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Outlook on South-East European power system until 2050: Least-cost decarbonization pathway meeting EU mitigation targets

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ABSTRACT

Climate change forces humankind to strong reduction measures for greenhouse gas (GHG) emissions. Following this scientific consensus the European Union obliged it's member states to achieve high reduction targets to almost zero emissions – especially in the power generation sector – until 2050. Evidence-based strategies to implement cost-effective reduction pathways are necessary to achieve these targets. We developed a multi-regional power system model – *elesplan-m* – to analyze a least-cost decarbonization pathway for Europe with special focus on South-East-Europe (SEE). The analysis seeks for optimal strategies in the power sector while it neglects cross-sectoral demand shifts coming up with the electrification of transport and the use of heat pumps. Results underline both, the possibility and the enormous efforts required to achieve the intended decarbonization. SEE needs to increase its photovoltaic capacity to 120.7 GW, wind power capacity to 92.4 GW and transmission capacities to neighboring countries to 32.7 GW until 2050 to achieve the GHG emission reduction targets. The power system transformation requires annual average investments of almost one billion EUR in SEE. Resulting levelized cost of power supply of this region adds up to 12.1 ctEUR/kWh.

1. Introduction

Climate change mitigation goals declared by the European Union (EU) [1], underpinned by the recent global *Paris-Agreement* [2], oblige European countries to pursue strong decarbonization pathways. Such a decarbonization strategy requires enormous efforts and changes especially in the power sector. Our paper focuses on South-East Europe (SEE) which comprises the countries Serbia, Kosovo, Bulgaria, Republic of Macedonia, Albania, Greece, Slovenia, Bosnia and Herzegovina, Croatia and Montenegro as showcase region to understand the detailed impact of the required changes in the context of the European *Energiewende*. This region accounts for 12.6% of the current European greenhouse gas (GHG) emissions and is partially connected to the centralized European power supply system [3–5]. Thus, it is necessary to analyze the entire European supply system in order to derive the decarbonization pathway for SEE. Strong decarbonization goals fundamentally change structure of current power supply systems, therefore it is important to develop cost-efficient transition pathways. A valuable assessment of such pathways is required to provide reliable recommendations for policy decision makers concerning transformation of the power sector.

So far, no comprehensive least-cost decarbonization pathway for SEE exist. Our work aims to identify such least-cost transition pathway of the SEE power sector that meets given GHG emission reduction targets (nearly zero emissions in 2050) in context of an increasingly integrated European power supply system [6]. This will help to understand SEE's role in the decarbonized European supply system and to give indications about costs and benefits of the transition towards zero GHG emissions. Capacities and generation shares of suitable technologies for climate change mitigation and its spatial allocation are identified with the help of a complex simulation and modeling tool. In addition, costs of this transition and the associated investment needs in power supply infrastructure are outlined up to 2050. Furthermore, the inner-European dependency regarding power supply – especially for the SEE countries – on a cost-optimal transition pathway are analyzed. These steps are conducted by using the power system model *European long-term electricity system planning model (elesplan-m).*

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Research on power systems in context of climate change mitigation and renewable energy sources (RES) integration in Europe has been conducted by different research groups as presented in the following. Schaber et al. investigated the impact of variable RES [7,8] and Bussar et al. focused on an optimal allocation of storage systems [9]. Lund et al. found feasible danish energy supply options based on a 100% RES [10]. Jägemann et al. analyzed deep cuts in European power supply related GHG emissions and found investment costs for 90% reduction targets compared to 1990 levels that vary between 139 and 633 billion EURO [11]. Heide et al. and others investigated optimal wind and photovoltaic (PV) power shares and resulting balancing needs in a simplified manner based on high resolution weather data [12–14]. This approach was extended for analyses of optimal configurations of storages and balancing power plants in power systems with high penetration of RES [15–17]. Rodríguez et al. took this modeling approach to examine interrelationship of generation mix and necessary transmission system capacities [18]. Based on extrapolation of historic capacity expansion and national renewable action plans Becker et al. draw a picture of pan-European power system transformation until the year 2050 [19].

Effects of electricity reforms, liberalization of the electricity sector and SEE regional energy market as well as SEE countries' role in an EU internal market has been analyzed by various studies. Hooper et al. analyzed historic power supply mix of the SEE region that was dominated by fossil and nuclear fuelled power generation [20]. Višković et al. conducted a study on effects of regulation on investments in coal-fired power plants for Croatia and Bosnia and Herzegovina [21]. Other studies analyzed opportunities and challenges of establishing a regional energy market [22,23]. Their studies suggest enhanced regional electricity trade. Adoption to EU legislation was discussed for Slovenia [24], Republic of Macedonia [25], Romania [26] and SEE in general [27]. European Union compliant electricity market regulation is seen as logically consistent step after establishing a SEE regional electricity market. Climate change mitigation is addressed as well by studies looking at SEE. Teseska et al. identified significant GHG reduction potential of current coal based power supply system on the example of Macedonia [28]. Bjelić and Rajaković analyzed the GHG reduction by RES and energy efficiency measures according to the EU-2030 targets in Serbian power system [29].

The presented literature review reveals that methodologies are available to model power systems and analyze those regarding transition pathways towards low-carbon power supply. Nevertheless, a regional study for SEE that analyzes power system transition pathway is lacking. Such a study could guide the local decision makers in implementing a least-cost decarbonization strategy.

Our paper analyzes regional decarbonization pathways of the SEE power supply system – integrated in the European power supply system – under consideration of long-term GHG reduction targets by the EU. This goes beyond previous country studies and beyond the decarbonization targets analyzed by country case studies in SEE. Regarding the methodology of modeling decarbonization pathways of European power supply, we apply an integrated long-term investment planning model based on optimal dispatch – *elesplan-m* – as presented earlier by Pleβmann and Blechinger [30]. This model simulates at higher temporal resolution in order reflect volatility of RES feed-in as in other work [31,32] and realizes stronger decarbonization targets compared to Ref. [11,33].

In our paper we present an analysis of potential transition pathways for SEE. Section 2 introduces the power system model *elesplan-m* and describes data used in this study. Afterwards findings on the overall European power supply and regional findings for the SEE region are presented in the results section. These results are analyzed, related to other studies and limitations are discussed in the discussion & conclusions section.

2. Power system model *elesplan-m*

The assessment of least-cost decarbonization options of the European power system is a challenging task caused by complex interrelationships in the power supply system – in particular when volatile RES power supply and energy storage technologies are involved. Available low-carbon power generation technologies in combination with flexibility options provide several feasible power system configurations that meet GHG reduction targets. Thus, a sophisticated modeling approach is required to cover relevant aspects of power supply in the analysis. For this research paper the power system model *elesplan-m* was applied to assess the economically most viable option. The model *elesplan-m* is an hybrid approach settled between long-term energy system models and optimal dispatch models. It takes a social-planning perspective and consequently neglects current electricity trading schemes of the European power market.

2.1. Technologies and spatial coverage

elesplan-m covers the power supply sector and its main technologies with a focus on the renewable power supply technologies wind, PV and hydro power [34]. Among RES technologies *elesplan-m* represents three energy storage technologies: battery storage and pumped hydro storage (PHS) for short-term balancing needs and the power-to-gas (PtG) technology as a long-term energy storage. Furthermore, four thermal power plant technologies are included: Nuclear power plants, coal power plants, open cycle gas turbines (OCGTs) and combined cycle gas turbines (CCGTs). The latter two are used for re-electrification of synthetic natural gas (SNG) produced by the PtG unit as well as for the burning of natural gas. Fig. 1 illustrates power system technologies and its potential power flows.

The applied version of *elesplan-m* was adapted to represent Europe's power supply system. Fig. 2 presents a map of regions as we defined as Europe for this paper. It is defined as the union of member states of the EU and the European Network of Transmission System Operators for Electricity (ENTSO-E)[1]).

Elesplan-m aggregates single countries to representative regions in order to reduce computational-cost of a model run. Model regions are chosen according to the structure of the European transmission grid, typical country groups and the countries' impact on European's power supply.

2.2. Model characteristics

The model is formulated as linear optimization problem that takes a social-planning perspective by aiming for the European-wide least-cost solution of decarbonized power supply. A pathway is modeled by subsequently analyzing *decision year* in 5-years steps. Each *decision years* is used to determine necessary new investments to replace decommissioned capacities and to meet given GHG targets. Modeling of single *decision years* takes place at hourly temporal resolution whereas perfect foresight is applied. The optimization problem is solved by using *barrier methods* of GUROBI [35].

[1] Two exceptions exist: Albania is included in Europe although it is neither an EU nor an ENTSO-E member state. The Russian exclave Kaliningrad is not included in this work.

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