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Assessing the Role of Long-Term Electricity Storage in the Energy Transition

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To achieve the objective of attaining a low-emission energy system, it is necessary to have precise energy planning to reduce the total cost of the energy transition. In the long run, energy models based on cost-optimal solutions heavily rely on the cost projections of various technologies. The purpose of this study is to determine a generic cost-optimal route for the decarbonization of an energy system. A linear programming model has been developed for this purpose, considering the synergies of the power sector with the heating, transportation, and hydrogen sectors. The results suggest that it is theoretically possible to have a system powered almost entirely by renewable energy, even with limited flexibility provided through interconnections. Power-to-X technologies are essential for balancing purposes because they enable a percentage of non-dispatchable production that approaches 90 %. In particular, the role of seasonal hydrogen storage is pivotal for accommodating significant penetration of variable renewable energy sources, which can also be combined with limited flexibility provision from other flexibility services suppliers. However, dispatchable and controllable resources such as biomass are of utmost importance for the system's well-functioning.

1. Introduction

Several nations have established net-zero emission objectives and developed policies for the total decarbonization of energy systems in response to the growing understanding of the hazards of climate change caused by human activity. A significant first step toward a unified energy strategy was taken with the signing of the Paris Agreement (UNFCC, 2015), resulting in a rise in fascination with and concentration on renewable energy sources (RES). Energy and other systems are undergoing substantial changes to achieve the climatic objectives. These transformations include a considerable increase in the proportions of intermittent RES, mainly wind and solar, which may lead to a significant energy curtailment or excess energy produced (Migliari et al. 2024). Consequently, the utilization of intermittent RES brings up notable operational and balancing issues, and flexible energy systems have become necessary. Flexibility refers to the capability of a power system, as the backbone of the energy system, to effectively manage the uncertainties and variations caused by variable RES at different time scales. It involves maximizing the use of RES potential and ensuring a reliable supply of electricity to meet consumer demand (Koltsaklis and Knápek, 2023). Traditionally, supply-side resources typically provide flexibility due to the satisfying predictability and the generally slow-time dynamics of electricity demand. A representative example of this comprises the flexible hydroelectric and thermal power generating units. However, the combined effects of the significant penetration of intermittent and variable RES on the supply side and the increase in the total demand due to the electrification of other complementary energy sectors (e.g., heating, transportation, hydrogen, and renewable fuels) have created a global need to examine demand-side flexibility more thoroughly (IRENA, 2019). Addressing flexibility issues alone via electric batteries is deemed inadequate and costly (Ajanovic et al., 2020). Long-term electricity storage is crucial in mitigating the volatility and intermittent characteristics of renewable energy sources (RES) such as wind and solar power. It is vital in facilitating the transition towards a more sustainable energy system. As the globe moves towards reducing carbon emissions in the energy industry, the ability to store large amounts of electricity for extended periods of time becomes crucial for ensuring a reliable power supply and maintaining grid stability (Mayyas et al. 2020). Power-to-X (PtX) refers to various technologies that convert electrical power (usually derived from renewable

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energy sources) into other energy or chemical products. This concept is a key enabler of sector coupling, allowing the integration of renewable energy into various sectors like transport, industry, and heating (Onodera et al., 2023). Energy systems planning models are essential for assessing and constructing sustainable energy systems (Alabbasi et al., 2024). These models assist in assessing the prospective effects of various energy policies, technological advancements, and market dynamics on energy supply, demand, and environmental results (Santos et al., 2024). The study of 100 % renewable energy systems has grown significantly in recent years. Several energy planning tools have been created to analyze various elements of the energy transition (Breyer et al., 2022). Multiple studies indicate the feasibility of decarbonizing the power and other energy sectors (Hansen et al., 2019). For instance, Aghahosseini et al. (2023) presented an energy systems modeling framework to analyze and compare several worldwide paths for transitioning to cleaner energy sources in the power sector. An optimization framework for long-term power systems planning was presented by Koltsaklis et al. (2013). Feijoo et al. (2022) presented an open-source, linear programming framework to evaluate the whole energy system. This model has hourly resolution and enables long-term capacity planning for all power generation units and various PtX and demand response technologies, including the heat, industry, power, and transport sectors. Onodera et al. (2023) created a linear programming model to optimize energy systems by integrating P2X technologies. The study specifically examined the effects of P2X flexibility on the system configuration and energy costs. The incorporation of P2X technologies for a sustainable nationwide RES system with RES penetration was also assessed by Lim et al. (2021).

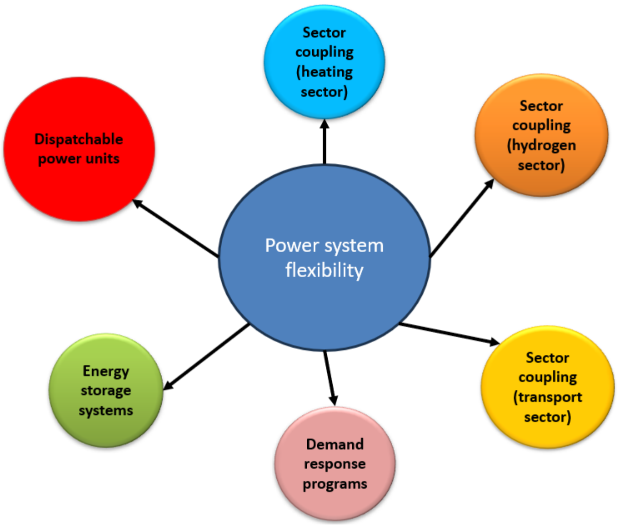

Figure 1: A graphical superstructure of power system flexibility providers

Figure 1 is a flowchart illustrating the many sources of power system flexibility considered within the suggested systematic framework. In light of this, the purpose of this study is to fill in this gap and contribute to the current body of research by developing an integrated and systematic optimization framework that models ESSs, EVs, and demand response activation measures as well as sector coupling options (heating, transportation, and hydrogen). The suggested framework adds to the literature by developing a systematic linear programming framework that considers the optimal development and operation of a RES-based power system by coupling it with heating, transportation (through the penetration of electric vehicles with both grid-to-vehicle and vehicle-to-grid options), and hydrogen sectors. Within the power-to-hydrogen concept, electricity is used to produce hydrogen via water electrolysis. The hydrogen can be used directly in fuel cells, for industrial processes, or as a feedstock for further chemical reactions. The power-to-heat one converts electricity into heat. Electric boilers and heat pumps comprise devices that use electricity to produce heat. On top of that, considering thermal storage options enables excess electricity to be stored as heat in materials like molten salts or large-scale thermal storage systems for later use. The proposed model focuses on planning an energy system on an annual time horizon with an hourly time step for energy dispatch. It optimizes the scale of capacity increases for various technologies, including variable renewable and Power-to-X technologies.

2. Methodology

The developed mathematical model integrates the decision-making process for designing and operating a power system, taking into account flexibility service providers such as energy storage systems (ESSs), demand response measures, and sector coupling options with the heating, transportation, and hydrogen sectors. The overall system is optimized over a year with an hourly time step. The model's objective function (1) refers to minimizing the total annual system development and operation cost from a system operator's perspective. It includes the following terms: (i) annualized investment and fixed operational and maintenance cost of technologies tech, including electricity supply technologies (renewables such as wind and solar photovoltaics, natural gas-fired, biomass-fired, and hydroelectric power units, ESSs, and fuel cells), heating sector technologies including heat pumps, electric boilers, fuel-based boilers (biomass, natural gas, oil), as well as thermal storage technologies, (hydrogen sector technologies including electrolyzers and hydrogen storage technologies, (ii) fuel cost for the operation of natural gas-fired and biomass-fired units as well as for fuel-based boilers, (iii) the electricity trading net cost including electricity imports cost and electricity exports revenues, and (iv) additional penalty costs including the cost of unmet energy demand, and the cost of curtailed energy.

$$\begin{aligned} Cost = {} & \overbrace{\sum_{tech} c(tech)\cdot\left(AI_{tech}+FOM_{tech}\right)}^{Annualized\ investment\ \&\ fixed\ operational\ and\ maintetnace\ cost} + \overbrace{\sum_{th}\sum_{t} p_{th,t}\cdot VC_{th}}^{variable\ operating\ cost\ of\ thermal\ power\ units} \\ & + \overbrace{\sum_{bo}\sum_{t} fuel_{bo,t}\cdot VC_{bo}}^{fuel\ cost\ of\ heat\ only\ boilers} + \overbrace{\sum_{t} p_t^{unmet}\cdot UEC}^{Unmet\ energy\ cost} + \overbrace{\sum_{t} p_t^{curt}\cdot ECC}^{Energy\ curtailment\ cost} + \overbrace{\sum_{t}\left(im_t-ex_t\right)\cdot BP_t}^{Net\ electricity\ imports\ cost} \end{aligned} \tag{1}$$

Apart from the objective function, the model includes a plethora of constraints. According to the electrical energy supply and demand balance (2), the entire electrical energy supply from all types of suppliers es, which provides for conventional power units, renewable energy sources, fuel cells ($\sum_{es} p_{es,t}$), power discharge from both ESSs ($\sum_{st} p_{st,t}^{dis}$) and electric vehicles (EVs) ($\sum_{ev} p_{ev,t}^{dis}$), the electricity imports (im_t) as well as the amount of demand that has not been satisfied (p_t^{unmet}), must be sufficient to satisfy the electricity demand after the activation of the demand response (d_t^{EDR}), the charging load from both ESSs ($\sum_{st} p_{st,t}^{ch}$) and EVs ($\sum_{ev} p_{ev,t}^{ch}$), the electricity required as input to the heat pumps (heating sector) (d_t^{E2H}) and electrolyzers (hydrogen sector) (d_t^{E2H2}), the electricity exports (ex_t), and the amount of curtailed energy (p_t^{curt}) in each period.

$$\sum_{es} p_{es,t} + \sum_{st} p_{st,t}^{dis} + \sum_{ev} p_{ev,t}^{dis} + p_t^{unmet} + im_t = d_t^{EDR} + d_t^{E2H} + d_t^{E2H2} + \sum_{st} p_{st,t}^{ch} + \sum_{ev} p_{ev,t}^{ch} + p_t^{curt} + ex_t \tag{2}$$

The thermal energy supply and demand balance states that the total thermal energy supply from heat pumps, electric boilers, and fuel-fired boilers must satisfy the expected thermal energy load. The design limitations specify the maximum capacity of newly installed technologies (electrical power units, electricity storage units, heat pumps, boilers, thermal storage technologies, electrolyzers, fuel cells, and hydrogen storage technologies). The operational constraints define the electrical power plants' yearly permissible power output levels based on their annual capacity factors and the minimum operational levels for storage technologies. The renewable energy production restrictions establish the maximum amount of renewable energy that RES units may produce in each period. The ESSs' modeling includes constraints determining the state-of-charge level in each period and the maximum charging and discharging limits. EVs' modeling is similar, also taking into account the electricity consumption of EVs for their transportation needs. Concerning the hydrogen sector, the model calculates the amount of hydrogen produced from the electrolyzers, which is directed to the hydrogen storage technologies. The available options are to (i) remain stored for later utilization, (ii) utilized as an input to fuel cells for electricity generation, and (iii) consumed to satisfy the expected hydrogen load. The modeling of demand response activation includes constraints that (i) quantify the dynamic nature of energy demand rather than relying on deterministic values and (ii) guarantee that the total energy demand remains constant over the planning time horizon. The problem is defined as a linear programming problem to minimize total costs and is subject to the restrictions above and equations. The key model outputs include: (i) the optimal development path of the studied energy system (dimensioning of the considered technologies), (ii) operational scheduling of the studied system, including electrical and thermal energy mix as well as the charging and discharging cycles of the storage technologies, and (iii) total cost synthesis.

3. Case study

Chapter 2 The proposed model has been tested using an illustrative case study. The economic data of new candidate power units (Table 1) include the annualized investment (CAPEX) and fixed operational and maintenance cost (FOM), as well as the maximum allowable capacity (Pmax). The total annual electricity demand amounts to approximately 64 TWh, and heating demand equals 36 TWh annually. Table 2 presents the techno-economic data for battery storage alternatives that are explored for ESSs. Each energy storage technology's energy rating is a decision variable that is limited by the given maximum. Ten percent (10 %) of the maximal energy capacity is the comparable minimum. The maximum power outputs for ESS charging and discharging are determined by their respective energy-to-power (E2P) ratios. Five scenarios were considered and distinguished according to the maximum permitted limit of electricity exports. In particular, in the "Exports Unlimited" scenario, the possibility of unlimited electricity exports is adopted. In contrast, in the remaining four scenarios, it is assumed that there is a maximum annual allowed limit that starts from 5 TWh ("Exp_5 TWh"), with a decreasing step of 1 TWh.

Table 1: Economic data of new candidate power units related to their installation

Candidate unit	CAPEX (€/MW)	FOM ($/(MW×y))	Pmax (MW)
New Wind	107,643	20,091	30,000
New PV	95,730	14,510	30,000
Conventional hydropower	301,161	118,671	5,000
Biomass	243,140	91,459	4,000

Table 2: Techno-economic data of candidate energy storage technologies

Type	Charging (discharging) efficiency (%)	E2P ratio	Capital cost (€/MWh)	Fixed cost (€/MW)
Battery-1	90	4	42,133	22,145
Battery-2	90	2	42,260	11,519

4. Results

4.1 Total cost and Capacity additions

The problem has been globally optimized using the CPLEX solver within the General Algebraic Modeling System (GAMS) Studio 37 (GAMS, 2007). Restricting the flexibility provided by electricity exports leads to a gradual increase in the cost of developing and operating the system. In particular, this starts from 8.25 billion euros in the "Exports Unlimited" scenario, escalating to 8.43×109 EUR in the "Exp_2 TWh" scenario. Regarding the selected capacities, the impact of the reduction in the possibility of electricity exports is seen in the installed capacity of renewable energy technologies (wind and solar PV), where a decrease of almost 11% is observed, from 33.3 GW to 29.7 GW between the "Exports Unlimited" and "Exp_2 TWh" scenarios (Figure 2). The capacity of photovoltaics remains stable, with negligible fluctuations, in all scenarios, while the decline is observed in the installed capacity of wind farms. The reduced flexibility due to the decreased ability to export electricity is reflected in the increased installed capacity of electricity storage units as a provider of increased flexibility. This increases by 173 % from 3.5 GWh to 9.5 GWh between the "Exports Unlimited" and "Exp_2 TWh" scenarios. Regarding other investments, those in biomass plants remain unchanged in all scenarios (1 GW). A slight decrease, from 4 GW to 3.6 GW, between the "Exports Unlimited" and "Exp_2 TWh" scenarios is observed in the natural gas combined cycle (NGCC) units. This reduction is offset by an increase in the capacity of hydroelectric plants, from 357 MW to approximately 682 MW between the same scenarios. The reduction in the overall capacity of electricity generation technologies combined with the reduced flexibility due to the electricity exports' limitation leads to a significant decrease in the capacity of heat pumps from approximately 1.7 GW in the "Exports Unlimited" scenario to 0.8 GW in the "Exp_2 TWh" scenario.

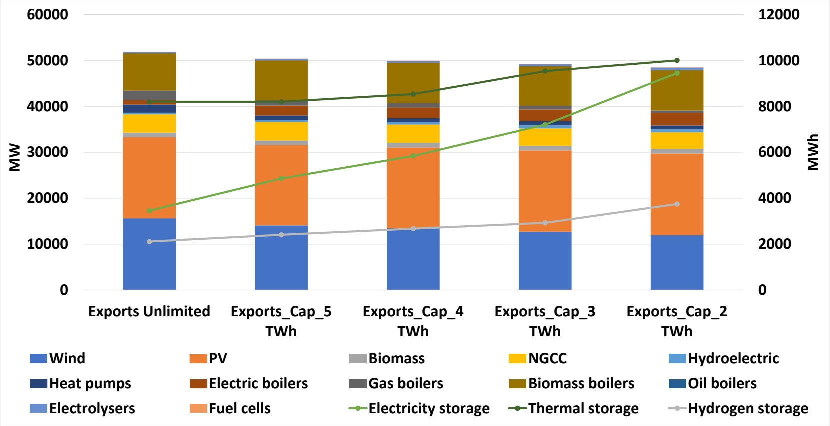

Figure 2: Capacity additions in each examined scenario

Most of this reduction is offset by increased investments in electric boilers whose capacity more than doubles from approximately 1 GW in the "Exports Unlimited" scenario to 2.7 GW in the "Exp_2 TWh" scenario. In addition, a significant drop is also recorded in gas boilers from 2 GW in the "Exports Unlimited" scenario to 0.5 GW in the "Exp_2 TWh" scenario, while biomass boilers increase their capacity from 8.1 GW to 8.7 GW among the "Exports Unlimited" scenarios" and "Exp_2 TWh". No investments are made in oil boilers in any scenario, while the capacity of heating storage technologies increases from 8.2 GWh to 10 GWh between the scenarios above. Regarding the hydrogen sector, the installed capacity of electrolyzers almost doubles between the "Exports Unlimited" and "Exp_2 TWh" scenarios, from 291 MW to 564 MW. A similar increase is noted in the fuel cells' installed capacity between the respective scenarios, from 46.6 MW to 79.3 MW. The capacity of hydrogen storage technologies registers a significant increase from 2.1 GWh to 3.7 GWh between the same scenarios.

4.2 Energy generation and Hydrogen flexibility

Chapter 3 Regarding the total electricity production, this decreases from approximately 81.5 TWh in the "Exports Unlimited" scenario to 75 TWh in the "Exp_2 TWh" scenario (Figure 3). In contrast to PV plants, which maintain a constant production profile, the overwhelming part of the reduction comes from the contribution of wind turbines, as their production drops from 36 TWh to 27.6 TWh between the two scenarios. Biomass units, hydroelectric units, and fuel cells increased production, while NGCC units recorded a marginal decrease. It should be noted that the total electricity production is reduced due to the limitation of the flexibility of electricity exports. Nevertheless, this is partially compensated by the increased demand for electricity in heating (gradual replacement of high-efficiency heat pumps by less efficient electric boilers and biomass units) and hydrogen sectors (increased flexibility needed for long-term storage). Figure 4 shows the hourly difference in stored hydrogen on an annual basis. The results highlight the additional flexibility the hydrogen sector provides alongside the reduced flexibility of electricity exports. During 90 % of the h on a yearly basis, the level of stored hydrogen is higher in the "Exp_2 TWh" scenario than in the "Exports Unlimited" scenario with an average value of 987 MWh (peal value of 3,535 MWh), while it is lower in 10 % of the h with an average value of 310 MWh (peal value of 1,445 MWh).

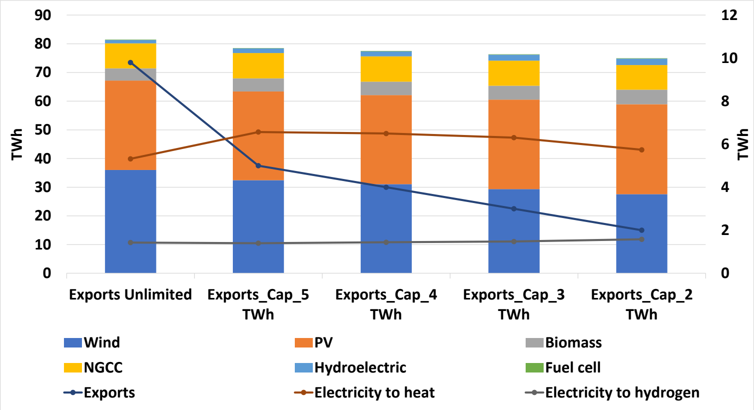

Figure 3: Energy generation and demand mix in each examined scenario

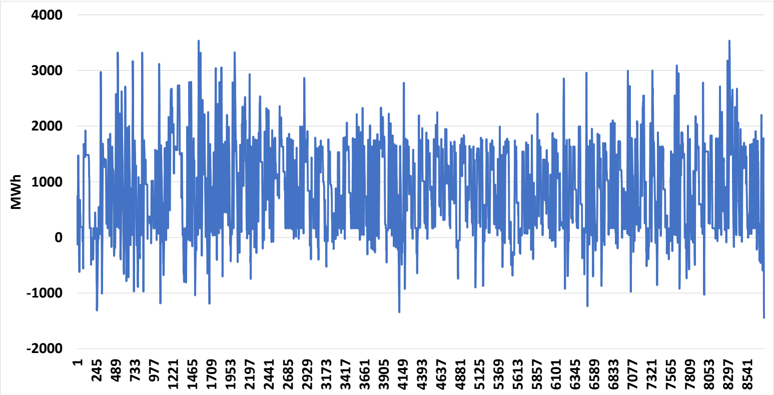

Figure 4: Stored hydrogen difference between "Exp_2 TWh" and "Exports Unlimited" scenarios

5. Conclusions

The results show the significant flexibility that long-term electricity storage through hydrogen provides in the effort to balance intermittent renewable energy sources, especially when accompanied by reduced availability of other flexibility providers. The transition to a low-carbon economy demonstrates the importance of demand-side flexibility. The green electrification of complementary energy sectors requires the optimization of synergies between technologies such as heat pumps, electrolytes, fuel cells, and various energy storage technologies. Future research plans include the incorporation of more detailed constraints on the operation of the electricity system, as well as the incorporation of renewable fuels as additional flexibility options.

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