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The influence of continued reductions in renewable energy cost on the European electricity system

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ABSTRACT

In the recent years, variable renewable energy (VRE) technologies – most importantly solar photovoltaics and wind power – have undergone a remarkable transformation from niche technologies to increasingly competitive energy suppliers. As the potential for VRE is distributed unevenly across Europe, a Europe-wide cost optimal expansion of VRE will lead to different national and regional expansion rates of VRE. To facilitate such a Europe-wide cost optimal expansion of VRE a fair cost distribution among all European countries is needed. Therefore, we analyse and discuss how expected future decreases in investment costs for selected VRE (photovoltaics, concentrated solar power, wind onshore, and wind offshore) will affect the pan-European and national electricity systems. This is done by comparing three cost scenarios with a reference case, calculated using a European electricity system model. Our results show that the assumed cost reductions lead to an especially pronounced increase of PV distributed unevenly across Europe. In addition, higher shares of VRE show the effect of shifting electricity exchange patterns throughout Europe which also reduce cost benefits for economies of electricity exporting countries. Hence, there might be a lack of agreement in Europe about where and how to expand and integrate VRE if costs of expanding and integrating VRE are not distributed in a fair way between the European countries. In addition, these possible barriers of expanding VRE Europe-wide in a cost-optimal way might hinder the exploitation of cost synergies or even slow down VRE expansion on a European scale.

1. Introduction

More and more countries and regions worldwide have set themselves ambitious climate targets, likely to be accelerated through the *Paris Agreement* in 2015, aiming to hold "*the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*" [1]. Europe has its specific energy and climate goals [2] and goals for single member states. Germany, for example, intends to reduce its greenhouse gas emissions by more than 80% by 2050 compared to 1990 [3] and France seeks, amongst other goals, to diversify electricity generation and reduce the share of nuclear to 50% by 2025 [4]. Whether and how these goals can be achieved is the subject of coordinated energy and climate policy research, which can be supported by appropriate modelling approaches in order to analyse possible transformation pathways of the energy system towards a low-carbon future.

Due to those climate targets, a greater number of demand sectors – especially the transportation, heating and cooling sectors – are likely to be electrified to a greater extent (cf. [5,6,7]) possibly in combination with other pathway options like energy efficiency measures [8], biofuels [9] and/or energy storage [10]. Newly emerging technologies such as e-mobility and heat-pumps, are often employed to bring about this electrification. These "non-traditional" loads caused by this electrification trend need to be powered by carbon free electricity sources to be in line with the climate targets. In addition, non-renewable sources lack public acceptance in several European countries, in particular nuclear [11] and CCS power plants (cf. [12,13,14,15]) which limit the technical options to decarbonize the energy system. Hence, variable renewable energy sources (VRE) – most notably their potential, costs and public acceptance – are decisive for the success of climate protection. Nonetheless, the potential to integrate VRE into the European energy system is highly correlated with grid extensions and/or energy storage to avoid curtailment of VRE feed-in Ref. [16] as well as climate change influences [17]. In addition, grid extensions are also required to

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Abbreviations

VRE	Variable Renewable Energies
REF	Reference Scenario
IRENA	International Renewable Energy Association, here also used as scenario descriptor
EXT	Extended Scenario
DIF	Differing Scenario

achieve the politically desired European-wide single energy market [18].[1]

In recent years, VRE technologies – most importantly solar PV and wind power – have undergone a remarkable transformation from niche technologies to increasingly competitive energy sources. Today, VRE already serve as the major source of electricity in some countries, e.g. Denmark [19]. This development went along with or was partly caused by drastic cost reductions of VRE technologies [20]. A variety of literature sources have been dealing with the implications these cost reductions of renewable energies. Currier [21] examines investment costs reduction policies through green certificates on a theoretical basis and demonstrated that green certificates can result in increased emissions from fossil-based sources. MacGillivray et al. [22] investigate the sensitivity of wave and tidal stream marine technologies to the capital cost of first commercial devices, the level of deployment before sustained cost reduction emerges, and the average rate of cost reduction with deployment. They applied a single factor learning rate model and show that even small changes to input assumptions can have a dramatic effect on the overall investment required for a sector to reach parity with benchmark technologies, in their case offshore wind energy. González-Portillo et al. [23] analyse the impact of thermal energy storage on electricity cost reductions in solar thermal electric plants. In a study focusing on Africa done by IRENA [24] the cost reduction potentials for solar home systems including the option of a connection to a micro-grid, are demonstrated and the authors come to the conclusion that Africa could have installed more than 70 GW of solar PV capacity by 2030.

Perera et al.'s [25] research points in a different direction, by showing that electrical hubs, when they are optimized and their power is dispatched properly, can help increase the share of solar PV and wind power to meet over 60% of Sri Lanka's annual demand. Schlachtberger et al. [16] focus on Europe's interconnected power systems and consider how high shares of variable renewable energies can be integrated into the existing system by comparing the balancing at continental scale via transmission grids versus balancing at local scale via storage units. They find a cost-optimal system to be dominated by high shares of wind (65%) and hydro (15%), which is shifting towards solar and storage with increasing transmission restrictions. However they do not take a steady decrease in investment cost into account, but assume fixed costs, taken from literature for the year 2030. Mauleón and Hamoudi [26] shed light on the learning rates, implicitly assumed in IEA's roadmaps for solar PV and wind energy, and their uncertainties for investors. By performing parameter variations, they show that alternative investment paths do not necessarily lead to a significant increase in the accumulated final investment and advocate accelerated deployment paths to fight climate change.

However, no literature has been found that examines (a) cost reductions potentials based on a detailed technological analysis (b) for several types of different technologies (c) applied to a wide and connected geographical area such as Europe and (d) within a model-based environment.

[1] For detailed insights into these, short-term market models (such as unit commitment models) and/or node-specific grid simulations are required, which are not scope of long-term modelling approaches such as this one here.

The study presented here focuses on the electricity sector, especially renewables but also on conventional power plant capacities and their electricity generation in Europe. A further decrease in VRE costs will impact the European electricity system among others in terms of energy mix, exchanged electricity and costs for electricity. Such changes within a liberalized energy market will probably lead to uneven investments in power generation capacities and, therefore, in cost distributions on a national scale. As the electricity industry is part of national economies there might be resistance to such shifts in investments. This leads to the unsolved question of how to balance the impact of those investments and their costs in a fair way. The same question applies for grid and storage expansions in Europe. However, we focus here on VRE technologies. Therefore, the main issues to be addressed within this work are:

- Evaluating the long-term impacts of expected further cost reductions of the four major types of VRE (photovoltaic, concentrated solar power, wind onshore and offshore) on the European power plant fleet and electricity exchange,
- Identifying which cost decrease might have the biggest impact on the investments in power generation and distribution infrastructure, both overall and country wise, and
- Addressing the need for a fair cost distribution of power plant portfolios to fully exploit possible synergies in power plant expansion in Europe.

This is done by comparing three costs scenarios with a reference case (cf. Section 2.2), calculated with a European electricity system model (cf. Section 2.1) implemented in TIMES [27] based on completely transparent data (cf [28]. and supplementary). We show the results in Section 3 and complement them with a sensitivity analysis in Section 4. Subsequently, we discuss the results and their implications in section 5 and draw the most important conclusions in Section 6.

2. Approach

2.1. The European electricity system model

To analyse the impact of possible further decreases in costs of VRE, we apply a European electricity system model which is fully based on transparent data to allow for contentious discussions of results. An overview of the applied model is given in Fig. 1. It is implemented in the broadly established model framework TIMES [27]. The mathematical background in TIMES are linear programming formulations for a capacity expansion model. This means in a nutshell that the sum of all cost elements over all time-steps over all regions over all technologies is being minimized subject to a set of boundary conditions. These cost elements incorporate (a) the variable cost of generation through commodity flows (fuel costs), (b) fixed and variable costs for operations and maintenance, (c) investment costs of existing and new capacity, (d) decommissioning costs for units beyond their technical lifetime, and (e) further politically imposed costs such as taxes and revenues, in our case CO_2 emission costs. All of those costs are discounted to a base year, in our case the year 2015. The boundary conditions make sure that the imposed constraints of technical (e.g. energy flows), of structural (e.g. geographical potentials), of political (e.g. emission limits), and of purely mathematical nature are being taken into account. More detailed information concerning the TIMES formulation can be found in Ref. [29].

The model covers 28 countries in Europe, precisely the EU-28 with the exception of Malta and Cyprus plus Norway and Switzerland. The model consists of 29 regions, since it is common modelling practice to model Denmark as two different regions, i.e. Denmark-West and Denmark-East, since these two are asynchronous and belong to different control zones [30]. This spatial resolution is able to take into account the Single European Energy Market in order to depict the regionally