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Least-cost options for integrating intermittent renewables in low-carbon power systems

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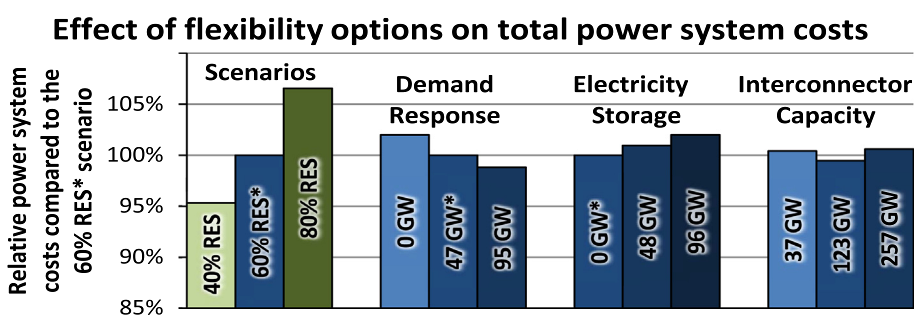
HIGHLIGHTS

- Simulated the 2050 West-European power system with 40%, 60% and 80% RES penetration.
- Assessed if 5 options can complement intermittent RES and lower total system costs.
- 3 options lower costs: demand response, gas-fired generators(+CCS) and curtailment.
- Power storage is too expensive and extra interconnectors are valuable at RES ⩾60%.
- Virtually all generators encounter a revenue gap in the current energy-only market.

GRAPHICAL ABSTRACT



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ABSTRACT

Large power sector CO_2 emission reductions are needed to meet long-term climate change targets. Intermittent renewable energy sources (intermittent-RES) such as wind and solar PV can be a key component of the resulting low-carbon power systems. Their intermittency will require more flexibility from the rest of the power system to maintain system stability. In this study, the efficacy of five complementary options to integrate intermittent-RES at the lowest cost is evaluated with the PLEXOS hourly power system simulation tool for Western Europe in the year 2050. Three scenarios to reduce CO_2 emissions by 96% and maintain system reliability are investigated: 40%, 60% and 80% of annual power generation by RES. This corresponds to 22%, 41% and 59% of annual power generation by intermittent-RES. This study shows that higher penetration of RES will increase the total system costs: they increase by 12% between the 40% and 80% RES scenarios. Key drivers are the relatively high investment costs and integration costs of intermittent-RES. It is found that total system costs can be reduced by: (1) Demand response (DR) (2–3% reduction compared to no DR deployment); (2) natural gas-fired power plants with and without Carbon Capture and Storage (CCS) (12% reduction from mainly replacing RES power generation between the 80% and 40% RES scenarios); (3) increased interconnection capacity (0–1% reduction compared to the current capacity); (4) curtailment (2% reduction in 80% RES scenario compared to no curtailment); (5)

Abbreviations: CAES, Compressed Air Energy Storage; CCS, Carbon Capture and Storage; CHP, Combined Heat and Power; DR, Demand Response; ECF, European Climate Foundation; ETP'14, Energy Technology Perspectives 2014; FOM, Fixed Operation and Maintenance; GT, Gas Turbine; iRES, Intermittent Renewable Energy Sources; LCOE, Levelized Cost of Electricity; Li-ion, Lithium Ion Battery; LWA, Load Weighted Average; MAE, Mean Absolute Error; MIP, Mixed Integer Programming; NaS, Sodium Sulfur Battery; NGCC, Natural Gas Combined Cycle; NGCC-CCS, Natural Gas Combined Cycle with CCS; PHS, Pumped Hydro Storage; PC, Pulverized Coal; PC-CCS, Pulverized Coal with CCS; RES, Renewable Energy Source; TCR, Total Capital Requirement; TOC, Total Overnight Costs; UCED, Unit Commitment and Economic Dispatch; VOM, Variable Operation and Maintenance; VRB, Vanadium Redox Battery.

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electricity storage increases total system costs in all scenarios (0.1–3% increase compared to only current storage capacity). The charging costs and investment costs make storage relatively expensive, even projecting cost reductions of 40% for Compressed Air Energy Storage (CAES) and 70% for batteries compared to 2012. All scenarios are simulated as energy only markets, and experience a "revenue gap" for both complementary options and other power generators: only curtailment and DR are profitable due to their low cost. The revenue gap becomes progressively more pronounced in the 60% and 80% RES scenarios, as the low marginal costs of RES reduce electricity prices.

1. Introduction

Anthropogenic climate change is leading to unprecedented changes that are, and will be, affecting both the biosphere and humanity in many ways [1]. To mitigate climate change, large reductions of CO_2 emissions are required. Decarbonizing the power sector is of particular importance, as this has the potential to happen more quickly than in the industrial, building and transport sectors [2].

Projections of decarbonized power sectors show that intermittent renewable energy sources (intermittent-RES) and power plants with Carbon Capture and Storage (CCS) will be important CO_2 mitigation options. They are projected to generate 20–80% (intermittent-RES) and 10–50% (power plants with CCS) of total electricity in Europe by 2050. The remainder is mainly generated by nuclear and non-intermittent renewable power plants [3–7].

As electricity demand and supply need to be kept in balance at all times, power systems will need to absorb the fluctuating electricity generation of intermittent-RES and account for intermittent-RES forecast errors [8,9]. Studies have shown that low-carbon power systems with large shares of intermittent-RES require more operational flexibility and more backup generation capacity. These requirements on the power system increase when intermittent-RES penetration increases [7,8,10].

Overall, the integration of intermittent-RES affects the power system in three ways: physically (how power generators are dispatched), economically (whether the business cases of all generators are sound), and in terms of security of supply (whether the power system meets its reliability targets).

Five complementary options have been suggested to improve the integration of intermittent-RES. Large scale electricity storage and expansion of interconnection capacity can balance supply and demand both temporally and spatially. Flexible natural gas-fired power plants with and without CCS can provide mid-merit and peak generation capacity at relatively low fixed costs. Demand response (DR) can reduce load during hours of capacity scarcity at low fixed costs, and hence reduce the peak generation capacity required. Lastly, curtailment of intermittent-RES generated electricity can be cost-effective [6,7,11].

Qualitative comparison between these five integration options have been made in the past [12–14]. These studies highlight the advantages and disadvantages of each technology, but they do not provide guidance on which options might be most suitable in future low-carbon power systems with varying deployment of intermittent RES.

Quantitative approaches are better suited to provide such guidance, but the fundamentally different principles of operation between the options complicate such an approach. Past studies have primarily focused on the optimal deployment level of a single type of complementary option. Examples include thermal power plants [15]; electricity storage [16]; and demand response [17]. In addition, some studies have quantified the effect of deploying one type of complementary option on another type of option: e.g. how interconnections and storage affect optimal thermal power plant deployment [18] and how demand response affects optimal interconnection capacity [19]. A last group of more comprehensive studies included all five complementary options in power system simulations. These studies focus on high-level conclusions and have not paid specific attention to the optimal deployment of complementary options, however [3,7,20].

As a consequence, there is insufficient understanding on which options are most suitable for low-cost integration of intermittent-RES in future low-carbon power systems. This knowledge gap has been identified by a number of studies [14,21,22]. Insights are needed to guide research and support policy makers and energy companies to identify and invest in portfolios of electricity generation, transmission and other complementary technologies that facilitate a cost-efficient, low-carbon future.

This study directly compares integration options for future low-carbon power systems by comparing the effect of their deployment on the total system costs. Thus, it answers the research question: ***Which complementary options should be deployed in low-carbon systems with high shares of intermittent RES to minimize total system costs?*** The study focusses on Western Europe in the year 2050 and simulates a reliable power system with a 96% reduction in CO_2 emissions compared to the year 1990. Two research steps are taken. First, the fossil generation capacity is least-cost optimized for plausible, exogenous scenarios with 40%, 60% and 80% RES penetration with varying shares of complementary options. Next, operation of the resulting full generation portfolios is simulated with a time step of 1 h to determine the total system costs.

This study accounts for intermittent-RES impacts on the power system, including increased sizes of balancing reserves, efficiency losses of thermal generators caused by intermittent-RES, displacement of thermal power generation and integration costs of intermittent-RES. The article focuses mainly on the simulation and calculation methods (Section 2), results (Section 4), discussion (Section 5) and Conclusion (Section 6). This study's input data are provided in Section 3 and Appendices A–G.

2. Methods

Western Europe is the study area, in which six regions are distinguished based on their prevalent types of intermittent-RES potential and the expected bottlenecks in future interconnection capacity between regions (see Fig. 1). Only transmission constraints between regions and not within regions are accounted for. The year 2050 is studied because a low-carbon power system is planned to be realized by then [23]. The period before 2050 is not simulated and no legacy power plants are included. Nevertheless, by varying the contribution of RES and intermittent-RES in 2050, insights are also obtained about the impact of an increasing contribution of intermittent-RES along the road towards 2050.