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Development of a Method for the Ecological Assessment of Grid-Connected Energy Storage Systems Focusing Wind Energy Curtailment

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ABSTRACT

Energy storage systems are seen as key technologies in the decarbonisation of energy systems and are expected to ensure flexibility and security of supply in various applications. Depending on their operation within these applications, they contribute to changing the environmental impact of a specific energy system. In this study, energy storage is used to avoid wind energy curtailment. In order to show the effects on different energy systems, various comparable scenarios based on real energy systems were created. In the respective scenarios, a simulation was carried out without storage, then storage was added and its operation was optimised so that as much of the wind energy as possible was integrated. The ecological effect of this integration was analysed using the LCA method. The results show that in the scenarios where wind energy is curtailed, the use of storage has a positive environmental effect, because if the wind energy is integrated less fossil fuels are used.

Keywords: energy storage, curtailment, optimisation, PyPSA, LCA

NONMENCLATURE

Symbols	
I	Ecological Impact
G	Generator
P	Power
E	Generated energy

1. INTRODUCTION

Energy storage systems that are directly or indirectly connected to an electrical grid can be used in a variety of applications and contribute to emission reduction, for example through their operation in this specific application and in the defined energy system. These application-specific implications have hardly been investigated so far, whereas the purely technology-related implications for various energy storage systems are state of the art. The most studies that consider an ecological evaluation of energy storage systems are using life cycle assessment for quantifying the ecological impact of energy storage systems. The aim of this work is to analyse the applications of energy storage and to determine possible pollutant emissions, but also possible saved emissions using energy storage in specific energy systems. In their review of grid-scale lithium ion batteries, Pellow et al. [1] recommend that future studies consider the environmental impact of the use-phase and use appropriate models for the use of the batteries, as these have hardly been considered so far. This applies not only to lithium-ion batteries, but also to all energy storage systems connected to the power grid. Only a few studies include the use-phase of the energy storage systems and most of them do not show any positive ecological aspects of storage use. Two Studies evaluate positive ecological aspects in the specific regions Switzerland [2] and Normandy [3]. In contrast, this study aims to quantify the environmental impacts in different comparable energy systems in order to make a more general statement on the extent to which energy storage contributes to a reduction or increase in emissions, when the energy storage is used to integrate wind energy that is otherwise curtailed. The general method should be transferable to other applications of grid-connected energy storage systems.

2. METHODS

In order to calculate the effects in the use phase, a simulation is carried out in an energy system model, taking into account different electricity mixes and different key parameters of storage. After the simulation of the storage operation in the energy system, the resulting change in the electricity mix is evaluated with LCA methodology.

2.1 Energy System Scenarios

Scenarios are created that represent different electricity mixes in energy systems. In order to establish comparability, a total electricity consumption of 500 TWh per year is assumed in each scenario. The

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scenarios are intended to represent the generation of electricity, as it exists in different countries around the world. The energy generated in individual countries is first analysed on the basis of data published by the International Energy Agency (IEA) in its energy statistics [4]. The focus is on the member countries of the IEA. The year 2019 is selected for consideration, as it was the most recent year fully available at the time of the analysis. After the analysis, five scenarios are developed in which the electricity mix of various IEA member states are used as an example for the composition. The chosen installed capacities are displayed in Table 1. These are based on the load hours determined from the data published on the ENTSO-E transparency platform [5].

Table 1: Installed generation capacity in GW per generation type in the considered scenarios

generation type	medium	wind	nuclear	fossil	water
lignite	13	0	0	22	0
hard coal	28	40	12	60	6
natural gas	15	20	9	29	11
oil	3	3	3	3	3
biomass	4	7	1	2	5
nuclear	8	0	43	0	0
geothermal	0.1	0	0	0.6	0
waste	6	7	1	5	7
wind onshore	58	117	20	23	23
wind offshore	8	17	0	0	0
solar pv	34	14	14	23	9
hydro run-of-river	10	3	1	8	47
hyro reservoir	5	0	54	5	177

2.2 *Optimisation approach*

The energy system is simulated with a single bus, what represents the energy system to which all generators and the consumption are connected. In this application, the optimisation mode of the free toolbox PyPSA [6] is used. In order to show the effect of energy storage. Storage systems with storage capacities of 5 to 100 GWh are simulated in the model for each scenario. Since wind energy is the first to be curtailed in this case, it is assumed that other renewable energies except biomass will not be curtailed and there full energy will be used. To guarantee that only wind energy is stored, an additional bus is added to which the storage and wind energy generators are connected, when the storage capacities are simulated. From this bus, the energy can only flow to the bus that represents the energy system. The objective function in the PyPSA optimisation mode is to minimise total system costs. In order to optimise the application, no real costs are used, but the costs are chosen so that the application is fulfilled. So no capital costs were considered in the model and the marginal costs for the generators where used to create an order of dispatch, while negative costs are attributed to wind energy generation. The biomass generators are dispatched first followed by the lignite generators, the hard coal generators, the natural gas generators and the oil generators. According to the installed capacity, and the typical size of power plants, several power plants are often necessary to reach the installed capacity. Due to the lack of knowledge about the exact individual conditions, all power plants that are operated with the same energy source are modelled as one single generator. To make the modelling more accurate, generation characteristics are obtained from the ENTSO-E transparency platform [5]. Four characteristic factors, depending on the installed capacity of each generator type, are used to constrain the active power P_{Active} and the change of active power between timesteps ΔP_{Active} of the generators: a minimum power fraction ρ_{min} and a maximum power fraction ρ_{max}, a ramp-up factor δ_{up} and a ramp-down factor δ_{down}. These Factors are depending on the total installed power. The constraints for the generators are shown in equations 2.2.1.

$$\mathrm{P_{installed}} \cdot \rho_{\max} < \mathrm{P_{active}} > \mathrm{P_{installed}} \cdot \rho_{\min}$$

$$\Delta \mathrm{P_{active,up}} < \delta_{\mathrm{up}}$$

$$\Delta \mathrm{P_{active,down}} < \delta_{\mathrm{down}} \qquad (2.2.1)$$

Since the maximum power fraction is not 100 %, there is a certain backup capacity in the system that can be used when the maximum power share of all generators is reached. The optimisation is carried out on an hourly basis for a whole year. Input data for solar pv and wind energy timelines are obtained by the work of Staffel and Pfenniger [7,8]. Due a lack of data for water inflow in hydro reservoirs, a steady inflow of water is assumed throughout the year, so the reservoirs dispatch can be optimised in the model. For hydro run-of-river plants data from the ENTSO-E transparency platform [5] is used to create timelines.

2.3 *Ecological analysis of the simulation results*

For quantifying the impacts of the generation in the scenarios the Ecoinvent 3.7 [9] database is used together with the "openLCA 1.10" software to model the generators. For that, the global market datasets from the database are used. The impacts are divided into variable impacts I_{var} resulting from the construction of the respective generation technologies and fixed impacts I_{fix} resulting from the operation of the generation technologies. As impact method the ILCD-midpoint method [10] is chosen, because it shows a wide range of impact categories and it was developed as EU standard. The fixed impacts are divided by the suggested lifetime of the generation technologies so the yearly impacts are considered. The Impacts of the energy system I_{Sys} for the generation emissions of electrical energy are calculated as shown in equation 2.3.1.

$$I_{Sys} = \sum_{G} I_{fix,G} \cdot P_G + I_{var,G} \cdot E_G \qquad (2.3.1)$$

3. RESULTS & DISCUSSION

The first part of the results, shows how much wind energy can be integrated in contrast to the energy systems without energy storage. In the second part, the changed environmental impacts of energy systems with storage systems are shown in comparison to those without storage systems.

3.1 Results of energy system modelling

The model shows, that there is no storage needed in the fossil scenario or in the water scenario for integrating wind energy. In the fossil scenario, the small amount of wind energy can be used fully, because the fossil power plants operate flexibly enough; this also applies to the water reservoirs in the water scenario. In the other three scenarios, wind power generation is curtailed when no storage is considered in the simulation. In the medium scenario, 9.4 TWh of the wind energy cannot be integrated, while in the wind scenario 35.2 TWh and in the nuclear scenario 0.5 TWh cannot be integrated. The results show, that in these three scenarios the storage systems can help to integrate wind energy. For an exemplary representation, Figure 1 shows how much wind energy can be integrated for certain storage sizes in the respective scenarios for the average efficiency of 80% and a capacity-to-power ratio of 1. It can be seen that in the nuclear scenario, the highest amount of wind energy can already be integrated with a storage capacity of 80 GWh, which corresponds to a share of 72% of the wind energy curtailed in this scenario. With a storage capacity of 20 GWh, a share of 60% of the lost energy is already integrated. In contrast, in the wind scenario with a storage capacity of 20 GWh, only 2% of the otherwise curtailed wind energy is integrated. Whereas in the simulation with the capacity of 100 GWh 9% could be integrated. Only 0.8 TWh less can be integrated in the medium scenario with a storage capacity of 100 GWh, which corresponds to 27% of the curtailed wind energy in the simulation without storage. With lower capacity below 10 GWh, even more wind energy can be integrated in the medium scenario than in the wind scenario, although the generation potential of wind energy is greater in the wind scenario.

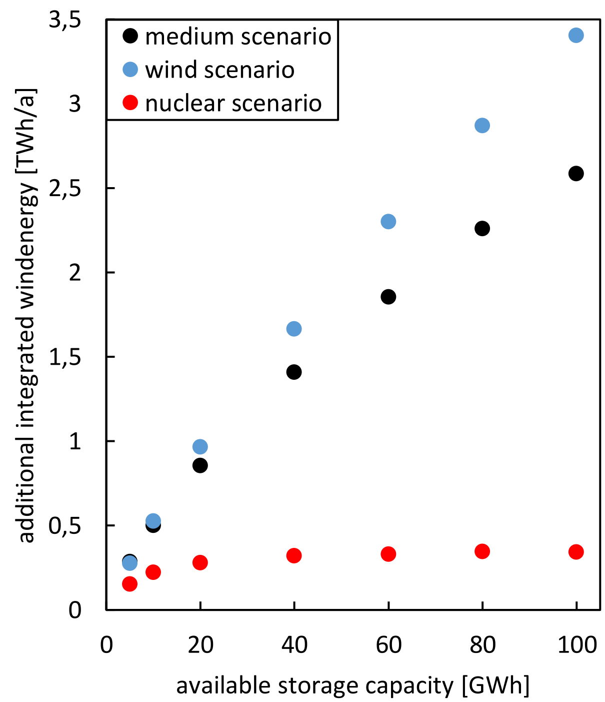

Figure 1: Additionally integrated wind energy in TWh/a at a certain storage capacity in GWh, in the respective scenarios for an efficiency of 80% and a capacity-to- power ratio of 1.

3.2 Results of the ecological assessment

In order to investigate to what extent wind energy integration has an ecological impact, the climate change impacts are first calculated in the scenarios without storage. The medium scenario shows climate change impacts of 229 million t-CO_2-eq per year, while the wind scenario shows impacts of 208 million t-CO_2-eq per year and the nuclear scenario only 63 million t-CO_2-eq per year. To compare the effects in the individual scenarios, the difference in climate change impacts is formed from the simulation results with storage and the simulation results without storage. These differences are then put in relation to the climate change impacts in the scenarios without storage. These ratios are shown as percentages in Figure 2. In the nuclear scenario, hardly any further effect is achieved above a storage capacity of 60 GWh, as this is also the point at which most wind energy is already integrated. The small reduction when using higher capacities can be explained by the fact that larger capacities allow longer storage times for the same amount of energy and thus other energy sources can be replaced by wind energy. With a small amount of storage capacity, the nuclear scenario has the highest relative reduction in impact, but the lowest absolute reduction, as emissions are already low without storage. In contrast, the medium and wind scenario still achieves a reduction in climate change impacts even with a storage capacity of 100 GWh. The largest relative and the largest absolute reduction is achieved in the wind scenario. This is due to the greater amount of wind energy that replaces fossil fuels in particular. The medium scenario shows a smaller reduction in climate change impacts compared to the wind scenario, but with a storage capacity of more than 10 GWh a larger relative reduction compared to the nuclear scenario.

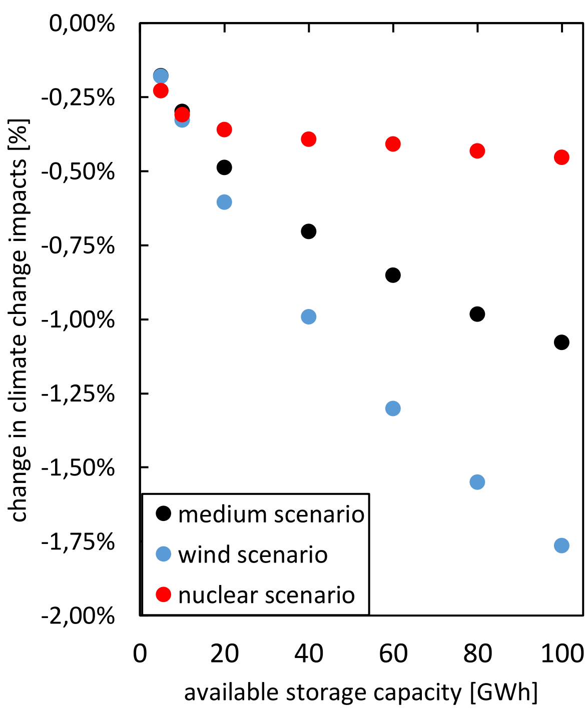

Figure 2: Reduction of climate change impacts in the scenarios with different available storage capacities compared to the scenarios without storage

3.3 *Discussion of the ecological results*

To assess whether the ecological effect in the energy systems is sufficient, the changes in the energy system must also be compared with the climate change impacts that arise during the production and disposal of the energy storage systems. If only lithium ion batteries (170 t-CO2-eq/MWh [11]) are used in the medium scenario, they would have amortised themselves ecologically after one year in the case of 5 GWh installed capacity and only after 15 years in the case of 100 GWh, assuming a lifetime of 20 years. As there are several studies and different energy storage systems that are considered with different impact methods further research is needed to evaluate ecological amortisation in the energy system with the ILCD-midpoint-method.

3.4 *Discussion of the method*

The method shows positive ecological aspects of storage use, but simplified conditions are assumed in the simulation. The advantage of agglomerating the power plants of the same type into one generator is that a simulation can be carried out quickly and efficiently. However, this does not reflect the operation behaviour of the individual power plants. By implementing the factors mentioned, a behaviour that corresponds to that in the past can be approximated. It would be useful to use a detailed model of the storage systems that includes further performance aspects, such as cycle stability, partial load efficiency and self-discharge. However, there is no such model in the format used, especially one that can represent all types of storage.

4. CONCLUSION

The simulations and calculations have shown that energy storage systems used to capture wind energy that would otherwise be curtailed in the energy system contribute to a reduction in climate change impacts. The used scenarios represent currently existing energy systems. However, there is a shift within energy systems and it may be useful to explore scenarios with a higher share of renewables as expansion of renewable energy capacity is pushed forward. It would be possible to analyse other storage applications using the same methodology and it would be useful to investigate to what extent several storage applications that simultaneously affect an energy system influence the climate change impacts.

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References

[1] Pellow MA, Ambrose H, Mulvaney D, Betita R, Shaw S. Research gaps in environmental life cycle assessments of lithium ion batteries for grid-scale stationary energy storage systems: End-of-life options and other issues. Sustainable Materials and Technologies 2020;23:e00120.

[2] Vandepaer L, Cloutier J, Bauer C, Amor B. Integrating Batteries in the Future Swiss Electricity Supply System: A Consequential Environmental Assessment. Journal of Industrial Ecology 2019;23(3):709–25.

[3] Elzein H, Dandres T, Levasseur A, Samson R. How can an optimized life cycle assessment method help evaluate the use phase of energy storage systems? Journal of Cleaner Production 2019;209:1624–36.

[4] International Energy Agency (IEA). Electricity Information: Annual data on electricity and heat supply and consumption for OECD and selected non-OECD countries. [August 03, 2021]; Available from: https://www.iea.org/data-and-statistics/data-product/electricity-information.

[5] European network of transmission system operators for electricity (ENTSO-E). ENTSO-E Transparancy Platform [May 03, 2021]; Available from: https://transparency.entsoe.eu/.

[6] Brown T, Hörsch J, Schlachtberger D. PyPSA: Python for Power System Analysis. Journal of Open Research Software 2018;6.

[7] Pfenninger S, Staffell I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy 2016;114:1251–65.

[8] Staffell I, Pfenninger S. Using bias-corrected reanalysis to simulate current and future wind power output. Energy 2016;114:1224–39.

[9] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I). Int J Life Cycle Assess 2016;21(9):1218–30.

[10] European Commission, Joint Research Centre, Institute for Environment and Sustainability. Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods: Database and supporting information: Publications Office of the European Union; 2013.

[11] Hiremath M, Derendorf K, Vogt T. Comparative life cycle assessment of battery storage systems for stationary applications. Environmental science & technology 2015;49(8):4825–33.