologies

	Average Heat Rate (MJ / MW)	CO2 Emission (kg / MWh)	Generation Slope (%)
Hard Coal	10,000	900	12.5
Brown Coal	10,000	900	12.5
Nuclear	11,000	0	0
Natural Gas	7,500	380	50
Oil	12,000	900	12.5
Biomass	10,000	100	12.5
Hydro	0	0	100
Run of river	0	0	100

7.2 MAIN REFERENCES OF COST DATA

General costs:

- IEA, NEA. (2020). *Projected Costs of Generating Electricity*. Available at: https://iea.blob.core.windows.net/assets/ae17da3d-e8a5-4163-a3ec-2e6fb0b5677d/Projected-Costs-of-Generating-Electricity-2020.pdf
- IRENA. (2020). *Renewable Power Generation Costs in 2019*. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Power_Generation_Costs_2019.pdf
- Kost, C., Shammugam, S., Fluri, V., Pepper, D., Davoodi Memar, A., Schlegl, T. (2021). *LEVELIZED COST OF ELECTRICITY - RENEWABLE ENERGY TECHNOLOGIES.* Fraunhofer Institute For Solar Energy Systems ISE. Available at: https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/EN2021_Fraunhofer-ISE_LCOE_Renewable_Energy_Technologies.pdf
- McKinsey. (2010). *Transformations of Europe Power System's until 2050*. Electric Power and Natural Gas Practice. Available at: https://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/epng/pdfs/transformation_of_europes_power_system.ashx
- Mongird, K., Viswanathan, V., Vartanian, J., Sprenkle, V., Baxter, R. (2020). *2020 Grid Energy Storage Technology Cost and Performance Assessment*. Technical report No. DOE/PA-0204. Available at: https://www.pnnl.gov/sites/default/files/media/file/Final%20-%20ESGC%20Cost%20Performance%20Report%2012-11-2020.pdf
- Stehly, T., Beiter, P., Duffy, P. (2020). 2019 *Cost of Wind Energy Review*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-78471. Available at: https://www.nrel.gov/docs/fy21osti/78471.pdf

Hydropower:

- IEA. (2021). *Hydropower Special Market Report Analysis and forecast to 2030*. Available at: https://iea.blob.core.windows.net/assets/4d2d4365-08c6-4171-9ea2-8549fabd1c8d/HydropowerSpecialMarketReport_corr.pdf
- IRENA. (2012). *RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES – Hydropower.* Volume 1: Power Sector Issue 3/5. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2012/RE_Technologies_Cost_Analysis-HYDROPOWER.pdf

Storage:

- Atb.nrel.gov. 2022. *Pumped-Storage Hydropower | Electricity | 2021 | ATB | NREL*. [online] Available at: https://atb.nrel.gov/electricity/2021/pumped-storage_hydropower
- IRENA. (2017). *Electricity Storage and Renewables: Costs and Markets to 2030*. Available at: https://www.irena.org/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf
- IRENA. (2020). *Electricity Storage Valuation Framework: Assessing system value and ensuring project viability*. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Mar/IRENA_storage_valuation_2020.pdf

Hydrogen:

- Cihlar, J., Mavins, D., Van der Leun, K. (2021). *Picturing the value of underground gas storage to the European hydrogen system*. Gas Infrastructure Europe. Available at: https://www.gie.eu/wpcontent/uploads/filr/3517/Picturing%20the%20value%20of%20gas%20storage%20to%20the%20European%20hydrogen%20system_FINAL_140621.pdf
- Landinger, H., Bünger, U., Raksha, T., Weindorf, W., Simón, J., Correas, L., Crotogino, F. (2014). *Assessment of the Potential, the Actors and Relevant Business Cases for Large Scale and Long Term Storage of Renewable Electricity by Hydrogen Underground Storage in Europe*. HyUnder. Available at: http://hyunder.eu/wp-content/uploads/2016/01/D2.2_Benchmarking-of-large-scale-seasonal-hydrogen-underground-storage-with-competing-options_final.pdf
- Vickers, J., Peterson, D., Randolph, K. (2020). *Cost of Electrolytic Hydrogen Production with Existing Technology*. DOE Hydrogen and Fuel Cells Program Record. 20004. Available at: https://www.hydrogen.energy.gov/pdfs/20004-cost-electrolytic-hydrogen-production.pdf