# How flexible electrification integrates fluctuating renewables

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## Overview

Supply and demand for electricity will play a pivotal role in the transformation towards an energy system that achieves the targets of the Paris Climate Agreement.

On the supply side, wind and solar must replace generation from fossil fuels, but despite substantial decline in levelized cost, integration of wind and solar remains challenging. Especially at high shares, fluctuating renewable require complementary technologies, like storage, carbon neutral thermal plants, or transmission infrastructure, to provide flexibility.

At the same time, decarbonization will also have a profound effect on the demand for electricity. Mitigating emissions beyond the power sector in heating, industry, and transport requires renewable electricity as a primary source of energy, either directly or indirectly using synthetic fuels produced from electricity. Both options entail close integration with the power sector, but differ in how they affect the total level, the pattern, and the elasticity of electricity demand - all factors decisively shaping the need for flexibility in renewable systems.

In conclusion, the provision and need for flexibility is shaped by interactions and synergies of both, electricity supply and demand. Yet, existing analyses of decarbonized power systems are predominantly focused on the supply side (e.g., Brown et al. 2018; Heggarty et al. 2019; Luderer et al. 2021). Typical studies assess the interplay of fluctuating renewables with different storage systems, thermal power plants, and interconnection to achieve a reliable and decarbonized supply of electricity, but the assumed level, profile, and elasticity of demand are based on historical data and do not reflect decarbonization beyond the power sector. Other studies do consider changing demand, but still assume it to be an exogenous factor, focusing their analysis on the supply side.

Extending the existing literature, this paper transcends the focus on supply-side options and investigates how synergies with decarbonization beyond the power sector can mitigate flexibility needs and reduce system costs.

## Methods

The paper applies a bottom-up planning model (Göke 2021; Göke 2022) that optimizes expansion and operation of technologies to satisfy final demand by minimizing total system costs. To capture the interplay of electricity supply and demand, it is not limited to the power sector, but equally captures operation and expansion of technologies in the heating, transport, and industry sector. For instance, in space heating the model optimizes the trade-off between electric heat-pumps that might induce additional investment into thermal power plants to cover demand peaks during winter and district heating that could mitigate such peaks by deploying long-term thermal storage. Overall, the scope includes 22 distinct energy carriers that can be stored and converted into one another by 120 different technologies to satisfy final demand and transported by four different types of transmission infrastructure.

The model deploys a graph-based formulation specifically developed to model high shares of fluctuating renewables and sector integration, which is capable to vary temporal and spatial resolution within a model. Thanks to this feature, we can apply an hourly resolution in the power sector to accurately capture fluctuations of wind and solar, but model other energy carriers, like synthetic gases or hydrogen, at a coarser resolution to reduce computational complexity. In addition, the approach can capture the inherent flexibility, or elasticity, of electricity demand from other sectors. Space heating for instance, is modeled at a four-hour resolution to capture the thermal inertia of buildings.

Spatially the model covers the European continent subdivided into 96 regions. A large spatial scope and resolution are essential to capture how transmission infrastructure can smooth local variations of wind and solar generation and add flexibility to the system.

To investigate how electricity supply interacts with demand and decarbonization beyond the electricity sector, the paper compares four different scenarios. Reflecting how decarbonization of the energy system is not only a techno-economic but also a social challenge, these scenarios vary the role of two technologies that are often met with public opposition: wind energy and power transmission. For wind the potential is reduced to the lower end of literature values; for power transmission expansion beyond today's level is prohibited.

## Results

For the analysis, flexibility needs can be distinguished on two specific timescales that drive the underlying patterns of solar generation, ambient temperature, and human behavior. The need for short-term flexibility is driven by daily; long-term flexibility by seasonal patterns.

On the short-term scale, results exhibit substantial benefits from flexible electrification. Demand from battery electric vehicles, heat-pumps and electrolyzers adopts to the profile of solar generation mitigating the need for short-term battery storage. These synergies are even more pronounced in scenarios with higher solar generation due to less wind potential or no expansion of power transmission. In these scenarios, often further flexibility is added by paring residential heat-pumps with thermal storage systems.

Long-term flexibility is driven by the seasonal mismatch of solar generation and residential heat demand. To prevent demand peaks from residential heat-pumps in winter, district heating technologies like more efficient heat-pumps, seasonal heat storage, combined heat-and-power plants, and backup boilers provide a major share of heat. Overall, the need for thermal backup plants is small, but increases substantially, if the wind potential is small and more solar generation occurs during the summer, or if transmission expansion is restricted.

## Conclusions

Our findings show that an isolated analysis of decarbonization in the power-or any other-sector, will miss key interactions and is at high risk of not identifying the most cost-efficient strategy. Accordingly, links and synergies between sectors should be considered more carefully in governmental energy planning.

In addition, our results suggest to tap the potential of battery electric vehicles to provide short-term flexibility by giving consumers corresponding price incentives.

## References

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