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Spatio-temporal assessment of integrating intermittent electricity in the EU and Western Balkans power sector under ambitious CO_2 emission policies

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ABSTRACT

This work investigates a power dispatch system that aims to supply the power demand of the EU and Western Balkans (EUWB) based on low-carbon generation units, enabled by the expansion of biomass, solar, and wind based electricity. A spatially explicit techno-economic optimization tool simulates the EUWB power sector to explore the dispatch of new renewable electricity capacity on a EUWB scale, under ambitious CO_2 emission policies. The results show that utility-scale deployment of renewable electricity is feasible and can contribute about 9–39% of the total generation mix, for a carbon price range of 0–200 €/tCO_2 and with the existing capacities of the cross-border transmission network. Even without any explicit carbon incentive (carbon price of 0 €/tCO_2), more than 35% of the variable power in the most ambitious CO_2 mitigation scenario (carbon price of 200 €/tCO_2) would be economically feasible to deploy. Spatial assessment of bio-electricity potential (based on forest and agriculture feedstock) showed limited presence in the optimal generation mix (0–6%), marginalizing its effect as baseload. Expansion of the existing cross-border transmission capacities helps even out the variability of solar and wind technologies, but may also result in lower installed RE capacity in favor of state-of-the-art natural gas with relatively low sensitivity to increasing carbon taxes. A sensitivity analysis of the investment cost, even under a low-investment scenario and at the high end of the CO_2 price range, showed natural gas remains at around 11% of the total generation, emphasizing how costly it would be to achieve the final percentages toward a 100% renewable system.

1. Introduction

To boost transformation of the carbon-intensive supply chain of today's energy infrastructure into a low-carbon one, the expansion of Renewable Electricity (RE) deployment must be facilitated. Energy models, based on scenario assumptions that take into account how energy is harnessed, delivered, and used, can help explore such technological transformations as well as their impacts on the existing energy system. Currently, the energy supply (i.e., the power, heat, and transportation sectors) of the European Union (EU) is met to a large extent from fossil fuels and nuclear technologies. Nonetheless, the deployment of intermittent renewables has been increasing steadily over the last two decades. In the EU, the aggregated installed capacity of solar photovoltaics (PV) and onshore wind turbines reached about 111 GW in 2010 and 241 GW in 2016, up from about 13 GW in 2000 [1].

Decarbonization of the energy sector through the integration of intermittent renewables is often discussed as a mitigation measure. Since 2009, the EU has been implementing the so-called EU 20–20–20 climate and energy policy package which mandates: (i) 20% reduction in EU GHG (greenhouse gas) emissions in 2020 compared to 1990 levels, (ii) 20% increase in the share of

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renewables in final energy use (of which 10% in the transportation sector), and (iii) 20% increase in energy efficiency [2]. To guide a long-term vision, the 2009 package was followed by a new directive in 2014 setting the EU roadmap up to 2030, in which the target for reduction of GHG emissions was raised to 40% (compared to 1990 levels) and the target for the share of renewables to 27% [3].

EU energy and climate policy targets are characterized by high shares of variable renewables (in particular, wind and solar), and this is associated with significant challenges. Several countries in the region are already in the fast lane for the expansion of variable RE, the notable large economies being the United Kingdom (UK) (onshore and offshore wind) and Germany (solar and onshore wind). Both countries, however, have a long way to go to achieve their pledged carbon emission target by 2050, (i.e., 80% lower compared to 1990 levels [4]). In this study, we focus on the expansion of onshore wind power and solar PV supplemented with bioenergy. The coupling of solar and wind plants to thermal generators, and the use of new load management technologies to align the demand for power with the variable supply, offer promising pathways for aggressively reducing the amount of carbon that the power industry disposes in the atmosphere.

To provide sufficient insight to address these issues, a system-level approach with adequate representation of both the spatial and temporal features of renewable energy sources is essential. In prior studies, various modeling and evaluation approaches were applied to analyze the complexity of a European high–share variable RE system. Gils et al. [5] used an optimization model with multiple spatial nodes, each representing a region in the EU, and hourly temporal resolution, to investigate an integrated European electricity market with high shares of variable RE supply, with focus on balancing strategies. Using a dynamic linear electricity system model, Jägemann et al. [6] studied the economic implications of decarbonizing the EU power sector by 2050. The impact of the EU 2030 energy target on the electricity sector was assessed by Knopf et al. [7] using a linear electricity model of the European electricity system, with each country being represented by a spatial node. The current state of renewable energy performance in the EU was assessed at the country level by D'Adamo and Rosa [8] for the period 2015–2020, based on averaged values of the period 2008–2014, in order to suggest a new reference RE trajectory. Bussar et al. [9] performed a sensitivity study on the storage demand of a European power system with high shares of RE in 2050 using a power system model of Europe, the Middle East, and North Africa (EUMENA) represented by 21 regions. Buttler et al. [10] assessed the variability of wind and solar power in the EU based on the installed capacities of 2014. Several other studies have assessed country-level strategies, for example, focusing on integrating RE in Germany [11–13]; these analyzed and discussed long-term scenarios and strategies [11], the importance of transmission grid capacity expansion [12], and in the context of long-term energy-economy models using residual load duration curves [13]. The management and engineering aspects of large-scale integration of variable RE have become essential subjects to compensate for intermittency of wind and solar power, for example, using a market-based principle [14], and using energy storage systems coupled to stochastic modeling of wind energy [15].

The approach used in our assessment combines a high spatial (0.4°) and temporal resolution (representing a period of one year), which allows us to analyze regional differences as well as temporal effects. This approach can capture reasonably high-resolution load-matching, which is often overlooked by country or regional-level aggregated dynamic linear models used for planning long-term consequences, e.g. Refs. [5–7]. The objective this work is to assess the potential for reducing CO_2 emissions from the EU and Western Balkans (EUWB) electricity sector. We explicitly target the high CO_2-emitting technologies in the existing generation fleet and evaluate how they compare against a spatio-temporally explicit RE portfolio supplemented by a state-of-the-art natural gas combined or open cycle (NGCC or NGOC) depending on the nature of the load. This paper also aims to identify the optimal spatial distribution of new RE plant installations, as well as the most beneficial, from a cost as well as CO_2 emission mitigation perspective, power generation mix, given grid specific biomass resource availability, insolation, wind speed, and the locations of major power transmission hubs connecting new RE installations to the demand sites.

The spatially explicit dimension of our approach enables the simultaneous optimization of the capacity of, and the investments in, new RE plant installations at the grid level. This is particularly important for balancing the space for intermittent plant installations and other ecosystems services, such as designated protected areas, which in this text is considered based on harmonized International Union for Conservation of Nature (IUCN) categories I through VI [16]. In the absence of adequate energy storage, power systems with high-share of intermittent RE rely on flexible baseload to maintain stability. Our analysis also highlights not only the importance of a low-carbon baseload, such as biomass, nuclear, and hydropower, complemented with battery storage units, but also the potential benefits of cross-border transmission capacity expansion.

Brief descriptions of the optimization model and the input data processing are presented in Section 2. The main results are presented in Section 3, where a sensitivity analysis of the optimal generation mix toward expansion of existing transmission capacities between EUWB nations is also performed and presented. The main findings are further discussed in Section 4, where a sensitivity analysis regarding the impact of the investment cost on the salient features of a highly renewable EUWB power system is also introduced and discussed. Section 5 summarizes the main conclusions drawn.

2. Methodology and input data

In this study the BeWhere model [17] is used to simulate a highly renewable power dispatch system at the European level. The BeWhere model is a geographically explicit mixed-integer linear programming (MILP) model which was originally developed for optimizing the capacity and localization of bioenergy facilities. The model is written in GAMS and uses CPLEX as solver. The adaptability of the model to different applications has been demonstrated in previous studies, for example, on bioenergy and intermittent RE coupled with carbon capture and utilization (CCU) [18], bioenergy with carbon capture and storage (BECCS) [19], algae cultivation from captured CO_2 [20], and, recently, decarbonization of steel production in Europe [21]. BeWhere has been used for national [22–24] and regional [18,25] studies, as well as for studies at the European scale [26].

2.1. Model setup

To investigate the techno-economic potential of transitioning the EUWB power system, the model is reconfigured to assess expansion of RE units. The version used here has a spatial coverage of the EU28 and Western Balkans (Bosnia and Herzegovina, Montenegro and Republic of Serbia), herein referred to as EUWB. Input data for RE resources is considered at grid level, formulated based on ~40 km × 40 km spatial resolution. The electricity demand data are considered at the country level. The model is run for a period of one year with a temporal resolution of 192 h, corresponding to the peak and median demand days of each month at a 3-hourly step.

The objective function is to minimize the total cost of an energy