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Residual load, renewable surplus generation and storage requirements in Germany☆

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HIGHLIGHTS

- I examine the effects of fluctuating renewable energy on residual load.
- Surplus energies are generally low, but there are high surplus power peaks.
- Increasing the flexibility of thermal generators substantially reduces surpluses.
- Allowing curtailment of 1% renders storage investments largely obsolete by 2032.
- Both storage requirements and the share of seasonal storage increase by 2050.

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ABSTRACT

I examine the effects of increasing amounts of fluctuating renewable energy on residual load, which is defined as the difference between actual power demand and the feed-in of non-dispatchable and inflexible generators. I draw on policy-relevant scenarios for Germany and make use of extensive sensitivity analyses. Whereas yearly renewable surplus energy is low in most scenarios analyzed, peak surplus power can become very high. Decreasing thermal must-run requirements and increasing biomass flexibility substantially reduce surpluses. I use an optimization model to determine the storage capacities required for taking up renewable surpluses. Allowing curtailment of 1% of the yearly feed-in of non-dispatchable renewables would render storage investments largely obsolete until 2032 under the assumption of a flexible power system. Further restrictions of curtailment as well as lower system flexibility strongly increase storage requirements. By 2050, at least 10 GW of storage are required for surplus integration, of which a sizeable share is seasonal storage. Results suggest that policy makers should work toward avoiding surplus generation, in particular by decreasing the must-run of thermal generators. Concerns about surpluses should not be regarded as an obstacle to further renewable expansion. The findings are also relevant for other countries that shift toward fluctuating renewables.

1. Introduction

The German government has decided to phase out nuclear power completely by 2022. At the same time, renewable power generation is to be expanded substantially. Renewable energy sources (RES) have to account for at least 35% of German gross electricity consumption by 2020 (BMWi and BMU, 2010). This share was around 6% in the year 2000 and grew to 23% by 2012 (BMU, 2013). The target values for 2030, 2040 and 2050 are 50%, 65% and 80%, respectively. The largest part of renewable power will come from wind and photovoltaics (PV). According to the medium scenario of the network development plan drafted by German transmission system operators (TSOs) in 2012, onshore and offshore wind account for around 45% of gross power demand by 2032, whereas PV contributes around 10% (NEP, 2012, scenario 2032B). Afterwards, the shares of wind and solar are projected to grow further until 2050 (cp. DLR, et al., 2012).[1]

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[1] An English summary of DLR et al. (2012) is provided by Pregger et al. (2013).

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Wind power and PV differ from conventional power generators in many respects (cp. Joskow, 2011, Hirth, 2013). In particular, their power production is fluctuating, as the hourly generation capacity strongly depends on weather and season, as well as on the time of the day. Moreover, generation is only weakly correlated with hourly load profiles. Growing shares of these technologies thus have a strong influence on residual load, for example resulting in temporary situations of both power shortage and renewable surplus generation (Denholm and Hand, 2011). Integrating growing amounts of wind and PV into the power system thus increasingly requires the application of dedicated integration measures, among them different types of energy storage, demand-side measures, network expansion, flexible thermal back-up plants and renewable curtailment (NREL, 2012).[2]

In this paper, I study the effects of future renewable expansion on residual load in Germany under a range of varying assumptions. I am particularly interested in the power and energy of temporary renewable surplus generation, as renewable surpluses have recently attracted increasing attention of policy makers.[3] It is also investigated which capacities of different storage technologies would be required for taking up temporary renewable surpluses. In doing so, three stylized types of storage are distinguished: batteries, pumped hydro storage (PHS), and power-to-gas. As an alternative to electricity storage,[4] temporary curtailment[5] of renewable generation is considered. The interrelation of storage and renewable curtailment is explored: how do storage requirements vary different levels of allowed curtailment? The analysis includes a large number of sensitivities with respect to the development of the plant fleet, thermal must-run restrictions, the flexibility of biomass generators, various meteorological years for wind and PV feed-in, and improvements in energy efficiency. The scenarios used draw on quasi-official projections of the German network development plan (*Netzentwicklungsplan*, NEP, 2012) for the years 2022 and 2032, and on a quasi-governmental long-term scenario for 2050 (DLR et al., 2012).

Different aspects of renewable surplus generation, curtailment and storage requirements have been analyzed in the international literature. Denholm and Sioshansi (2009) show how wind power revenues could be improved in U.S. power systems by avoiding curtailment with a mix of storage and network investments. Denholm and Hand (2011) simulate different scenarios with high shares of variable renewables in the Texas power system. They show that increasing system flexibility substantially reduces surpluses. For very high renewable penetrations, both daily storage and demand-side management are required for avoiding excessive curtailment. Lamont (2013) develops a model for determining optimal storage investments, both in terms of charging/discharging and reservoir capacity, and calibrates it to price and load parameters from California. He finds that storage-related changes in spot prices not only have an impact on the penetration of storage itself, but also on optimal investments in fluctuating renewables and other generation technologies. Carson and Novan (2013) evaluate the social benefits of additional bulk storage in Texas. Because of low renewable penetration, storage cannot be used to avoid renewable curtailment. As a consequence, additional storage increases base load generation and emissions of CO_2 and SO_2. Esteban et al. (2012) determine the storage capacities required in a 100% renewable power scenario for Japan largely based on wind and solar power. In this system, which has a peak demand of more than 240 GW, nearly 20 GW of pumped hydro would be necessary. In addition, battery storage with a capacity of 41 TWh is required. Mason et al. (2013) develop a fully renewable scenario for New Zealand and find that wind curtailment can be largely eliminated by PHS. Yet this system is hydro-dominated with wind constituting only around a quarter of the energy mix, so it can hardly be compared to systems with high shares of fluctuating renewables.

Next, related literature with a European focus is presented. Pérez-Arriaga and Batlle (2012) review the challenges of integrating increasing amounts fluctuating renewables into power systems and identify necessary regulatory adjustments. Lise et al. (2013) quantify the costs of renewable integration and present European residual load duration curves, according to which considerable renewable surpluses occur by 2050 even under the assumption of extensive interconnection. According to Rasmussen et al. (2012), a fully renewable pan European power system could be achieved with a combination of moderate over-capacities of wind and solar, 2.2 TWh of short-term storage and 25 TWh of seasonal storage because of synergies between storage and balancing. Tuohy and O'Malley (2011) analyze the impact of additional pumped storage on wind curtailment in the Irish power system. They find that building new storage is only economic for very high levels of wind penetration, whereas curtailment is cheaper for moderate shares of wind power.

As for Germany, the much-discussed '*Energiewende*' has increased interest in the future development of residual load, renewable surpluses and storage requirements. Wagner (2014) develops a model for residual demand in order to simulate the effect of fluctuating renewables on prices in the German day-ahead market. Steffen and Weber (2013) use load–duration curves to model efficient electricity storage investments for the integration of fluctuating renewables. Agora (2012) simulates German residual load in the year 2022, drawing on weather data of 2011.[6] Excluding must-run constraints and trade with neighboring countries, they determine around 200 h of renewable surplus generation. EWI (2013) use a cost-minimizing dispatch model that includes internal transmission constraints and cross-border trade to show that hardly any renewable curtailment should be expected until 2022 in Germany if existing transmission bottlenecks are removed. BET (2013) determine yearly surplus generation of around 2 TWh by 2020 and 35 TWh by 2030 for Germany, assuming thermal must-run of 10 GW in 2020 and 5 GW in 2030 and flexible biomass generation. With sufficient flexibilization of both the demand side and the supply side, additional storage capacity is required only after 2030. Nicolosi (2012) applies a

[2] Renewable integration studies that focus on specific flexibility options in the German context are provided by Dena (2011) and VDE (2012a, 2012b and 2012c). Sioshansi et al. (2012) point to technical issues as well as policy-related barriers to actual storage deployment in power markets. Borden and Schill (2013) review policy efforts for storage development in the U.S. and Germany.

[3] See, for example, The Economist (2013). The left-hand side of the residual load curve, i.e., peak load, is not a major concern in this analysis, as generation capacity is adequate in all scenarios analyzed in this study.

[4] To be more precise, I focus on power-to-power storage, which draws power from the grid and feeds back power to the system in later periods. I do not consider other storage options that transform electric power to other energy carriers, for example power-to-heat or power-to-gas. Beaudin et al. (2010) review the status quo, development potentials and challenges of different electricity storage technologies that can be applied for wind and solar power integration. Østergaard (2012) compares different storage options in a 100% renewable energy scenario for a Danish city and shows that electricity storage can better facilitate wind integration compared to biogas storage or heat storage.

[5] Jacobsen and Schroder (2012) define different categories of renewable curtailment. Drawing on case studies, they show that – contrary to public belief – some level of curtailment of variable renewables is optimal from a system cost perspective, for example by avoiding excessive grid investments.

[6] In September 2013, Agora published updated simulations for the years 2023 and 2033 in the form of presentation slides. However, a written report of this analysis, which also includes a spatial component, is not available so far. Importantly, Agora shows renewable and conventional generation in a graphic representation for every subsequent hour of the year. In contrast, I present simulation results in an aggregated form, for example in the form of load-duration curves, bar charts and histograms.