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The underestimated potential of solar energy to mitigate climate change

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Supplementary Note 1 – Detailed electricity sector modeling with high shares of PV and wind

To explore the challenges of integrating high shares of variable renewables, it is necessary to model the electricity sector in detail. Here, this includes four different types of detail. The first is temporal detail, meaning that the variability of wind, solar and load need to be represented. This requires a high number of time steps, such as hourly modeling over a full year or even several years. (Some questions like short-term balancing can only be answered using sub-hourly resolution. However, past analysis has shown that while sub-hourly resolution is important when determining cycling of power plants, it has little influence on total system costs and thus the aggregated analysis of integration challenges [1]). The second is regional detail, to allow representation of the smoothing effect as well as costs of grid expansion. Third is representation of different power sector flexibility options, such as short- and long-term storage and demand response. The final one is sector-coupling detail to allow analysis of future flexibility options provided by other sectors, such as vehicle-to-grid or long-term heat storage.

For the analysis of high VRE shares, it is important to distinguish on the one side dispatch/unit commitment models that optimize plant dispatch while assuming a given generation system, and on the other side dispatch and investment models that optimize both the dispatch as well as the power plant capacities that are available. Pure dispatch models represent the short-term view – what happens if VRE shares are increased within years, so the system does not have time to adjust the standing capacities. Therefore, integration challenges found with dispatch models are substantially higher than integration challenges found with dispatch and investment models, which take into account that high VRE shares beyond 40-50% will only be reached over decades, thus the rest of the system can adapt. Accordingly, dispatch-and-investment models see much lower integration challenges, because the optimized systems provide much more flexibility and have little baseload capacities.

Over the last decade, research of VRE integration has made substantial progress, but a range of topics still need more research.

Most of the VRE integration studies focus on (sub-regions of) the EU and US where data is easily available[2–12]; only a few studies focus on other regions [13–17], where one of the main challenges is to derive the required time series for load as they are usually not publicly available. The load time series is one of the most important modeling inputs as it determines the (anti-) correlation of wind, solar, and load.

A number of studies explicitly analyze the smoothing capability of grid expansion[2,4,10,12,16,18,19], while others do not represent this integration aspect or at least do not make their assumptions transparent.

Few of the scenarios contain a full interface between the electricity sector, transport and energy demand in buildings and industry, which would be

necessary to analyze how relevant the ability of other sectors to provide flexibility options to the power sector is to further decrease integration challenges [7,20]. Electrification of transport, the use of heat pumps to provide heat, the usage of power-to-gas or power-to-liquid conversion, or increased demand-side management in industry are all options that may facilitate increasing the share of VRE. This remains an important focus for future research.
All of the recent detailed studies show that technically, it is possible to integrate large shares of variable renewables (40-80%, some even model 90% or 100%) if sufficient flexibility options are deployed. However, the exact mix of VRE technologies (PV, wind, or CSP) as well as the economic evaluation of the scenarios varies both between the studies and between the modeled regions. The differences between regions can be explained from the underlying fundamentals, with the two main factors influencing VRE choice being a) the quality of the resource, thus regions with high insolation like the Middle East, Africa, India, Central America and South Asia have a tendency to show higher PV shares compared to regions with lower insolation like Europe, Canada, or Russia, and b) the correlation between each VRE type and load, thus warm regions with high (current or future) deployment of air conditioning, which therefore have a good correlation between demand and PV supply, have a tendency for higher PV shares.

The differences between models is also to be expected - as with all modeling, electricity sector modeling results for future electricity systems depend on input assumptions, such as resource prices, technology parameters such as efficiencies and costs, assumed climate mitigation policies, the years from which wind, solar and load time series were derived, inclusion of flexibility options such as short-term storage, demand response, long-term storage, sector coupling, etc.
As an example for scenario results and how assumptions drive the results, the REMIX scenarios by Scholz et al [12] show that the cost-optimal gross VRE share in Europe increases from ~40 to ~70% as carbon prices increase from 50€/tCO2 to 450€/tCO2, with an even mix of wind and solar having similar costs like a 80:20 mix wind:solar, while a solar-dominated mix increases costs – in Europe, solar generation and load are not very well correlated. Breyer et al find VRE shares between 15% in Eurasia, 27% in Europe, and roughly 50% in South-east Asia, South America and Africa [14]. In a detailed study of Middle-East and North African countries, Kost [16] finds a cost-optimal solar share of 50% (and a total VRE share of ~75%), and in a 100% renewable energy scenario finds a solar share of 79% for this region.

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