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Achieving 100% renewable power system in Germany

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ABSTRACT

Most recently, the federal government in Germany published new climate goals in order reach climate neutrality by 2045. This paper demonstrates a path to a cost optimal energy supply system for the German power grid until the year 2050. With special regard to regionality, the system is based on yearly myopic optimization with the required energy system transformation measures and the associated system costs. The results point out, that energy storage systems (ESS) are fundamental for renewables integration in order to have a feasible energy transition. Moreover, the investment in storage technologies increased the usage of the solar and wind technologies. Solar energy investments were highly accompanied with the installation of short-term battery storage. Longer-term storage technologies, such as H2, were accompanied with high installations of wind technologies. The results pointed out that hydrogen investments are expected to overrule short-term batteries if their cost continues to decrease sharply. Moreover, with a strong presence of ESS in the energy system, biomass energy is expected to be completely ruled out from the energy mix. With the current emission reduction strategy and without a strong presence of large scale ESS into the system, it is unlikely that the Paris agreement 2° C target by 2050 will be achieved, let alone the 1.5° C

Keywords: Energy Market, Energy Planning, 1.5-Degree-target, Energy Storage Systems, Grid Integration, Energy System Optimization

NONMENCLATURE

Symbol	**Description**
i	Year
$\mathscr{M}_{y}$	Maximum yearly potential
g	Generation technology
n	Network node
Ɛ	Newly added capacity
ɩ	Element lifetime
Ӽ	Existing capacity
κ	Annualized capital cost per unit capacity
ӽ	Dispatch of existing generation capacity
o	Marginal cost per unit dispatch
ε	Dispatch of newly added generation capacity
s	Storage technology
Ꜧ	Storage dispatch
t	Time
ɕ	Storage technologies state of charge
fc	Cost increase/decrease factor

1. INTRODUCTION

Recently, the trend in energy systems is to compensate removed fossil-based fuels with the clean renewable energies resources to cover the ever-growing energy demands and stay in line with reducing the global emissions. However, due to the gap and time difference between producing times of renewables and demand time in the energy system, the need of temporally storing electric power have a great necessity. Batteries have the ability to support the electrical system with a range of several kWh to large capacities of MWh [1]. Moreover, pumped hydro storage and reservoir storage systems have a higher scale of capacity, yet their use and potential are limited due to their specific geographic requirements and already reached their maximum potential in Germany. [2]

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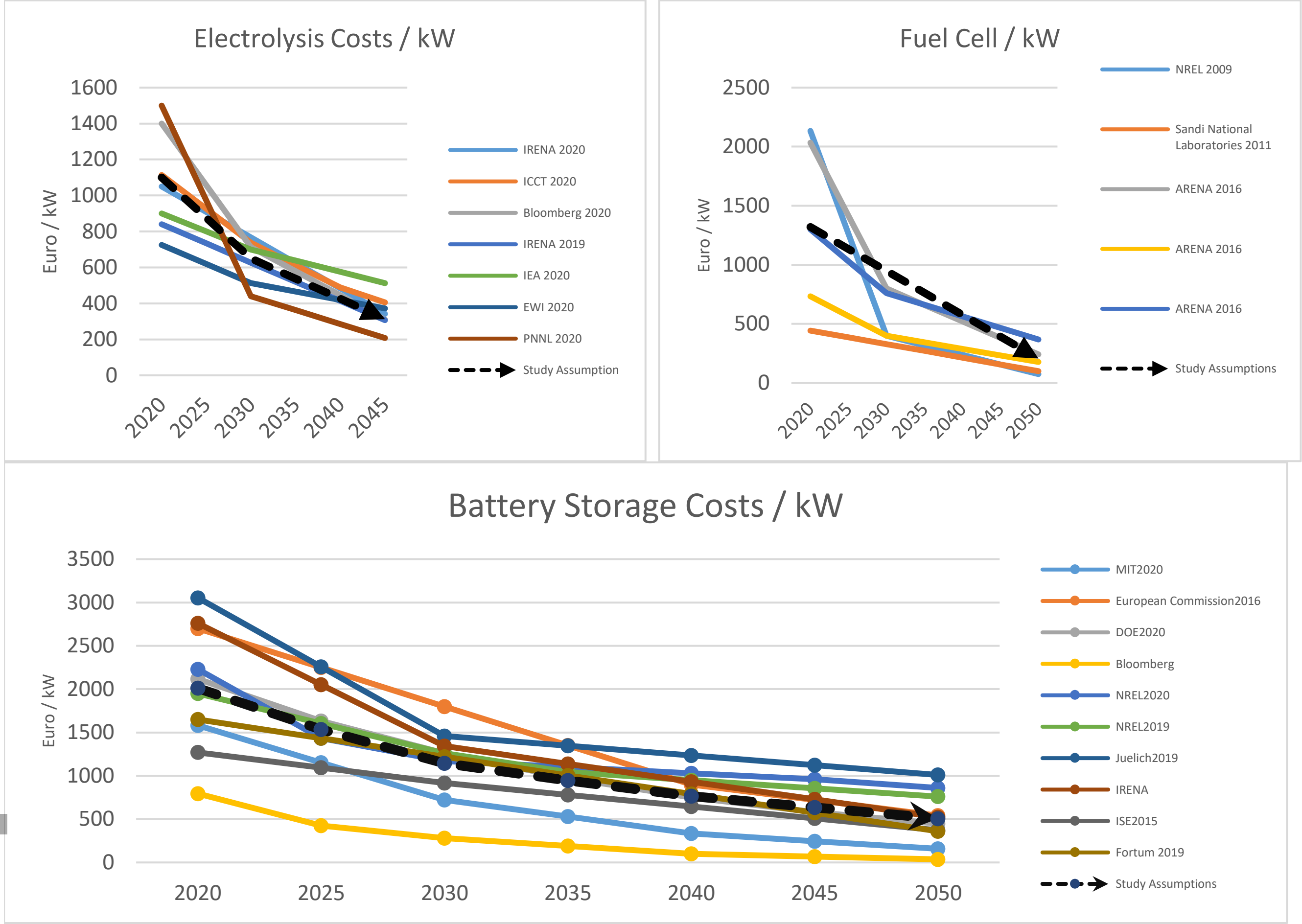


Figure 1: Cost development for storage technology components. [16] to [26]

The fluctuating nature of renewable energy resources such as PV and Wind is a key challenge to system operators, as they cannot be relied on directly to either form a stable grid, or to support the system as a standalone unit without the use of synchronous generators, which is basically found in thermal power plants. Thus, the use of fossil-based fuels conventional power plants will remain an essential part to operate the grid, meaning that the CO_2 reduction targets cannot be fulfilled effectively. Therefore, stationary ESS offer a solution to that problem, as their supply is uninterrupted and offer to stabilize the grid, even with the highly prominent time varying renewable energy resources, they can be used to balance their fluctuations [3].

Large energy storage systems have been increasingly deployed in the energy system, however their potential and role in the energy transition is yet to be exploited [4].

The national hydrogen strategy expects 90 to 110 TWh of hydrogen will be needed by 2030 along with 5 GW of capacity to cover this demand [5]. Moreover, another 5 GW of additional capacity will be needed by latest 2040. In order to investigate the need for ESS in Germany, with a regional outlook on the energy system, MyPyPSA-Ger model was used, a myopic optimization brownfield model with high spatiotemporal resolution for the German energy system with the ability to construct a roadmap for the energy transition path [6].

2. MODEL DEVELOPMENT

In this section, only changes to the original MyPyPSA-Ger [6] model are presented as rules within the model.

2.1 Costs of storage units

Despite their benefits and key role in the energy system, ESS still have the problem of a being an expensive solution with complex maintenance. Although it is most recently subject to a significant drop in their investment costs, they still account for the highest share of an energy system cost, making it a least favored solution compared to back up generation when it comes to a cost-effective solution for energy systems [7].

Several studies showed different cost projections for batteries and hydrogen storage technologies in the future as shown in Figure 1. As the model optimizes with a myopic approach, it is crucial that the cost projections of battery and H2 storage technologies are taken in a timely manner. For the sake of this study, the modest cost decrease assumptions are implemented.

The cost components considered in the model are, the battery inverter (Eur/kW) and the cost of battery energy storage (Eur/kWh) with 6 hours of maximum storage capability, while for the hydrogen storage are the electrolysis (Eur/kW), cavern (Eur/kWh) with 168 hours of maximum storage capability, and fuel cell (Eur/kW). The marginal cost of the batteries is assumed to be zero, which is justified as the cost of charging process of batteries is already part of the total system cost. The capital cost of the storage technologies changes over time based on the chosen learning curve.

$$\kappa_{s,i} = \kappa_{s,i-1} * fc_{s,i} \tag{1}$$

2.2 Convert extendable storage units to fixed rule

As this study is done with a myopic foresight, it is important that the model understands the concept of time in terms of new investments. In the original model, every component has an “extendable” option that allows for capacity extension per the optimization requirements and constraints. Therefore, for each storage element, a “fixed” component is added to the network at the same location with a deactivated extension option and a zero-capital cost so that it will not affect the total system cost of the network. The goal behind this is to store the newly added storage capacity as well as building over the previously installed capacities and consider them in the optimization process.

$$\text{Ꭓ}_{s,n,i=2020} = 0 \; \forall \; all \; s \; in \; extendables \tag{2}$$

2.3 Initialize state of charge

In the beginning of the optimization, it is assumed that the actual storage capacities of hydrogen and batteries in Germany are negligible. Moreover, the initial state of charge will be set to zero in the beginning of optimization for all storage technologies. During the optimization path, the last state of charge in a certain year must equal the first state of charge in the year after to guarantee continued sequence for the optimization.

$$\text{ɕ}_{s,n,t=0,i=2020} = 0 \tag{3}$$

$$\text{ɕ}_{s,n,t=1,i} = \text{ɕ}_{s,n,t=8760,i-1} \tag{4}$$

2.4 Update storage capacity

In the beginning of every year of the optimization path, the newly installed storage capacities are added to the previously existing ones. Moreover, the expired storage plants are removed from the network. For this study, a lifetime of 20, and 15 years is assumed for hydrogen and battery storage, respectively.

$$\text{Ꭓ}_{s,n,i} = \text{Ꭓ}_{s,n,i-1} + \mathcal{E}_{s,n,i} - \mathcal{E}_{s,n,i-\iota_s} \tag{5}$$

2.5 Set yearly investment limit

As the hydrogen and battery storage technologies do not require very specific geographical properties, it is not essential to apply regional investment limits like the renewable generation technologies. However, for each year, a limit on the overall installation of storage will be applied in order to be realistic in terms of yearly installed capacity and the social acceptance, and most importantly, to ensure that both storage technologies play an important role in the energy transition rather than only comparing them solely in terms of costs.

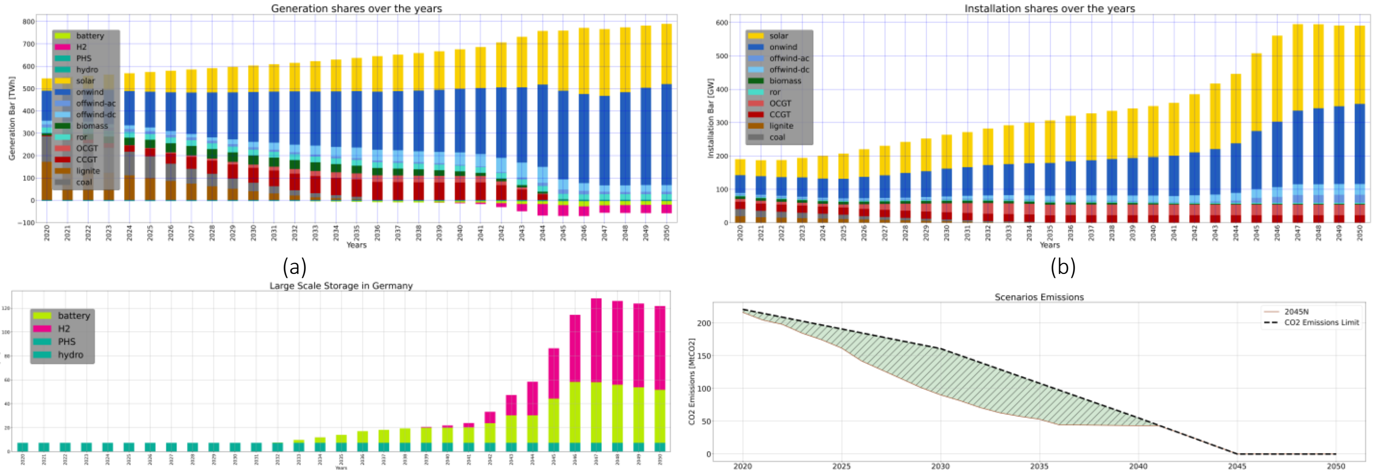
$$0 \leq \sum_{n} \mathcal{E}_{s,n,i} \leq \mathcal{M}_{y_{s,i}} \tag{6}$$

2.6 Update network constraints/objective function

The network constraints are updated annually to construct a road map for the German energy system, these are CO_2 limits, line loading and line expansion limits, load shedding, and technology investment potentials. The objective function of the model is constructed in the basic PyPSA-Eur model [8] and MyPyPSA-Ger [6]. However, the only change implemented in this model is presented below, which basically includes adding the myopic optimization of the battery capacity expansion to the objective function. The objective function of the model is minimizing the annual system cost as follows:

$$\min_{\substack{\mathcal{E}_{g,n,i},\varepsilon_{g,n,t,i} \\ \text{Ꭓ}_{g,n,t,i},B_{\mathcal{L},\ddot{\text{U}},i} \\ \text{Ƕ}_{s,n,t,i}}} \sum \begin{pmatrix} \kappa_{g,i} \cdot \mathcal{E}_{g,n,i} + o_g \cdot \varepsilon_{g,n,t,i} + o_g \cdot \text{Ꭓ}_{g,n,t,i} + \kappa_{\mathcal{L},\ddot{\text{U}}} \cdot \nu_{\mathcal{L},\ddot{\text{U}},i} \\ + \kappa_{s,i} \cdot \mathcal{E}_{s,n,i} + o_s \cdot [\text{Ƕ}_{s,n,t,i}]^{+} \end{pmatrix} \tag{7}$$

The optimization is implemented on a yearly basis with varying weather and demand conditions, with the goal of reducing the overall system cost on an annual basis.



(a) (b)

(c) (d)

Figure 2: 2045N scenario results, a) Myopic installation shares, b) Myopic generation shares, c) Myopic storage investments, d) Cumulative emissions

3. SCENARIOS DEVELOPMENT

For the scope of this study, only one scenario will be discussed, with the goal of reaching full decarbonization by 2045, with the help of storage technologies, while having constraints on the yearly and regional investment potentials. The load will be increased annually by 1 %, reaching nearly 730 TWh by 2050, the CO_2 allowance cost is 25 €/ton CO_2 with a coal phase-out by beginning of 2038, renewables will be limited with 25 GW as a yearly investment limit, and 3 GW per region[1], and the yearly investment limit for storage is 14 GW.

4. RESULTS AND DISCUSSION

Having a climate-neutral energy system by 2045 pointed out many interesting aspects. The system was totally dominated by wind and solar by 2045 (Figure 2-a), with a small contribution from clean biomass and run-of-river technologies, which have limited expansion potential in Germany. However, AC-offshore wind was not strongly used due to its lower capacity profile compared to DC-offshore, and its higher investment costs compared to other technologies. Yet, even with 100% renewable-based energy system, the overall CO_2 emissions were around 2400-ton CO_2, thus exceeding the country's ambitious target of staying well below the 1.5° goal.

In the myopic path, it can be clearly seen that renewables which were invested in within the first 5 years were not compensated after being phased out within 2045-2050 (Figure 2-b). This is explained through the storage investments, as more storage capacity was added to the system, especially hydrogen storage, thus increasing the flexibility capabilities of the network and reducing both the energy curtailment and the overall system investment costs. By 2050, The installed capacity of solar exceeded 50 % of the overall available potential in the country, mostly in locations with better capacity profiles, while for onshore and offshore wind it was 30 % and 60 %, respectively. To reach the climate neutrality by 2045, additional 7.5 GW/a for solar has to be added to the system, along with 4.8 GW/a and 1.5 GW/a for onshore and offshore wind, respectively.

Looking at the storage investment path (Figure 2-c), it can be clearly pointed out that long-term storage technologies were not part of the energy system until 2040 and short-term batteries were introduced by 2030 to the system, with 1.7 and 1.4 GW/a up to 2045, respectively. This is due to multiple reasons, on the one hand, gas fired power plants can still supply the system in times of renewables shortages without exceeding the CO_2 limit, as the model immediately was satisfied with less shares of Gas in the energy mix between 2025-2040 (Figure 2-d), thus the need for longer storage capabilities is not crucial. On the other hand, the cost of hydrogen storage was still very high compared to other generation technologies, thus not optimally feasible. However, as this is highly affected by the cost assumptions in the model, more investments of storage will lead to sharply reducing the capital costs, thus encouraging the integration of more storage flexibility in the system [9]. After 2040, hardly any battery storage investments were made and it was mostly replaced by hydrogen storage due to its longer storage capabilities.

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[1] For a 32-node network

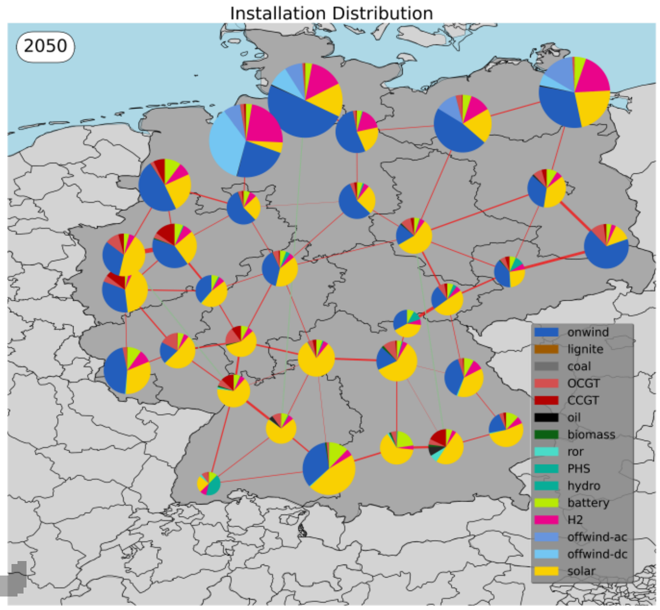

Figure 3: Installation regional distribution in 2050.

It was also noticed, that batteries investments started to ramp up after the complete phase-out of coal from the energy share (Figure 2-a), thus offering a flexible option to the network along with the gas fired power plants. However, hydrogen investments were boosted near the complete phase-out of gas from the system. This is due to their higher flexibility capabilities compared to batteries, but also their capital cost by 2040 was reduced about 50% compared to their cost in 2020.

Looking on a regional point of view (Figure 3), solar and wind were mainly installed in the southern and northern regions of Germany, respectively. This is due to the fact that those regions have better capacity profiles and installation potentials. Moreover, storage technologies allowed for better allocation for the installations where the better locations were utilized, leading to a more cost-efficient path towards neutrality. In other words, the need for investing renewables everywhere did not occur, thus a higher renewables utilization. Hydrogen was mainly connected to regions with higher wind technologies installations as it has a longer storage capability (168 hours), where short-term battery storage (6 hours) was largely connected to solar installations. In 2045, less than 1% of the overall load was disconnected corresponding to lack of adequate generation or storage capabilities. However, this did not occur in the years after as the newly installed capacities generation and hydrogen storage helped to satisfy the huge electrical demand. Moreover, having higher regional investment potentials will enable more investments, thus reducing the amount of load shedding.

5. CONCLUSION

The results showed that a 100% renewable energy system can be achieved through the utilization of storage technologies, yet not complying with the national hydrogen strategy nor the 1.5° goal of the country. It was found that, much more storage technologies, especially hydrogen, will have to be integrated into the system, along with a faster and expeditious plan in order to achieve full-neutrality by 2045 and stay well below the 1.5° target. None the less, as it was already seen, achieving 100% renewables power system in Germany will require large investments, in which the social acceptance of the energy transition will highly affect, or even more, preclude the whole climate action plan.

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