

Modelling power-system flexibility under high renewable penetration: A system dynamics case study of Germany

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Abstract. High shares of variable renewable electricity increase the need for power-system flexibility. This paper investigates how demand-side price responsiveness influences optimized generation-capacity requirements under contrasting power-system conditions. The analysis uses an hourly System Dynamics model of the German electricity market calibrated to the 2019 power system. Demand-side flexibility is represented at an aggregate level through the price sensitivity of electricity demand, and sensitivity experiments are conducted by varying this parameter across an optimized 2019 system and three 2050 scenarios representing High Carbon Tax, High Demand and Low Demand conditions. Across the tested cases, higher demand responsiveness generally reduces the capacity selected by the optimizer, with a particularly strong effect on dispatchable gas. For the 2050 High Carbon Tax case, the combined optimized capacity of gas, solar, onshore wind and offshore wind falls from 282.4 GW at a demand-price sensitivity of 0.01 to 125.5 GW at 0.25, while optimized gas capacity falls from 28.6 GW to zero. In the High Demand case, however, substantial gas capacity remains even at higher demand responsiveness. These contrasting results show that the capacity effect associated with demand responsiveness is strongly dependent on the level of electricity demand and the surrounding generation mix. The large capacity reduction obtained in the highest-sensitivity High Carbon Tax experiment should be interpreted as an exploratory model response rather than as an estimate of capacity savings directly achievable through real-world demand-response programmes. The aggregate demand formulation does not explicitly distinguish between permanent demand reduction and temporal load shifting or impose intertemporal conservation of shifted electricity consumption. Overall, the study shows that optimized capacity-planning outcomes can be highly sensitive both to the assumed level and to the representation of demand-side responsiveness, highlighting the importance of more detailed demand-flexibility modelling in future assessments of high-renewable power systems.

1. Introduction

The rapid and large-scale integration of variable renewable energy sources (RES), such as wind and solar photovoltaics, is transforming the operation of modern electricity systems [1]. Unlike conventional generation, the availability of these weather-dependent resources varies over time

and does not necessarily follow variations in electricity demand. As renewable penetration increases, periods of high renewable output may coincide with relatively low demand, while periods of low renewable availability may occur when demand is high. These conditions increase the need for flexibility to maintain the balance between electricity supply and demand [2-5].

The German electricity system provides an important case for examining these interactions. Periods of high wind and solar generation combined with relatively low demand can create oversupply conditions and downward pressure on wholesale electricity prices [6]. In 2024, the German electricity market recorded 459 hours of negative electricity prices, while the capture rate for solar generation fell below 50% during some high-generation months, illustrating the growing market effects associated with periods of high variable renewable generation [7]. At the same time, conventional generation may not always be able to reduce output sufficiently in response to renewable surpluses, contributing to system inflexibility [8]. These interactions highlight the increasing importance of flexibility, rather than installed generation capacity alone, as the share of variable renewable generation grows.

Power-system flexibility can be provided through several complementary mechanisms, including responsive conventional generation, energy storage, interconnection, and changes on the demand side. In the European context, reinforcement of cross-border interconnections can enhance market coupling, alleviate regional grid constraints, and facilitate the integration of variable renewable generation [9-11]. Energy storage provides another important source of flexibility, although its large-scale deployment remains influenced by technological and economic considerations [12]. Alongside these supply- and network-side options, Demand-Side Management (DSM) and Demand Response (DR) provide flexibility by allowing electricity consumption to respond to changing system or market conditions.

Demand response is particularly relevant because it changes the balancing problem from a purely supply-side question to a joint supply-demand problem. If electricity consumption can respond to price signals or other system conditions, part of the mismatch between supply and demand can potentially be managed without relying exclusively on additional dispatchable generation [13]. Previous studies have demonstrated the potential of demand-side flexibility in residential applications. Pallonetto et al. [14] reviewed the assessment and control optimization of demand-response programmes in residential buildings, while Diao et al. [15] examined the use of controllable electric water heaters for demand response. Yildiz et al. [16] showed how flexible electric-water-heating loads can be used to absorb excess photovoltaic generation, and Gibbons and Javed [17] investigated implicit demand response under real-time electricity pricing. Together, these studies demonstrate different mechanisms through which flexible electricity demand can respond to renewable availability and market signals.

Beyond individual buildings and flexible loads, demand-side flexibility has also been investigated from a broader power-system planning perspective, particularly in systems with increasing shares of variable renewable generation. Misconel et al. [18] incorporated country-specific hourly demand-response potentials into a large-scale European power-system optimization model and examined their effects on capacity and generation mix, storage requirements, renewable integration, emissions, and total system costs. Their results further showed that the value of demand response depends on the surrounding system configuration, with different effects in decentralized solar-dominated and centralized wind-dominated pathways. More recent system-level research has also incorporated detailed demand-side flexibility potentials into capacity-expansion modelling. A 2026 study examining alternative capacity mechanisms showed that market design can influence investment in demand-side

flexibility, further illustrating that the system value of flexibility depends not only on its technical potential but also on the surrounding market and planning framework [19]. Kiptoo et al. [20], at a smaller system scale, incorporated different demand-response strategies into joint capacity and operational planning of a renewable-energy-based microgrid and found that demand response can reduce both total annualized costs and required system-component capacities. More broadly, a recent systematic review of more than 1,000 studies of highly renewable energy systems identified demand response as one of several important flexibility options, while also finding it to be less frequently represented than other flexibility mechanisms [10].

The System Dynamics model used in this study was developed to investigate the German electricity transition and was calibrated against hourly 2019 electricity-market data. The model structure, price behaviour, renewable integration, conventional-generation inflexibility, and selected transition scenarios have been described in earlier works [21, 22]. Building on this framework, the present study focuses specifically on the relationship between demand-side price responsiveness and generation-capacity requirements. Previous studies have demonstrated that demand-side flexibility can influence both system operation and capacity planning; however, they have commonly represented flexibility through technology-specific load shifting or shedding, optimization-based demand response, or exogenously specified demand-response potentials [14, 18, 20]. In contrast, the present study represents demand-side flexibility at an aggregate level through the price sensitivity of electricity demand within a System Dynamics framework. This simplified representation is used as an exploratory sensitivity mechanism rather than a detailed operational model of individual demand-response technologies.

The main contribution of this study is therefore the quantitative examination of how alternative levels of demand-side price responsiveness affect optimized generation-capacity requirements under contrasting power-system conditions. The study addresses the following research question: How does increasing demand-side price responsiveness change optimized generation-capacity requirements under different power-system conditions, particularly under high-renewable and high-demand configurations? By applying the same demand-flexibility mechanism across contrasting scenarios, the analysis examines whether its effect on capacity requirements remains similar or changes with the surrounding generation mix and level of electricity demand.

2. Methodology

2.1 System Dynamics modelling and model boundary

System Dynamics (SD) is a simulation-based modelling approach used to analyse the behaviour of complex systems through feedback relationships, accumulations, delays and interactions among system components over time. Rather than representing individual market participants or power plants in detail, SD focuses on the aggregate structure and dynamic relationships that generate system-level behaviour [23]. This makes the approach suitable for examining interactions among electricity demand, generation, market price and flexibility under changing power-system conditions.

The model used in this study was developed and simulated in Stella Architect, a System Dynamics modelling and simulation software. The model represents four interacting sectors: electricity price, electricity supply, domestic demand and net imports. The supply sector includes coal, natural gas, nuclear, solar PV, onshore wind, offshore wind, run-of-river hydropower and reservoir hydropower. Electricity price responds to the demand-to-supply ratio and to traders' price expectations; conventional generation responds to price and operating constraints, while

wind and solar generation follow observed hourly capacity-utilization patterns. The demand sector combines an underlying hourly load profile with a price-responsive adjustment [21, 22].

The model boundary is the German electricity market and is designed to reproduce aggregate short-term market dynamics rather than detailed unit commitment, transmission-network power flows or individual consumer behaviour [21, 22]. The model therefore provides a system-level framework for investigating how changes in renewable generation, electricity demand and demand-side price responsiveness influence market behaviour and optimized generation-capacity requirements. **Accordingly, demand-side flexibility is represented at an aggregate system level rather than through explicit modelling of individual flexible-load technologies or consumer-level demand-response programmes.**

2.2 Calibration and reference year

Model validation is an important component of System Dynamics modelling because confidence in a model depends on whether its structure and behaviour are sufficiently consistent with the real system for the intended modelling purpose [24]. The model was calibrated and validated against the German power system in 2019, which serves as the reference year. **Historical hourly electricity demand data were obtained from Energy-Charts [25], while hourly wholesale electricity prices and electricity generation by individual technologies were obtained from the ENTSO-E Transparency Platform [26]. Installed generation capacities for the reference year were also obtained from Energy-Charts [25].** Parameters that could not be obtained directly from data, including price-response and adjustment parameters, were estimated with the calibration tools in Stella Architect. Model validation compared simulated and historical behaviour for electricity price, demand, coal, gas and nuclear generation, and total electricity supply [22]. The calibrated model is therefore used here as a historical experimental platform; the later scenarios are controlled model experiments rather than forecasts of the current German system.

2.3 Demand-price sensitivity

Demand flexibility is represented by the dimensionless parameter Price Sensitivity of Demand. This elasticity-like coefficient controls the proportional adjustment of hourly demand when electricity price deviates from a reference price. A larger value therefore means a stronger demand response to the same relative price deviation. The parameter is dimensionless and represents aggregate short-run price responsiveness in the model rather than a technology-specific or consumer-specific empirical elasticity. **More specifically, the demand sector uses a simplified aggregate price-response formulation in which hourly electricity demand is adjusted according to deviations of the simulated electricity price from a reference price, with an adjustment time of one hour. The formulation does not explicitly model temporal load shifting or impose an intertemporal constraint requiring demand reduced in one hour to reappear in subsequent hours. Price Sensitivity of Demand should therefore be interpreted as a measure of aggregate price responsiveness, which may include demand reduction, rather than as a direct representation of physically shifted load or of a specific demand-response technology [22].**

Through calibration of the model against the 2019 historical reference behaviour using the calibration tools in Stella Architect, the baseline Price Sensitivity of Demand was estimated at 0.10 [22]. Optimization experiments used 0.01, 0.10 and 0.25 for the optimized-2019 and High Carbon Tax cases, and 0.01, 0.10 and 0.20 for the High- and Low-Demand cases. Comparisons are made within each scenario [22]. The value of 0.10 therefore represents a calibrated model parameter rather than an independently estimated empirical short-run price elasticity for German electricity consumers. The alternative values used in the optimization experiments are sensitivity cases

designed to examine how optimized capacity responds to weaker or stronger aggregate price responsiveness. In particular, the higher sensitivity cases are exploratory parameter variations and should not be interpreted as empirically expected levels of demand-response participation.

2.4 Capacity optimization and scenarios

Generation capacities were determined using the optimization capability of Stella Architect. In this study, optimization was formulated as a policy-search problem in which the software searches for combinations of installed capacities for conventional and renewable generation technologies that maximize net social benefit. Net social benefit is defined as total benefits minus total costs, thereby representing both consumer and producer interests. The cost side of the objective includes the main economic consequences of the capacity choice: capital and annualized leasing costs, fixed operating costs, variable generation costs, fuel costs and carbon taxes. For each candidate capacity combination, the hourly System Dynamics model is simulated over the representative year, so the economic evaluation reflects the interaction of the proposed generation mix with hourly demand, renewable availability, electricity price and the operating response of dispatchable generation. The optimizer then identifies the capacity combination that provides the highest net social benefit under the assumptions of the case [22].

The optimization was first performed for the 2019 electricity system to establish a reference capacity mix. It was then applied to the 2030, 2040 and 2050 scenarios. For each scenario, the Price Sensitivity of Demand was varied to examine how different levels of demand-side price responsiveness affect the generation-capacity mix selected by the optimizer. The analysis uses the optimized 2019 system and three 2050 cases: High Carbon Tax, High Demand and Low Demand. In the High Carbon Tax case, the carbon price increases over time, changing the relative economics of fossil generation. The High Demand case assumes substantially higher electricity consumption, whereas the Low Demand case represents reduced electricity demand. Nuclear capacity is set to zero in the future optimization years and coal is excluded from 2040 and 2050, consistent with the phase-out assumptions embedded in the scenario design [22].

The capacity comparison reported here is limited to technologies whose capacities were varied in these optimization experiments: gas, solar, onshore wind and offshore wind (with coal and nuclear also included in the original optimization when allowed by the phase-out assumptions). Hydropower and run-of-river capacities were held constant in the scenario design and are therefore not included in the reported optimized-capacity totals. Batteries, hydrogen/power-to-gas and other dedicated storage technologies could be discussed as potential flexibility options, but they were outside the endogenous optimization boundary; no storage-capacity decision variable or storage-investment pathway was optimized [22]. Therefore, the reported 2050 capacity results include only the generation technologies represented in the optimization. They should not be interpreted as a complete future power system portfolio, since flexibility options such as storage and hydrogen are outside the model boundary.

3. Results

Demand responsiveness significantly affects the generation capacity selected by the optimizer. In the optimized 2019 case, the combined reported capacity of gas, solar and wind decreases from 199.4 GW at a sensitivity of 0.01 to 118.8 GW at 0.25, a reduction of about 40%. Gas capacity falls from 40.7 GW to zero. **These results describe the response of the model to alternative assumptions about aggregate demand-price sensitivity and should not be interpreted as physical peak demand**

disappearing; rather, within the model boundary, stronger price responsiveness changes the amount of generation capacity selected by the optimizer.

Table 1. Optimized generation capacities under alternative demand-price sensitivities. All capacities are reported in GW; 'Total' represents the sum of gas, solar, onshore wind, and offshore wind for each case.

Case	Price Sens.	Gas	Solar	Onshore Wind	Offshore Wind	Total
Optimized 2019	0.01	40.7	28.4	130.2	0.0	199.4
	0.10	25.4	35.4	114.3	0.0	175.2
	0.25	0.0	27.5	91.3	0.0	118.8
High Carbon Tax 2050	0.01	28.6	81.1	172.8	0.0	282.4
	0.10	4.5	62.1	137.5	0.0	204.2
	0.25	0.0	32.4	93.1	0.0	125.5
High Demand 2050	0.01	84.8	39.4	246.3	0.0	370.5
	0.10	56.1	58.3	222.9	0.0	337.2
	0.20	38.2	56.4	209.6	0.0	304.3
Low Demand 2050	0.01	17.9	94.4	90.6	11.8	214.7
	0.10	14.0	20.3	65.2	0.0	99.5
	0.20	0.0	78.2	70.2	6.2	154.6

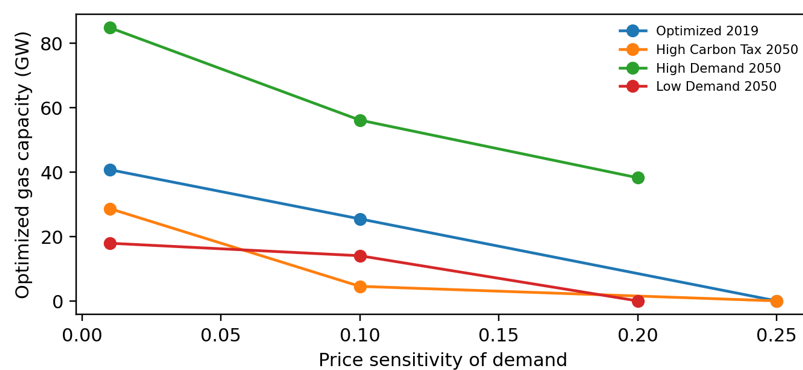


Figure 1. Effect of demand-price sensitivity on optimized gas capacity.

The strongest relative capacity reduction is visible in the 2050 High Carbon Tax case. Combined gas, solar and wind capacity falls from 282.4 GW at a sensitivity of 0.01 to 125.5 GW at 0.25, approximately 56%. Over the same range, gas capacity decreases from 28.6 GW to zero. Within the model, stronger aggregate price responsiveness is therefore associated with a substantial reduction in the generation capacity selected by the optimizer under this renewable-dominated configuration.

The magnitude of this reduction should, however, be interpreted with caution. The approximately 56% decrease between the lowest- and highest-sensitivity cases represents the response of the model under a strong aggregate price-sensitivity assumption and should not be interpreted as an estimate of the generation-capacity reduction achievable through real-world demand-response programmes. As described in Section 2.3, the demand formulation does not impose intertemporal conservation of flexible electricity consumption; demand reduced during a high-price period is therefore not necessarily shifted to a subsequent hour. Consequently, the highest-sensitivity experiments can produce stronger changes in the demand that must be served than would occur in a demand-response representation based exclusively on physical load shifting.

The High Demand case provides an important qualification. At the baseline sensitivity of 0.10, optimized 2050 capacity includes 56.1 GW gas, 58.3 GW solar and 222.9 GW onshore wind. Raising sensitivity to 0.20 reduces gas to 38.2 GW but does not eliminate it. Thus, within the model, greater demand-price responsiveness reduces optimized capacity requirements, while strong growth in electricity demand can preserve a substantial need for dispatchable capacity. The Low Demand case shows a different configuration; while it exhibits the lowest capacity requirements at lower sensitivities, the shift in the optimized capacity mix from gas towards solar at a sensitivity of 0.20 results in a total reported capacity of 154.6 GW, which exceeds that of the High Carbon Tax case (125.5 GW) at its highest responsiveness level. This non-monotonic behaviour further indicates that the capacity effect of the price-sensitivity parameter depends on the surrounding demand level and generation mix rather than representing a fixed capacity value of demand-side flexibility.

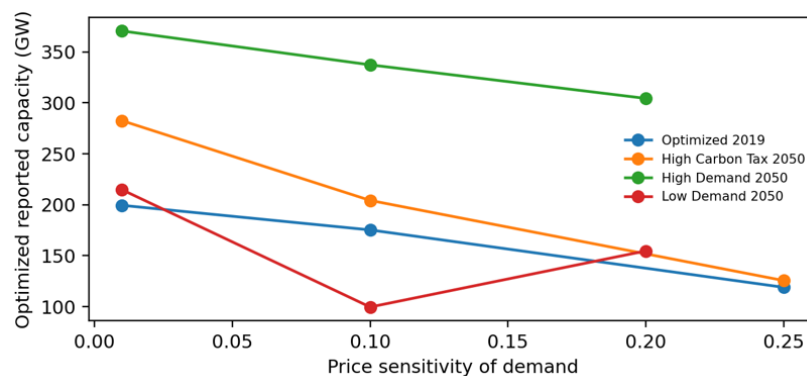


Figure 2. Combined optimized capacity of gas, solar, onshore wind and offshore wind under different demand-price sensitivity assumptions. Hydropower is held constant; storage and hydrogen are outside the optimization boundary. The sensitivity cases represent exploratory variations in aggregate demand-price responsiveness and should not be interpreted as empirically expected levels of demand-response participation.

4. Discussion

The results indicate that demand growth and demand flexibility should not be assessed independently. Within the model, a system with high renewable penetration but more responsive demand can result in a substantially different optimized generation portfolio from one in which consumption remains comparatively inflexible. The effect is particularly visible for gas capacity, which acts as a dispatchable flexibility option in the model. However, the High Demand results show that demand response is not a universal substitute for firm capacity: when electricity consumption increases strongly, significant dispatchable capacity can remain economically selected even with greater price responsiveness.

These findings should be interpreted within the original model boundary. The price-sensitivity parameter is a stylized representation of aggregate demand response rather than a detailed model of specific technologies, tariffs or consumer behaviour. As clarified in Section 2.3, the formulation represents aggregate price-responsive changes in electricity consumption and does not explicitly distinguish between permanent demand reduction and temporal load shifting. In particular, the model does not impose an intertemporal energy-conservation constraint requiring consumption reduced in one hour to be recovered in subsequent hours. Technology-specific flexibility limits, consumer participation constraints and rebound effects are also not explicitly represented. As specified in the Methodology, hydropower capacity is held constant, while batteries, hydrogen and other dedicated storage technologies are outside the endogenous capacity-optimization boundary. In addition, the model was calibrated to the 2019 German electricity system. The scenario results are therefore controlled experiments for studying structural interactions and are not forecasts of the current German power system.

These limitations are particularly important when interpreting the large capacity reductions obtained at the highest levels of price sensitivity. The approximately 56% reduction observed in the High Carbon Tax case should not be interpreted as a prediction of generation-capacity savings achievable through real-world demand-response programmes. Rather, it represents an upper-end response of the model under the tested aggregate price-sensitivity assumptions. Because the demand formulation permits aggregate consumption to respond to price without explicitly conserving shifted energy across time, the magnitude of the optimized capacity response may be stronger than that obtained with a technology-specific load-shifting representation. The large response therefore also demonstrates that capacity-planning outcomes can be highly sensitive to assumptions about how demand-side flexibility is represented.

The apparent anomaly in the Low Demand scenario—where total capacity increases as price sensitivity moves from 0.10 to 0.20—is associated with a substantial change in the optimized technology mix. As gas capacity drops from 14.0 GW to zero, the optimizer selects substantially more solar PV capacity, increasing it from 20.3 GW to 78.2 GW. Consequently, the combined reported capacity increases despite the higher level of demand responsiveness. This result highlights that changes in demand flexibility can alter not only the total optimized capacity but also the composition of the generation mix within the restricted model boundary.

A further implication is that the capacity effect of demand flexibility is scenario-dependent rather than a fixed technical quantity. This scenario dependence is consistent with previous system-level research showing that the value and capacity effects of demand-side flexibility depend on the surrounding power-system configuration [18, 19]. In the High Carbon Tax case, increased responsiveness strongly reduces the optimizer's reliance on gas capacity, while the High Demand case retains a sizeable gas fleet even at the higher tested sensitivity. This difference illustrates why flexibility assessments should be embedded in assumptions about future demand

and generation structure. The numerical values are model-specific, but the comparison highlights the structural point that flexibility needs emerge from the interaction between variable supply, demand level and demand responsiveness. Accordingly, the principal contribution of these experiments is not an estimate of a universally achievable capacity reduction from demand response, but an exploration of how assumptions about aggregate demand responsiveness interact with demand level and generation structure in determining optimized capacity requirements.

Future work should extend the demand-side formulation by explicitly distinguishing between demand reduction and temporal load shifting. A more detailed representation should incorporate technology-specific flexible-load potentials, limits on the amount and duration of shifted demand, consumer participation, rebound effects, and intertemporal energy-conservation constraints. Extending the endogenous flexibility boundary to include storage and other flexibility technologies would also allow interactions and potential substitution among different flexibility options to be investigated. Such developments would enable the capacity effects identified in the present exploratory analysis to be tested under more realistic operational constraints.

5. Conclusions

The optimization experiments from the System Dynamics model show that greater demand-side price responsiveness can generally reduce optimized generation-capacity requirements in most scenarios. However, the magnitude and composition of this capacity response depend strongly on the surrounding power-system conditions, particularly the level of electricity demand and the generation mix. In the High Carbon Tax case, the combined optimized gas, solar, onshore-wind and offshore-wind capacity decreases by approximately 56% between the lowest and highest tested demand sensitivities, while gas capacity falls to zero. In contrast, under the High Demand scenario, increased price responsiveness reduces gas requirements but does not eliminate the need for dispatchable capacity. These contrasting outcomes demonstrate that the capacity effect associated with demand responsiveness is scenario-dependent rather than a fixed technical quantity.

The large capacity reduction obtained in the highest-sensitivity High Carbon Tax experiment should not be interpreted as a forecast of generation-capacity savings achievable through real-world demand-response programmes. Demand-side flexibility is represented in the model through an aggregate price-response formulation that does not explicitly distinguish between permanent demand reduction and temporal load shifting or impose intertemporal conservation of shifted electricity consumption. The high-sensitivity results should therefore be regarded as exploratory model responses and, importantly, as evidence that optimized capacity-planning outcomes can be highly sensitive to assumptions about the representation of demand-side flexibility.

Overall, the analysis indicates that demand responsiveness can materially influence generation-capacity decisions in high-renewable systems, but its estimated capacity effect must be interpreted together with assumptions about future demand, generation structure and the representation of flexibility. Future work should test these interactions using more detailed demand-flexibility formulations that explicitly represent temporal load shifting, technology-specific flexibility constraints, consumer participation, rebound effects and intertemporal energy conservation, together with other flexibility options such as storage.

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