Strategies for a future European power system with high shares of renewable energy: A model-based analysis focusing on uncertainty

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The European electricity system is currently facing a major transformation, with renewable energy (RE) technologies being expected to constitute an important part of the future generation mix. In light of the recent debate on the European Union's (EU) energy and climate policy until 2030, this thesis contributes both to the academic and public discourse about RE targets and infrastructure needs, and to the methodological advancement of power system models. In particular, I focus on two major aspects: (i) the efficient representation of the RE's temporal variability in large-scale power system models, and (ii) the explicit consideration of uncertainty in analyzing investment strategies for the future European power system.

In the first part of this thesis, I present the long-term investment model for the European electricity system LIMES-EU. The model constitutes the methodological basis of the thesis; it facilitates the analysis of technically feasible and economically viable investment pathways for individual countries and for Europe on aggregate. LIMES-EU simultaneously optimizes investment and dispatch decisions for generation, storage and transmission technologies in an intertemporal way from 2010 to 2050. Despite the model's long-term focus until 2050, it effectively accounts for the short-term variability of electricity demand and infeed from wind and solar power plants. The fluctuations are reflected by modeling the operation of technologies for a set of representative days. These days are selected with a novel and computational efficient approach that is suitable for input data with a large number of different fluctuating time series (i.e. multiple different RE technologies and/or regions). With the approach that has been developed for this thesis it is possible to reflect the characteristic fluctuations of the input data already with a small number of model days. To enable its applicability for other models, it is based on an established clustering algorithm and transparently documented.

The second part of the thesis provides an in-depth analysis of cost-efficient future investment strategies for the European power system in order to reach the EU's long-term decarbonization targets until 2050. The analysis includes an explicit consideration of uncertainty and comprises both aggregate European and national results. Thereby, the work adds important aspects to the European Commission's official impact assessment on the 2030 policy framework as this impact assessment completely disregards the existence of uncertainties and provides only few results on national level. A major focus of the analysis is on the cost-efficient RE expansion until 2030. Their optimal share in the 2030 generation mix varies considerably across the studied scenarios that account for various uncertainties about future techno-economic developments, for example with regard to fuel prices and investment costs. The national results show a strong difference in optimal RE deployment across countries, which is caused by the unequal distribution of RE sources. A cost-optimal RE expansion would result in large international transmission needs and would make some countries importing a large share of their electricity demand from foreign power plants. In addition to determining cost-efficient investment pathways for different future scenarios, the thesis provides an analysis of investment strategies that help to increase the robustness of the power system, i.e. result in a system that performs reasonably well for a large variety of possible futures. The performance of different systems under short-term shocks is tested in a total of more than 40,000 model runs. The analysis shows, that despite the benefits of a further integration of the European electricity system, strategies promoting the capability of countries to produce at least 95% of their electricity demand domestically significantly help to increase the robustness of the European power system.