SYSTEMVISION2050
by amprion

The future of energy in Germany and Europe

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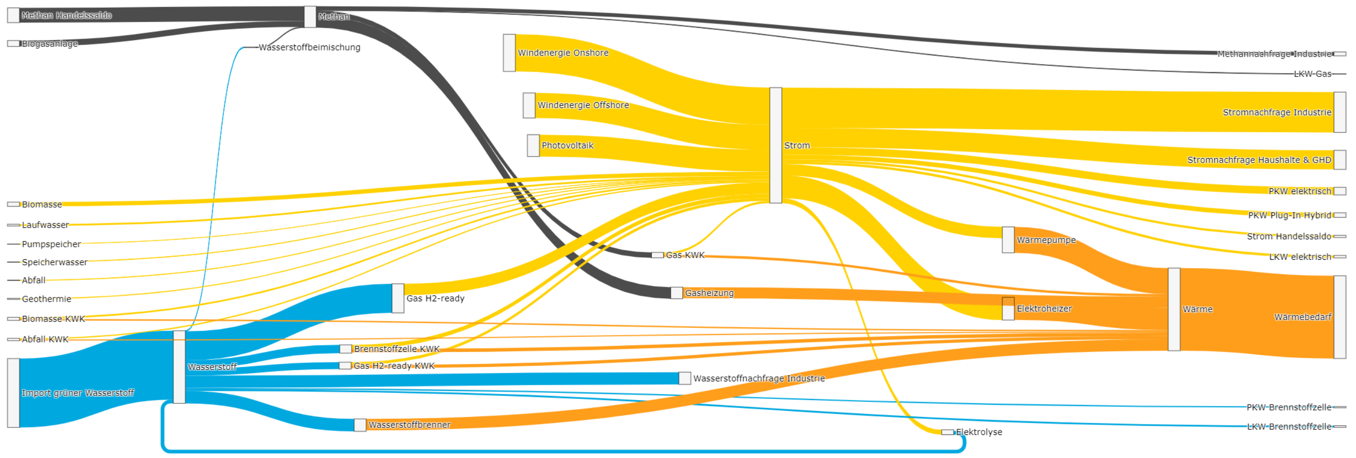
Hitachi ABB Power Grids



A technological pathway towards a more renewable, more electric, more interconnected system.

Motivation

There is a global consensus on the need to reduce greenhouse gas emissions and to abate climate change. Germany recently has raised ambitions and pledged net-zero emissions by 2045 compared to a previously announced target by 2050. This will require a very fundamental transformation of the energy system. Long-term scenarios are an important complement to usually more incremental policies, providing orientation and indications for fundamental decisions needed. As leading provider of technologies for electrical networks, Hitachi ABB Power Grids analyses the long-term perspectives of energy demand and supply in a climate-neutral world. These studies have resulted in three main conclusions:

- Electricity from renewable sources will be the main input for the entire energy system. Larger shares of variable renewable sources will therefore have to be accommodated.
- Transportation, buildings and industries should be directly electrified wherever possible. For the remaining applications, complementary sustainable energy carriers are needed.
- International collaboration is key for security of supply and cost-efficiency.

As nobody has ever built a climate-neutral energy system it is very unlikely that a single person or institution will be able to find the one and only scenario. Collaboration, exchange of views and findings and joint discussion and analysis are therefore key success factors. Amprion's "Systemvision 2050"-initiative offers a very valuable platform to achieve this in a systematic way. It allows partners to test their scenarios using Amprion's models. This leads to comparable results based on very different assumptions of the partners and therefore to a robust basis for discussions and further analysis.

First Core Assumption

By 2050, power generation will undergo a dramatic transformation with significant shifts. Total power generation capacity will more than double compared to 2020. With wind and photovoltaic capacity growing by more than 300 GW, fluctuating renewable energy (VRE) sources will be the undisputed leaders with an installed generation capacity of 85% by 2050.

Our scenario assumptions

Our scenario can be best described as a *"carbon-neutral energy system with electricity from renewable energy sources as a backbone and strong degree of electrification and international integration"*.

All scenario simulations have been performed by the Amprion modeling team using an in-house developed capacity expansion planning software solving a linear optimization problem with a set of constraints. The parameters of the scenario discussed in this article represent one of many possible futures we can envision depending on macro-economic trends, evolving public policies, speed of technological innovation, etc.
The following sections summarize our key scenario assumptions.

Massive electrification of final energy consumption

We expect the total energy consumption to decrease in the future due to deployment of more energy efficient technologies, consumer behavior changes and growing share of electrification in transport, industry and building sectors. At the same time the annual electricity consumption will more than double compared to today's levels – mainly driven by increased electricity use by electric road transport and heating while traditional industrial, commercial and residential demand will remain close to their respective volumes in 2020.

In order to test their potential, in our hypothetical scenario we consider that – as a complement to direct electrification – carbon-neutral gases are available at competitive prices. These are produced using green electricity in the case of hydrogen and captured carbon dioxide for synthetic methane. These gases will grow as a feedstock in various industrial processes from a traditional ammonia production expanding into new segments like steel and cement making, and as a potential fuel for vehicles (mainly heavy, long distance road transport) and gas boilers and fuel cells. The power generation sector will also use these gases for a balancing of more time-variant renewable sources and electricity consumption.

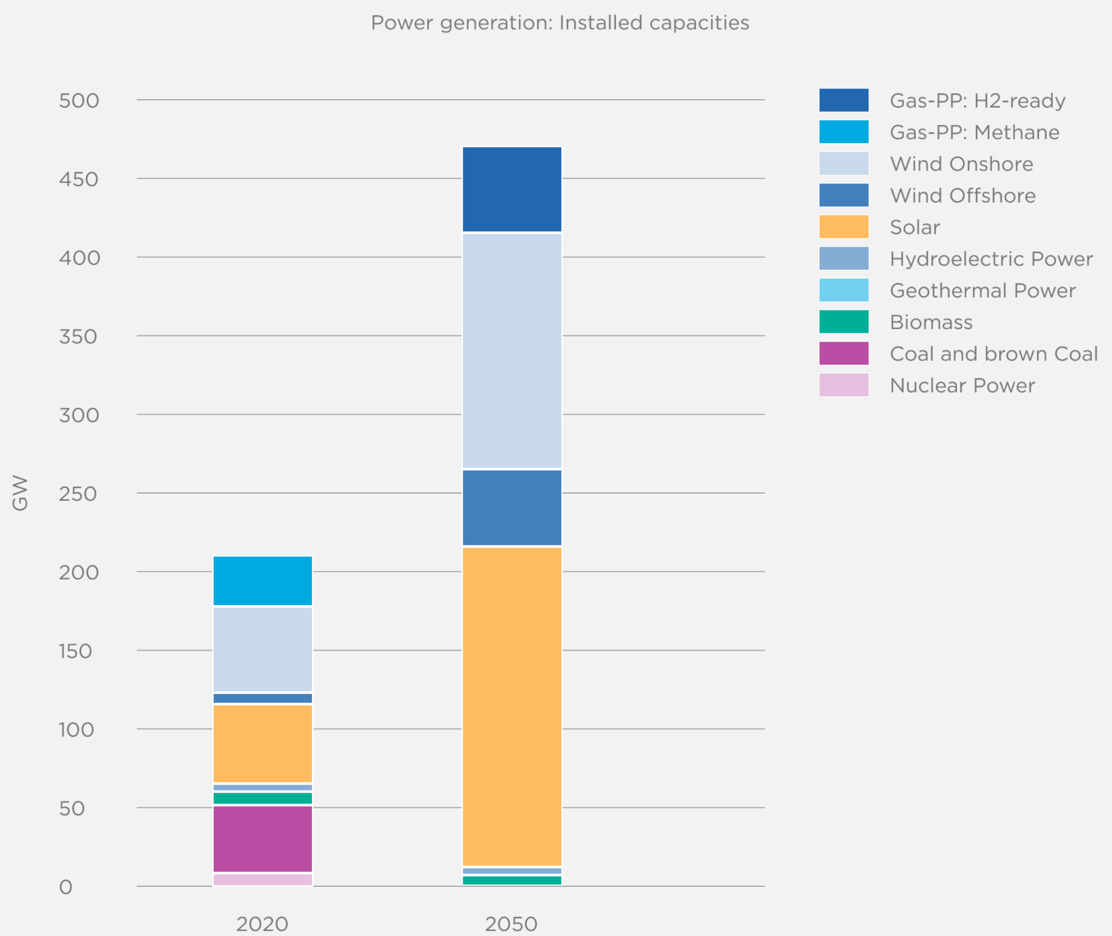
Renewable energy sources dominate the energy landscape

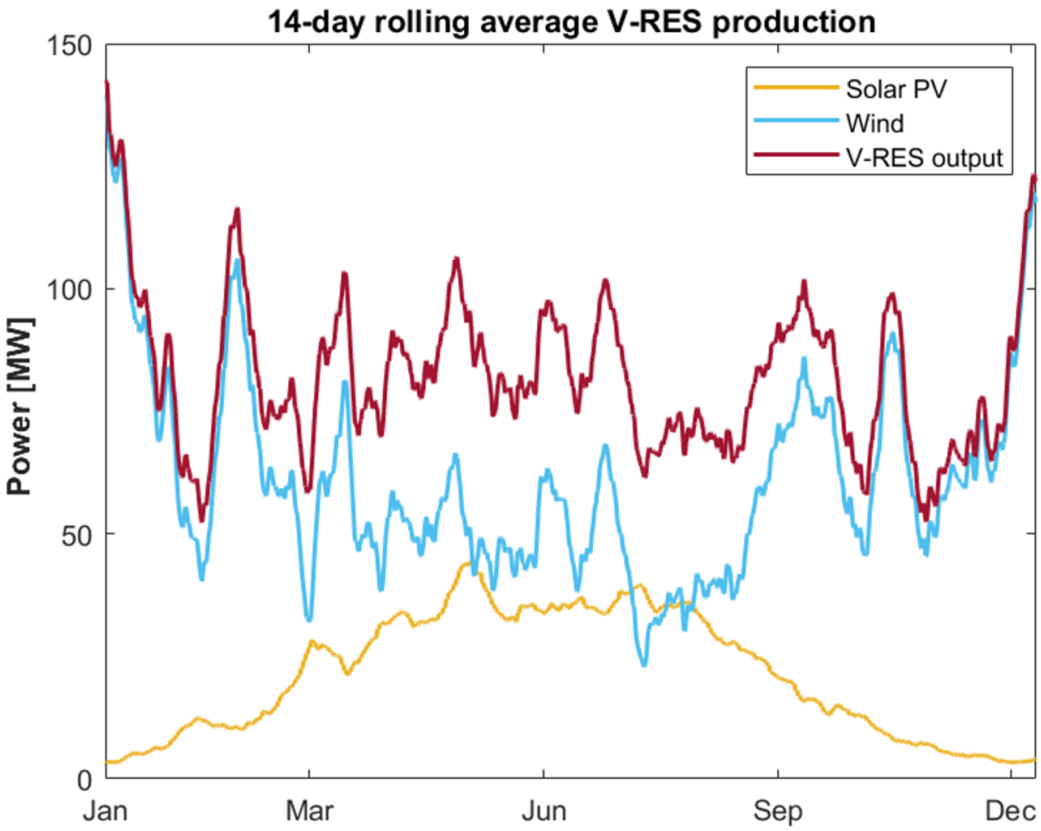
There will be a dramatic change and shift in the power generation landscape by 2050. Overall installed power generation capacity will more than double compared to 2020. With more than 300 GW of newly added wind and solar PV capacity, variable renewable energy sources (VRES) will be an undisputable champion accounting for 85% of total installed generation capacity by 2050.

Following the European power generation de-carbonization trends and safety concerns of nuclear power in Germany, we assume that coal and nuclear power plants will be fully retired. Biomass and hydro will remain at low levels, similar as in 2020 and in this particular future scenario we consider that gas fired power plants will be switching their fuel sources and using hydrogen and synthetic methane instead of fossil fuel to cover periods of low wind and solar generation.

Potential wind, solar and hydro generation outputs are represented by annual profiles in hourly resolution and proportional to typical values of wind speed, solar irradiance and water inflow. Wind and solar resources complement each other on the seasonal base with wind prevailing in winter, while solar PV predominates during summer.

Since, within the boundary conditions of the





particular scenario chosen for this study, green hydrogen is expected to contribute to the overall energy balance in Germany in 2050, we have allowed the model to build a domestic water electrolyzer capacity for green hydrogen production. By that we can explore the distribution between domestic production and import.

Many countries around the globe plan for a significant ramping up of green hydrogen production. For example, Middle East and North African countries, Australia all possess abundant land to install enough solar and wind generation capacity to feed into large scale water electrolysis based on desalinated water. Green hydrogen can be then shipped from those location to Germany in a liquified form. In order to explore the maximum consequences of such development, we have made a rather radical scenario assumption that an unlimited amount of imported green hydrogen could be delivered on demand at a competitive price.

Natural gas (synthesized) will play a limited role in the future energy landscape and is sourced via biogas production facilities and potentially via methanation plants. In this scenario we also assume an unlimited access to imported carbon-neutral methane.

Second Core Assumption

The future German energy system will rely heavily on weather-dependent power generation and will require the use of all flexibility sources. We include two main classes of energy storage in our scenario. The first is lithium-ion battery technology with more than 25 GW of installed capacity and energy storage of up to 10 hours. This short-term storage operates mainly on a diurnal basis. Second, we envision long-term storage for green hydrogen, with a storage potential of nearly 110 TWh in underground reservoirs such as salt caverns and depleted gas fields.

Strongly interconnected energy transport network

As part of the scenario there are two main energy transport systems connecting different model zones in Germany:

- Electric high voltage transmission network including AC and DC technologies.
- Hydrogen transport network based on high pressure trunk pipelines.

Third Core Assumption

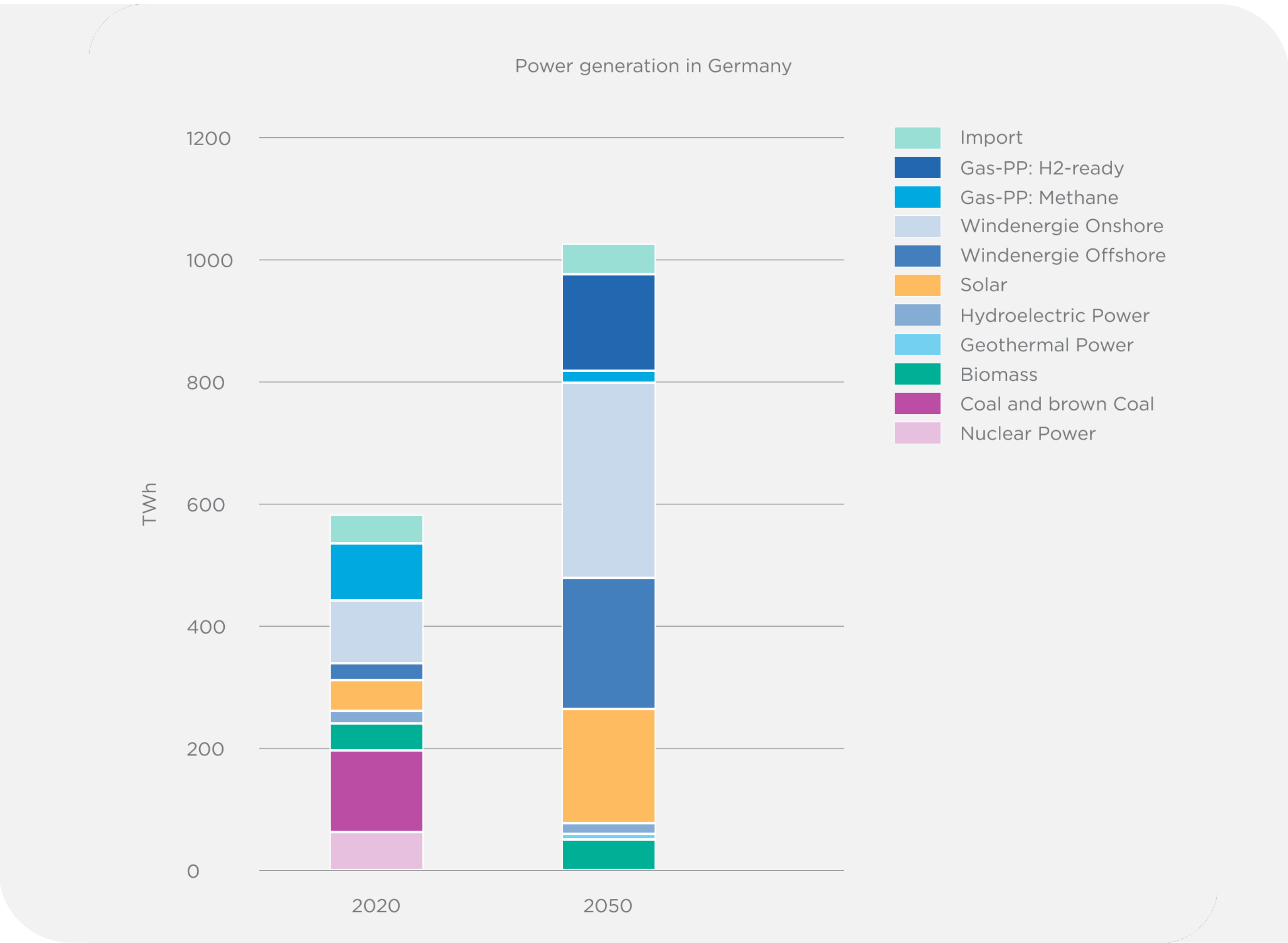
We assume about 6.5 GW of flexible electricity demand as well as controllable EV charging processes (without V2G technology).

The multi-zonal model of Germany is an integral part of the European power system. Therefore, our scenario includes electric cross-border interconnectors to several countries. We set a scenario cap for a newly added electric transmission capacity as 1.5 times of NEP 2040 (national network development plan) targets. The model has no cross-border hydrogen pipelines.

Energy storage and other sources of flexibility

The future German energy system as modeled in our scenario will heavily rely on weather dependent generation and will need all sorts of flexibility sources. We include two main classes of energy storage in our scenario. First is a lithium-ion battery technology with more than 25 GW of installed power capacity and up to 10 hours of energy storage. This short-duration storage will principally operate on diurnal base. Second is a long duration green hydrogen storage which can potentially store almost 110 TWh in underground reservoirs such as salt caverns and depleted gas fields.

In addition, we assume about 6.5 GW of flexible traditional electricity demand as well as controllable EV charging (without vehicle to grid functionality).



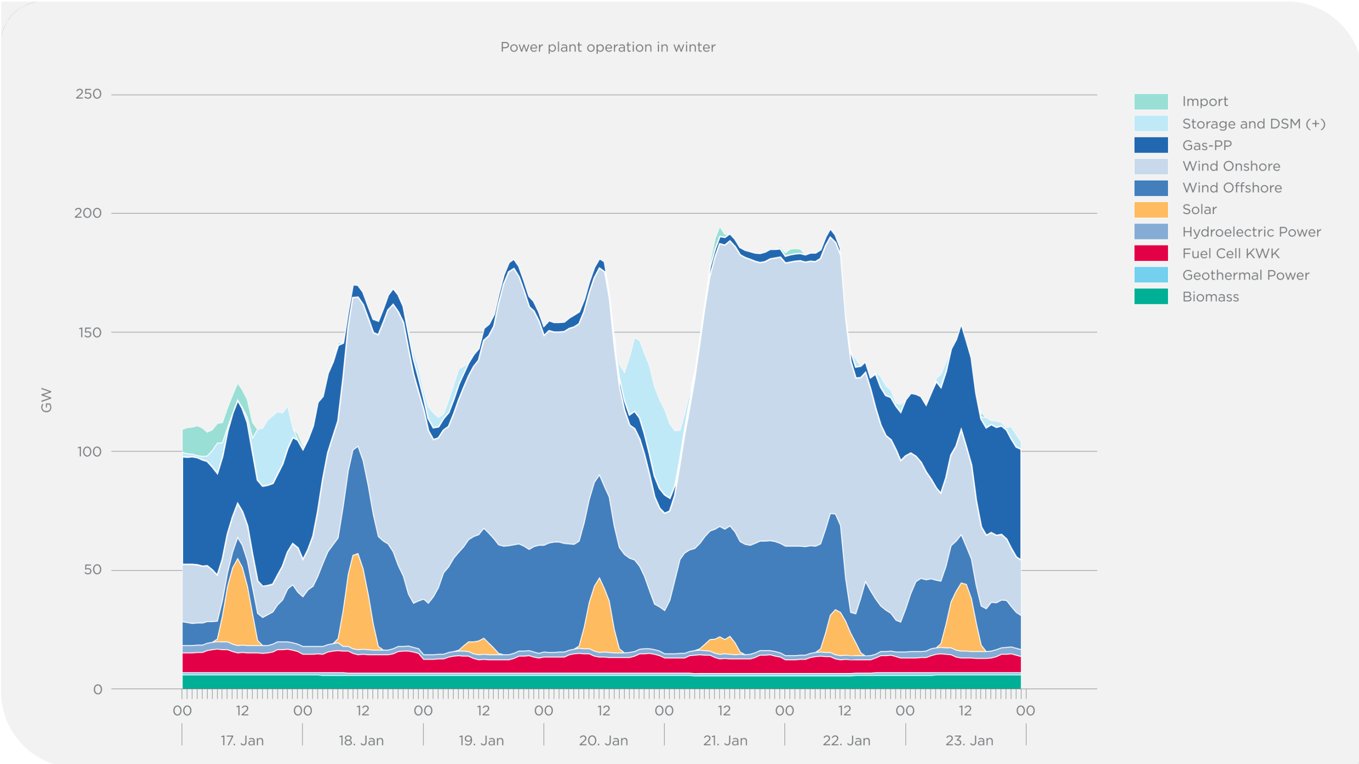
Our results

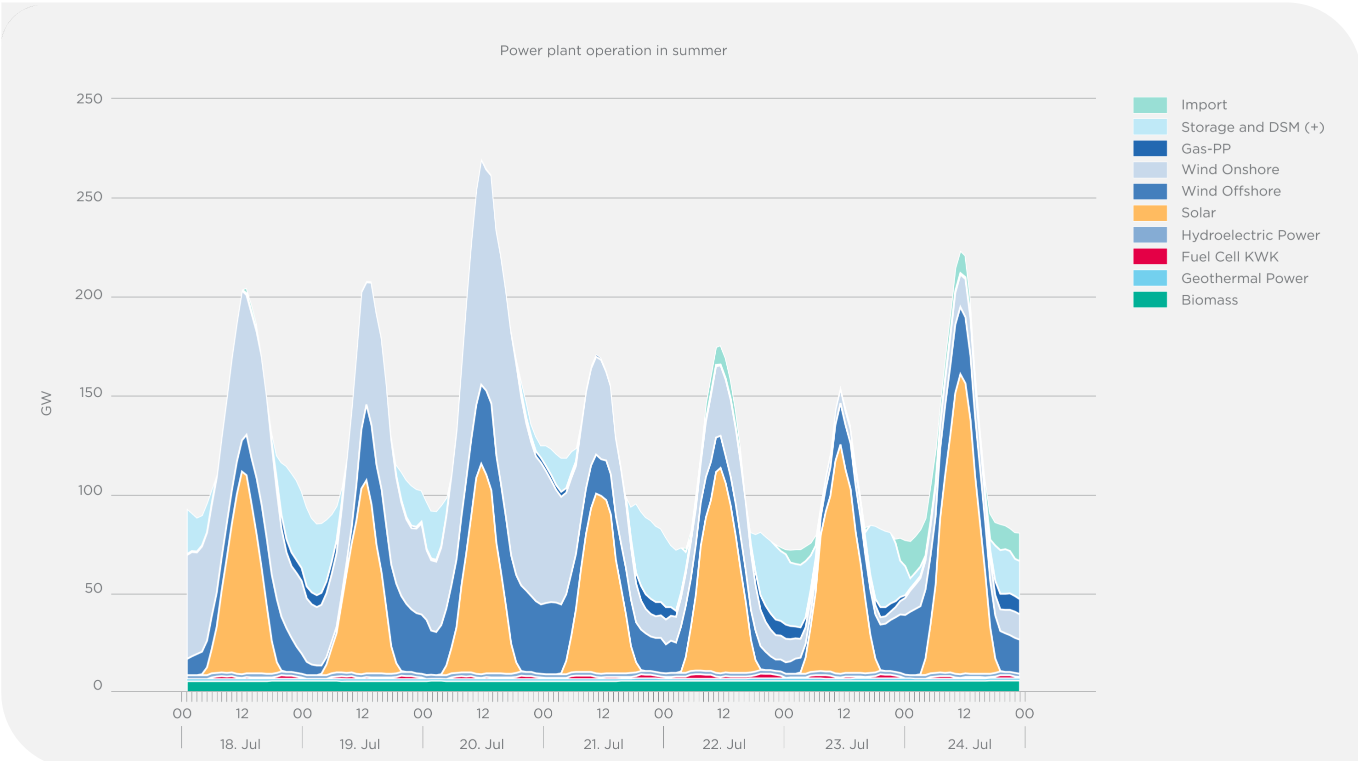
The most important outputs of our scenario are discussed in this section.

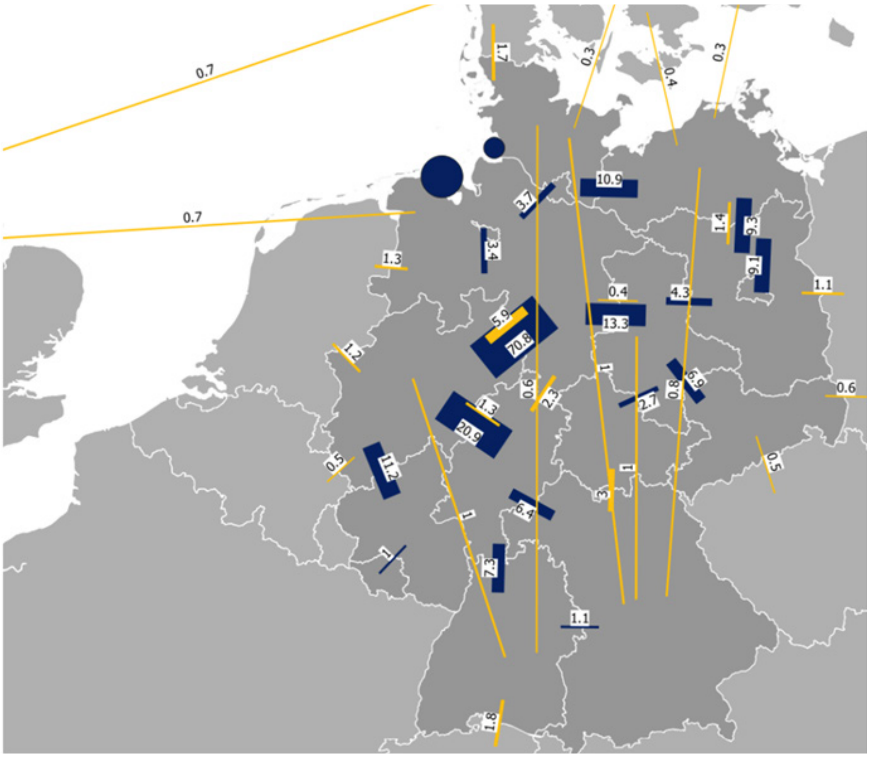
1. Electricity generation is dominated by variable renewables – wind and solar PV – which accounts for almost 75% of total generation. Hydrogen based gas turbines contribute to another 15% mainly playing a role of balancing source with a limited number of full load hours (~25%) while biomass and hydro will cover the rest as a base generation with high number of full load hours (almost 100%).

Both wind and solar resources frequently exhibit a significant variability on weekly and diurnal scale. Solar PV is characterized by a well predictable bell-shaped profile with rare distortions due to fast changing cloud conditions while a wind generation profile is more irregular and may demonstrate fast ramping up and down across a wide power range.

Despite a scenario assumption that there is a very large installed VRES capacity, it is not possible to supply all local energy needs including hydrogen and synthetic methane. Local electrolyzer capacity has a low utilization with full load hours not exceeding 17% while a local methanation capacity has zero utilization factor (which means that as a result of the simulation it should be removed from the input scenario). In these


Power plant operation in winter
250
200
150
100
50
0
GW
00
12
17. Jan
18. Jan
19. Jan
20. Jan
21. Jan
22. Jan
23. Jan
Import
Storage and DSM (+)
Gas-PP
Wind Onshore
Wind Offshore
Solar
Hydroelectric Power
Fuel Cell KWK
Geothermal Power
Biomass

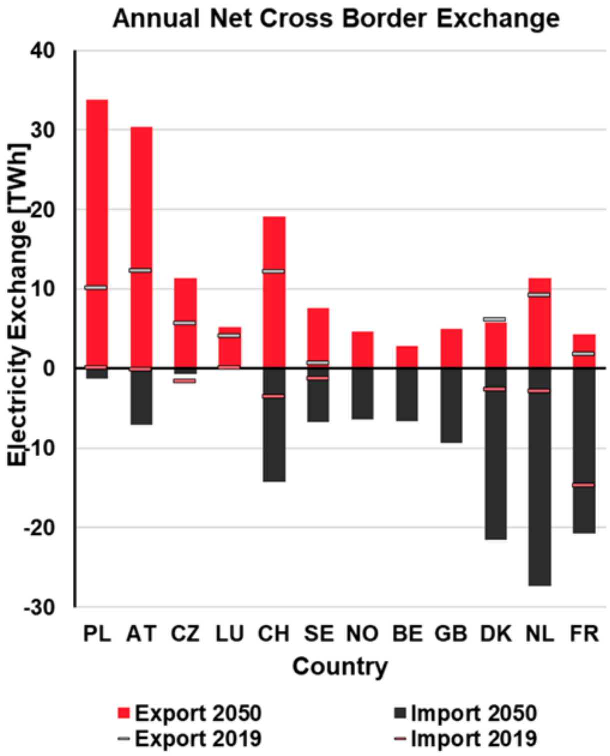

Power plant operation in summer
250
200
150
100
50
0
GW
00
12
18. Jul
19. Jul
20. Jul
21. Jul
22. Jul
23. Jul
24. Jul
Import
Storage and DSM (+)
Gas-PP
Wind Onshore
Wind Offshore
Solar
Hydroelectric Power
Fuel Cell KWK
Geothermal Power
Biomass

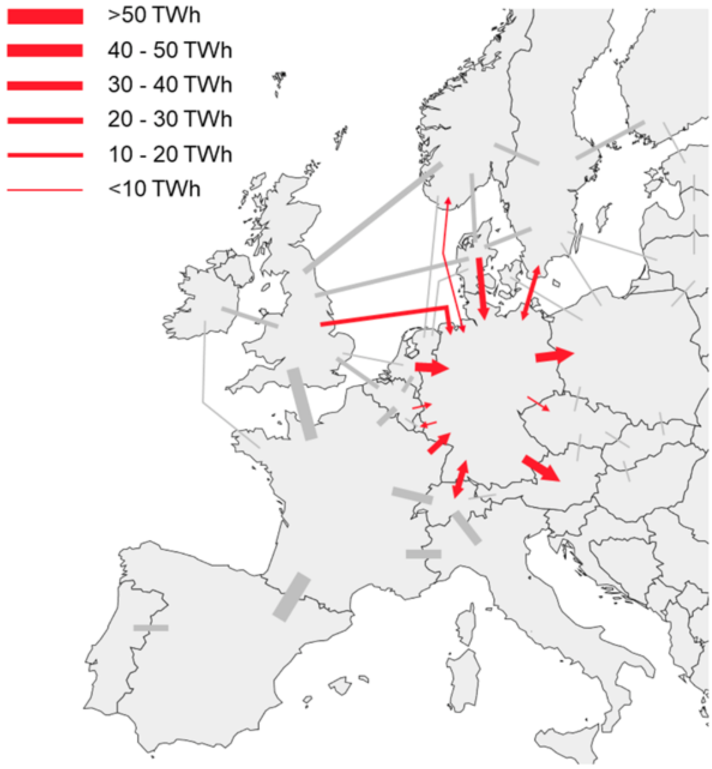


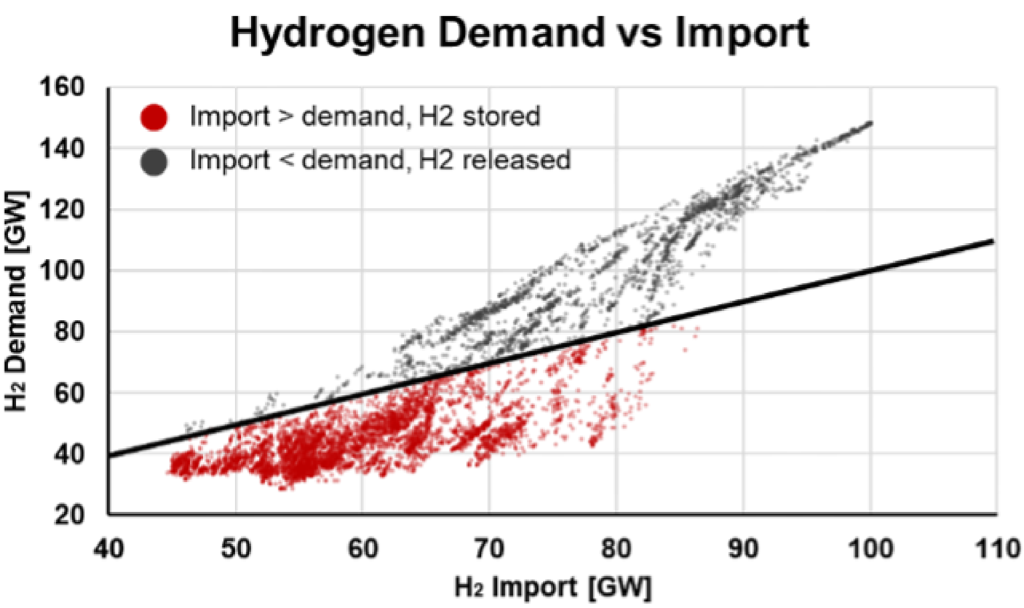
circumstances the model decides to import a significant amount of hydrogen and methane. 95% of all used green hydrogen is imported in liquified form via terminals located on North Sea coast and more than 60% is re-electrified in peaking fuel cells and gas fired power plants during the periods of low VRES availability which is illustrated by the hydrogen loop on a scenario Sankey plot. (See on Page 2)

Due to temporal and spatial complementarity of various types of renewable sources and energy consumption across Germany and Europe, a strong energy transport infrastructure will play a vital role in increasing a real-time utilization rate of wind and solar generation. The simulation results show a notable expansion of electric transmission grid, well beyond the NEP 2040 targets. International transmission capacity is increased from 30 GW in 2020 up to almost 80 GW in 2050 of which 11 GW is built on top of the NEP 2040 targets (~25% increase). From a geographic perspective the model adds more extra cross-border capacity on the western border while the southern border has the lowest additional capacity expansion. Looking at the map we can see a significant capacity increase of internal transmission network mainly along the north-south axis. Newly built hydrogen pipelines transport an imported green gas from the North Sea coastal areas towards south and east.

Germany has been playing a pivotal role of an energy flow crossroad and transit hub in Europe since decades. In the framework of our scenario analysis we have studied a potential strengthening of that role by analyzing simulated total (export + import) annual energy exchanges with each interconnected country in 2050. The results of our scenario analysis show that “west” will be the most dominated direction with about 40% of total energy exchange (mostly imports) while eastern direction will transmit only 18% (mainly exports). Three countries will account for almost half of total energy exchange with Germany, namely the Netherlands, Austria and Poland. Interconnectors across North and Baltic seas will contribute to about 17% of total energy exchange.

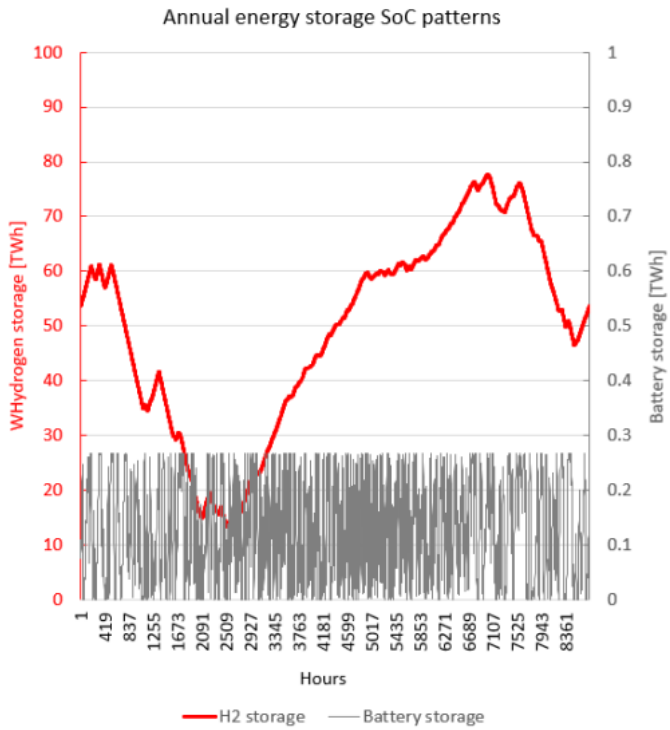

Annual Net Cross Border Exchange
Electricity Exchange [TWh]
40
30
20
10
0
-10
-20
-30
PL AT CZ LU CH SE NO BE GB DK NL FR
Country
Export 2050
Export 2019
Import 2050
Import 2019


>50 TWh
40 - 50 TWh
30 - 40 TWh
20 - 30 TWh
10 - 20 TWh
<10 TWh


Hydrogen Demand vs Import
Import > demand, H2 stored
Import < demand, H2 released
H2 Demand [GW]
160
140
120
100
80
60
40
20
40 50 60 70 80 90 100 110
H2 Import [GW]

2. Underground hydrogen storage could provide an economic alternative to peak capacity of liquefied hydrogen terminals which can be optimally sized and operate at constant rate of processing imported green hydrogen. We observed a theoretical seasonal cycle performed by underground hydrogen storage facilities with a peak stored energy in autumn and a nadir in spring.

Battery storage will most likely operate at much higher cycle frequency reaching maximum and minimum storage levels every couple of days. EV fleet charging can be adjusted to fit periods of maximum VRES oversupply. This will be possible because we assume that future EVs will be equipped with larger batteries and can drive for several days without consuming energy from the grid.



Reflection and conclusions/follow up work

The Systemvision 2050 model has confirmed the consistency of our carbon-neutral scenario for Germany achieved via a significant increase of wind and solar PV capacity, massive direct use of renewable electricity in road transport and heating sectors as well as via growing international power exchanges across Europe. The results demonstrate an importance of deploying all technologies capable to support an integration of a massive amount of time-varying renewable generation such as energy storage, controllable demand, dispatchable generation using green hydrogen and especially grid expansion.

One particular surprise of the model output was the high level of electrification using hydrogen-ready gas turbines for balancing time-varying, renewable generation sources. However, our input assumptions related to a domestic hydrogen production capacity via water electrolysis turned to be overestimated. Unlimited access of the model to imported green hydrogen and relatively limited amount of excessive renewable generation result in a low utilization of domestic electrolyzers. We will reduce the local green hydrogen production capacity and fine tune other scenario parameters in the next round of model improvement. There are some potential model enhancements which will be implemented as well, for example: inclusion of other means of transport (shipping, aviation), potential import of green hydrogen via a European gas pipeline network and use of EV batteries for grid support services (vehicle to grid). We are looking forward to continuing our collaboration with Amprion's experts to further advance the Systemvision 2050 analysis.

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