CO_2 Mitigation and Power System Integration of Fluctuating Renewable Energy Sources: A Multi-Scale Modeling Approach

Decarbonizing the electricity sector is of vital importance for mitigating greenhouse gas emissions due to increasing power demand, but also because of the broad portfolio of low carbon power generation options. Emission reduction policies are likely to incentivise an expansion of renewable power generation capacities far beyond current levels.

This thesis investigates the question of how renewable power generation can contribute to mitigate CO_2 emissions. It analyzes the system integration challenges that result from large shares of variable and spatially dispersed renewable power generation, how an expansion of long distance transmission and storage capacities can facilitate system integration, and how system integration issues -- and the availability of integration options -- affect long term strategies for power system decarbonization. More specific, it investigates if (and how) Europe can reach its ambitious power sector decarbonization targets by expanding renewable generation capacities. These questions are addressed in a series of model-based studies.

Results show that power system decarbonization in general and expansion of renewable power generation in specific play a crucial role for economy-wide mitigation efforts. They also demonstrate that investment decisions in transmission, storage and generation capacities are tightly interrelated. Adequate expansion of transmission and storage facilitates the integration of renewable supply, and limiting the availability of these options affects deployment and spatial allocation of renewable generation capacities.

It is shown that until 2050, Europe and the Middle East / North African (MENA) regions can achieve power system CO_2 emission reductions of 90% (relative to 2010) by expanding renewable power generation -- without relying on CCS or building new nuclear power plants. This target can be met without large-scale electricity transfers between Europe and MENA regions, but inside Europe, a clear pattern of importing and exporting countries emerges. Meeting the 90% emission reduction target leads to an increase of average electricity prices to 8.7 ct/kWh, if transmission and storage capacities are adequately expanded (compared to 6.8 ct/kWh in the baseline scenario). If transmission capacities are limited to current levels, electricity prices increase to 10.1 ct/kWh, and the requirements for storage capacities increase significantly.

Cost-efficient expansion pathways until 2050 are far from linear: Until 2030, the system is characterized by a mixture of wind and fossil generation, followed by a switch to a wind and solar based generation mix. This transition on the generation side results in different integration challenges, and it changes the interregional patterns of power transfer and the way the existing transmission infrastructure is used.

Feasible mitigation levels that can be achieved by renewable generation capacities are shown not to be limited by their technical potential, but by system integration issues. Electricity prices escalate if emission caps exceed a certain limit. In the presented scenarios, this threshold varies between 70% and 95% CO_2 reductions, depending on the availability of transmission and storage expansion. This shows that a coordinated expansion of renewable generation capacities and system integration options is crucial for achieving ambitious decarbonization targets.