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Opportunities and challenges of high renewable energy deployment and electricity exchange for North Africa and Europe – Scenarios for power sector and transmission infrastructure in 2030 and 2050

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A B S T R A C T

Climate change and limited availability of fossil fuel reserves stress both the importance of deploying renewable energy sources (RES) for electricity generation and the need for a stronger integration of regional electricity markets. This analysis focuses on North African (NA) countries, which possess vast resources of renewable energy but whose electricity supply is still largely dependent on fossil fuels. An analysis of cost-optimized deployment scenarios for RES is conducted in five NA countries in 2030 and 2050. Three electricity models are combined to derive results covering trans-regional to sub-national level, including a detailed analysis of grid capacities and future transmission challenges. Further, opportunities for integration of European and NA electricity markets are evaluated. Results confirm that, by 2050, high RES shares – close to 100% – are possible in NA. Wind energy is the dominant technology. Concentrated Solar Power (CSP) plants also play an important role with rising RES shares due to the possibility to store thermal energy. Electricity exports to Europe gain particular importance in the period after 2030. Substantial transmission grid reinforcements on AC-level and the construction of a high voltage DC overlay grid are prerequisites for the forecasted scenarios.

1. Introduction

Against the backdrop of climate change and the limited availability of global fossil fuel reserves, exploitation of renewable energy resources for electricity generation has become a topic of global concern. The member states of the European Union (EU), as well as a growing number of other countries worldwide have placed high priority on renewable energy sources (RES) and formulated respective deployment targets [1,2]. The EU envisages a RES share of 20% in final energy consumption by 2020, whereby this share can also be reached by physical imports of electricity generated from RES in non-EU countries [1]. By 2030, an EU-wide RES share of at least 27% is envisioned [3]. These plans open up opportunities for inter-regional cooperation in RES generation and trade, especially with adjacent countries in the Southern Mediterranean.

However, most of these neighbouring countries, including those in North Africa (NA), are themselves facing steep upward trends in their electricity demand and a limited access to fossil fuel sources, as well as a dominance of conventional generation technologies in their electricity systems [4,5]. On the other hand, NA is characterized by vast, untapped wind and solar energy resources [6,7]. This suggests that a stronger deployment of RES for the coverage of the growing domestic demand as well as for generating extra revenues from exporting electricity to the EU would be a sustainable future strategy for the NA region [8,9].

Previous studies and initiatives such as the 'Mediterranean Solar Plan' [10] or the vision of the 'Dii' [11] highlight the opportunities of

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a stronger inter-regional electricity market integration between NA and the EU [12–15]. Obviously, the realization of trans-regional electricity market integration also implies major challenges. Besides financial and regulatory issues, it entails considerable technical difficulties, in particular related to optimization of power plant dispatch and balancing and the development and proper operation of respective transmission grid capacities [16–20].

The challenges of inter-regional market integration do not only manifest themselves on a trans-national level (i.e. the bulk long-distance transmission of electricity), but also affect the national and local level (e.g. by influencing national transmission grids and local supply structures). Therefore, this study aims to comprehensively analyse the medium to long-term perspectives (2030 and 2050) for reaching high shares of RES in five NA countries (Algeria, Egypt, Libya, Morocco, and Tunisia) under different framework conditions (scenarios). The analysis includes an assessment of options for RES export from NA to the EU and involves an evaluation of the resulting transmission grid requirements on both national and international level (AC and HVDC grids). Besides the optimization of the electricity generation portfolios and transmission grids on national and international level, our study also involves analyses on sub-national level, evaluating the optimal power plant allocation and dispatch in accordance with local generation and load patterns.

Following this introduction, the paper is structured as follows: Section 2 describes the applied models and their interfaces. Section 3 presents the database utilized for the calculations and introduces the scenario framework and assumptions underlying the analysis. Section 4 summarizes the results, whereby subsection 4.1 focuses on the national and trans-national analyses (generation portfolios and export options), subsection 4.2 describes the sub-national optimization (power plant allocation and dispatch for the example of Morocco), subsection 4.3 presents the implications for transmission grids and subsection 4.4 discusses the policy implications of the outcomes. Section 5 concludes and elaborates on the policy implications of the presented scenarios.

2. Models and methods

Within the frame of this paper, three models are combined in order to cover different dimensions of technical challenges associated with the regional and inter-regional electricity market integration in a comprehensive analysis. Firstly, a derivation of cost-optimized electricity generation portfolios on national and trans-national level is applied with the model *PowerACE* (for a detailed model description see Ref. [21]). Major inputs for this analysis are the availability of RES potentials and costs as well as the development of the national electricity demand. Geographically, the analysis focuses on five NA countries (Algeria, Egypt, Libya, Morocco, and Tunisia) but also covers the EU plus Switzerland and Norway, in order to assess the opportunities resulting from an interconnected power system. Secondly, the analysis covers the sub-national level, which involves an optimization of allocation and operation of power plants with the model *RESlion*, in order to optimally combine local generation and consumption patterns at minimal costs (for more details see Ref. [8]). Thirdly, requirements regarding transmission grid capacities and operation are covered, using *DIgSILENT* PowerFactory [22]. The interfaces and data flows between the three models are illustrated in Fig. 1.

2.1. Long-term power system optimization with PowerACE

In a first step, an in-depth analysis of available wind and solar potentials with a geographic information system (GIS) is conducted using the software *ArcGIS* [23]. The available areas for RES deployment are identified based on information on the current land-use (e.g. agriculture, buildings, infrastructure, military areas, nature conservation) and the terrain (e.g. slope, elevation, soil properties). For the suitable areas, renewable energy resource data (wind and solar atlases) are applied to derive the available generation potential (see Section 3.3). As a second major input parameter to the power system optimization, estimations of the future electricity demand of the NA countries were derived. The analysis is based on econometric analysis of historical demand data and assumptions for population growth, development of the gross domestic product (GDP), energy intensity and future trends in energy efficiency (see Section 3.2). On this basis, cost-optimized electricity generation portfolios for the EU-NA power system are determined using *PowerACE*. The model applies a linear optimization algorithm using a CPLEX solver to derive an optimal mix of storage, transmission, conventional and RES generation technologies (optimized in terms of minimal total system costs) under different scenario conditions (see Section 3.1). A more detailed description of the general modelling approach is available in Ref. [21].

2.2. Regional capacity planning and short term power plant operation with RESlion

In a second step, an optimization of power plant allocation on sub-national level and their optimal short-term operation and dispatch (hourly) are carried out with *RESlion* [8]. In this regional optimization planning model, local site selection for RES power plants is carried out within a combined electricity system model for expansion planning and detailed hourly dispatch. The model considers existing power plant location, sub-national electricity demand and generation as well as constraints of the national electricity grid by minimizing total system costs. RES generation is optimized according to hourly weather data, in order to match the electricity demand at sub-national resolution. A definition of the sub-national regions is provided in the Appendix. By considering grid constraints for exchange of electricity between neighbouring regions, the model contains a link to the transmission grid structure, which is covered in the third model step.

2.3. Transmission grid analysis with DIgSILENT PowerFactory

In a third step, the existing transmission infrastructure is modelled and its ability to integrate additional volumes of RES is evaluated. Modelling of the grid is conducted for the alternating current (AC) transmission grid of 220 kV and above. Grid expansion needs are identified based on the power exchanges resulting from the modelling steps 1 and 2. In addition, a detailed HVDC overlay grid is developed and modelled. Modelling and analysis is done in the power system simulation tool *DIgSILENT PowerFactory* [22].

For modelling the European AC transmission grid, a dataset of Zhou & Bialek [24] is converted and implemented in *PowerFactory*. Modelling the NA transmission grid involved a manual implementation of grid maps for NA [25]. Single DC links for point-to-point connections are implemented in the AC transmission grid model, as well as interconnectors among NA countries and between NA and the EU as planned by 2020. Also synchronous areas are implemented as they exist today. Then transmission capacities are calculated based on the maximum current rating of conductors and number of parallel systems at the nominal voltage level. Hence the total transmission capacity (TTC) of the transmission grids is analysed and used for expanding the infrastructure.

To allow for pan-European-North African power exchange, an HVDC grid based on a feasibility study [26] is implemented in the first place and then expanded by the results from the modelling steps 1 and 2.