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Power Markets in Transition: Decarbonization, Energy Efficiency, and Short-Term Demand Response

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Abstract

Energy efficiency and short-term demand response are key issues in the decarbonization of power markets. However, their interaction and combined impact on market prices as well as on the supply side, is yet to be understood. We develop a framework to implement investments in energy efficiency and short-term demand response in detailed partial equilibrium power market models. We quantify our results using the EU-REGEN model for the European power market and find that energy efficiency contributes, under a 80% emission reduction target, only 11% of carbon emission reductions. Intermittent renewable energies such as wind and solar power account for the major share of 53%. However, both energy efficiency and short-term demand response have their merits in reducing marginal abatement costs and additionally exhibit an subadditive effect, at least under a 80% climate policy.

JEL code: C61, L94, Q41, Q51

Keywords: Energy efficiency, demand response, renewable energy, dispatchable technologies, energy modeling, optimal dispatch, investment planning

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1. Introduction

To keep global warming below 2° Celsius, 195 countries committed to emission reductions in the 2015 Paris Agreement. To limit the probability of warming above 2° Celsius, cumulative CO₂ emissions in the period 2000–2050 should not exceed 1,000,000 megatons (Mt), that is, approximately 20,000 Mt each year [51]. In 2017, just two years after the Paris Agreement, annual carbon emission peaked at 36,790 Mt, which is almost double the approximate annual emission budget and, moreover, means that almost half the 1,000,000 Mt budget has already been emitted. Thus, there is doubt as to whether the temperature target can be met.¹

One driving factor behind this development is the annual emissions from electricity generation, which increased from 6,300 Mt to 11,700 Mt in the period 1990–2013 [4] and thus accounts for around one-third of total emissions. Electricity demand increased by 94% in the same period and is expected to increase further due to rising household incomes (preference for using electricity), electrification (heating, transportation, power-to-gas), digitization (e.g., cryptocurrencies), and increased use of air-conditioning. To date, the power sector’s decarbonization efforts have mainly focused on its supply side. Policymakers introduced cap-and-trade systems (e.g., the European emission trading system) or initiated support schemes for renewable energies (e.g., feed-in tariffs). Concerning the latter, however, the intermittent supply pattern of renewables is a challenge to decarbonization. Complementing technologies that provide the necessary flexibility are either carbon-emitting (gas power), scarce regarding suitable sites (pumped hydro, biomass), still too expensive (batteries, power-to-gas), or difficult to incentivize (short-term demand re-

¹Note that even a warming of 2° Celsius comes at enormous cost. Supposing social costs of carbon of 100 US\$/tCO₂ (see [64] for a survey and [5, 52, 53, 65, 55] for estimates that vary between 10 and 805 US\$/tCO₂) and future emissions of 500,000 Mt, leads to economic costs of US\$ 50 trillion, which is 2,500 times the 2017 US GDP.

sponse²), and thus there is an increasingly strong focus on long-term demand response measures such as *energy efficiency*. For example, the International Energy Agency (IEA) calculates that improvements in energy efficiency reduced carbon emissions by 12.5% in the period 2000–2016 (IEA [37], p. 27) and predicts that further improvements will provide 44% (renewables 36%, fuel switching 2%) of the abatement necessary to meet the Paris Agreement targets (IEA [38], p. 28).

In this paper, we analyze how energy efficiency affects the decarbonization of power markets. It is well-known that improvements in energy efficiency reduce the relative price of electricity and thus have a rebound effect, the magnitude of which fundamentally depends on the *short-term demand response*, that is, consumers’ abilities to adapt their demand in the current period (*demand shedding*) and reschedule demand intertemporally (*demand shifting*). We develop a framework to integrate short-term demand response and energy efficiency improvements in detailed dispatch and investment models of power markets. We implement this framework in the EU-REGEN model to find the welfare maximizing level of investments in energy efficiency, quantify its impact for decarbonizing the European power sector, and elaborate on the role of short-term demand response and its interaction with the supply side.³

To account for European decarbonization goals, we implement a carbon constraint of 80% emission reduction in the period 1990–2050. We assume perfectly competitive firms that decide on production and capacity investments in the face of carbon prices. Consumer behavior is reflected by a downward sloping inverse demand function that accounts for demand shedding and shifting. The framework is set up from the perspective of a welfare-maximizing central planner. The central planner can invest in the level of energy efficiency

²Smart meters would make short-term demand response feasible, but the actual response is still behaviorally biased.

³The EU-REGEN model is a dynamic partial equilibrium model of the European power market with multiple regions that are linked via transmission lines (see Weissbart and Blanford [69]).

and thus reduce the amount of electricity necessary to provide the same amount of energy services. A performance parameter translates the investments into actual savings. This parameter is assumed to increase over time to account for exogenous technological progress in energy efficiency on the demand side.⁴

Until 2050, we calculate that there will be a need for approximately 180 GW less gas turbine capacity than is currently used in the European power market, but 52 GW more solar PV and 28 GW more wind would be installed. Nuclear, lignite, and coal power are hardly affected. Smart devices and tariffs with time-varying prices would incentivize consumers to adapt their demand in response to supply scarcity in the short term. This increases system flexibility and thus reduces the general need for flexibility on the supply side, which is mainly offered by gas power.⁵ Additionally, short-term demand response leads to more (less) consumption when wind and solar power generators have plenty (little) to sell. This flattens prices, which fosters the competitiveness of solar power but decreases gas power revenues. Wind power benefits less than solar power because its intermittency is less pronounced. For nuclear, lignite, and coal power, the flattening of prices translates into an intertemporal shifting of profits and thus does not affect their capacity in the long run.

We find that energy efficiency reduces electricity demand by 10% in 2050 and contributes 11% to the decarbonization of the European power market. Competing technologies such as wind, solar PV, and gas power are the chief means of meeting the emission target (intermittent renewables 53%, fuel switching 36%). These 11% are in sharp contrast to IEA [38], and also to the EU 2012 energy efficiency directive and its 2016 update, which set a target of 20% reduction in energy demand by 2020 and a 30% reduction target for

⁴Exogenous technological progress on the supply side is covered by technology-specific developments over time.

⁵Must-run generators such as nuclear, lignite, and coal power are not as flexible as gas power due to ramping times.

2030. Keeping our framework in mind, other studies seem to overestimate the economic attractiveness of energy efficiency, for two reasons. First, the interplay between short-term demand response and energy efficiency improvements leads to a rebound and thus diminishes the projected savings. However, we calculate that the rebound effect is 9% and hence does not play a crucial role. Second, on the supply side of the market, short-term demand response partly compensates the intermittent supply pattern of renewable energies and increases their economic viability.

The literature on energy efficiency is mainly concerned with two phenomena: the *rebound effect* and the *energy efficiency gap*.⁶ The rebound effect refers to the loss in energy efficiency savings due to economic response (Gillingham et al. [26]). The energy efficiency gap is understood as an energy efficiency level lower than the socially optimal level (Jaffe and Stavins [39]). The existence of a rebound effect is widely accepted and has been long discussed in the literature (e.g., Jevons [42], Khazzoom [45], Lovins [50]). In our partial equilibrium setting, we capture the effect on energy consumption of improved energy efficiency due to income and substitution effects (direct or *partial equilibrium rebound effect*) and abstract from income and substitution effects on all other goods (indirect or *general equilibrium rebound effect*).⁷

Regarding the energy efficiency gap, Gillingham and Palmer [25] recently wrote that “[d]espite more than thirty years of research on the energy efficiency gap, the issue of its size remains unresolved.” Two other publications have shed new light on this issue. Using evidence from an energy efficiency program for 30,000 low-income households, Fowlie et al. [21] find realized savings at roughly 30% of the projected ones. On the basis of a 100,000-household field experiment, Allcott and Greenstone [3] estimate savings of 58% in comparison to engineering projections. Moreover, they find no evidence for the informational or behavioral explanations that are often discussed in the literature, and conclude

⁶See [10, 13, 47] for theoretical contributions and [30, 41, 58] for literature reviews.

⁷See [22, 8] for a more detailed decomposition.

that modeling flaws such as hidden costs, exaggerated energy savings from engineering projections, and consumer heterogeneity contribute to the size of the observed energy efficiency gap. Note that exaggerated savings lead to higher estimates for the rebound effect and are one explanation for empirical evidence of rebound effects above 100%.

In this paper, our focus is not on discovering the actual size of the rebound effect and nor do we concern ourselves with the size or existence of the energy efficiency gap. We instead investigate whether engineering estimates might be wrong. In our default guess for the performance parameter, we find that energy efficiency accounts for 11% of carbon reductions, which is in sharp contrast to IEA [38]. However, Fowle et al. [21] and Allcott and Greenstone [3] suggest that actual performance might be only half of our guess. Under such a scenario and in the presence of a tight climate policy, the economic attractiveness of substitutes (wind, solar PV, gas power) results in negligible energy efficiency investment.

Partial equilibrium models of power markets usually assume that consumer's utility maximization leads to a generic downward-sloping demand curve (e.g., Fischer and Newell [20], Green and Leautier [29]). In the classical peak-load pricing literature (see Crew et al. [14] for a survey), consumers are able to adapt to expected prices (e.g., day-ahead or flat prices) but cannot react after the uncertainty has been resolved (e.g., real-time price) due to the lack of smart meters and suitable tariffs. Other studies consider that a fraction of consumers pay real-time prices and the remaining part faces flat tariffs (e.g., Borenstein and Holland [11], Joskow and Tirole [43, 44], Helm and Mier [32]), which is supported by empirical evidence that consumers do indeed adapt consumption in real time (Faruqui and Sergici [19]). Detailed power market models consider either short-term demand response or exogenously given temporal demand profiles. Zerrahn and Schill [70] represent short-term demand response by a system of equations, which limits the amount of demand and number of periods over which demand can be shifted. This approach keeps the problem linear and

their objective is to minimize costs.⁸ In contrast, Su and Kirschen [60] maximize welfare as the difference between the gross surplus and cost, where gross surplus is approximated by the product of consumers' marginal benefits and the quantity consumed. de Jonghe et al. [15] maximize welfare by using a first-order Taylor linearization of demand and thereby account for demand shedding, shifting, and the level of energy efficiency, which can be varied exogenously. Even though this paper explores a novel approach, the still exogenous level of energy efficiency and the lack of differentiation between demand for electricity and energy services limit its applicability. We borrow from de Jonghe et al. [15] to depict demand shedding but develop our own, more intuitive approach for demand shifting and energy efficiency. Other representations of energy efficiency in detailed partial equilibrium power market models are sparse and limited to cost-minimizing models [56].⁹ Like us, Lind et al. [48] model energy efficiency as an investment option with different cost classes and respective potentials.¹⁰ EPRI [18] use the US-REGEN model (see [7]) and integrate, similar to our model, energy efficiency as a separate technology in the market-clearing condition. For subsequent years, the performance of the energy efficiency measure depreciates. In our model, the performance of energy efficiency increases exogenously due to technological progress but the endogenous determined capacity of energy efficiency depreciates.

The remainder of the paper is organized as follows: Section 2 describes the model and the underlying optimization problem. Then, in Section 3, we develop the framework to implement short-term demand response and energy efficiency improvements in detailed power market models. Section 4 describes the calibration and Section 5 the results. Section 6 concludes.

⁸See [28, 54] for similar studies.

⁹See [6] for an approach that emphasizes the technological heterogeneity of energy efficiency measures.

¹⁰For quantification they use the TIMES-Norway model (see [49]).

2. The Model

Consider a dynamic partial equilibrium model of a multi-region electricity system. Our model comprises firms, consumers, and a central planner. The overall objective is to maximize welfare taking into account the behavior of firms and consumers. The market consists of regions r and consumption sectors i . We consider dispatchable and intermittent technologies j . The time horizon of the model is split into periods t and each period consists of segments s . We use y for production, q for new installed capacity, Q for aggregated capacity, and $C(\cdot)$ is for cost functions. The shape of the cost functions depends on the technology j and its absolute level varies among regions. We use subscripts i, j, r , and parentheses $(t), (s, t)$ to denote variables, for example, $y_{jr}(s, t)$ refers to technology type j , region r , segment s , and period t .

At the beginning of each period, firms invest $C_{jr}(q_{jr}(t))$ to install $q_{jr}(t)$. Each technology's capacity has a certain lifetime. Thus, $Q_{jr}(t)$ is reduced by the amount of capacity that reached the end of its lifetime in period t . Providing capacity costs $C_{jr}(Q_{jr}(t))$ makes it potentially beneficial to take some vintages out of operation before they reached the end of their lifetimes. In each time segment, firms decide on production, $y_{jr}(s, t)$, at private costs $C_{jr}(y_{jr}(s, t))$. Production leads to emissions, denoted by $e_{jr}(s, t)$, and is restricted by available capacity, i.e., $y_{jr}(s, t) \leq \alpha_{jr}(s) Q_{jr}(t)$, where $\alpha_{jr}(s)$ is the availability of technology j .

We assume that firms are perfectly competitive and emissions cause environmental damage by burning fossil fuels to generate electricity. Abstracting from any uncertainty and assuming price-responsive consumers, firms obtain zero profits in each period. Additionally, abstracting from dynamic market failures such as R&D spillovers, it is straightforward to show that firms would act efficiently if environmental externalities are perfectly internalized (e.g., Golosov et al. [27]).¹¹ We abstract from environmental externalities other than the

¹¹Externalities from R&D spillovers would require subsidies (e.g., Acemoglu et al. [2]).

carbon externality from burning fossil fuels. There are various policy instruments for addressing such market failures, for example, a carbon tax, direct control instruments to ban certain fossil fuel burning technologies, or certificates to limit emission quantities. We impose a quantity restriction path— $\bar{E}(t)$ denotes the emission target and $E(t) = \sum_r \sum_s \sum_j e_{jr}(s, t)$ is the actual emission level—which leads to an 80% emission reduction in the European power market in 2050.¹² For parsimony, we assume that the resulting certificate price internalizes all damages so that firms act efficiently.

Consumers obtain utility from the consumption of energy services. Sector-specific energy service demand is denoted by $x_{ir}(s, t)$, the resulting electricity demand by $d_{ir}(s, t)$, and $p_r(s, t)$ is the time-varying wholesale electricity price. We allow for short-term demand response, that is, demand shedding and shifting. We denote by $\epsilon_i^s < 0$ the ability to shed demand in segment s and by $\epsilon_i^{s, s'} \leq 0$ the ability to shift demand from s to s' . Taking this into account and noting that $x_r(s, t) = \sum_i x_{ir}(s, t)$ is the energy service demand of all sectors, consumers maximize their utility from the consumption of energy services by responding to time-varying electricity prices. This leads to the inverse demand function, denoted by $p_r(x_r(s, t))$, so that $\int_0^{x_r(s, t)} p_r(\tilde{x}) d\tilde{x}$ is the “gross surplus” from consuming energy services. Subtracting costs of purchasing electricity, yields consumer surplus

$$CS_r(s, t) = \int_0^{x_r(s, t)} p_r(\tilde{x}) d\tilde{x} - p_r(s, t) d_r(s, t). \quad (1)$$

Each region can trade electricity with other regions. Imports to a specific region r are defined by $IM_r(s, t) := \sum_{rr} IM_{r, rr}(s, t)$ and exports by $EX_r(s, t) := \sum_{rr} EX_{r, rr}(s, t)$, where rr defines a subset of regions that does not contain the specific region r . $IM_{r, r'}(s, t)$ and $EX_{r, r'}(s, t)$ denote the import or export volume, respectively, between two regions r and r' . Then, net imports are $TR(s, t) = IM_r(s, t) - EX_r(s, t)$. Noting that $\sum_j y_{jr}(s, t)$ is the total production of firms, consumers use energy services, $x_r(s, t)$, and purchase the necessary amount of electricity, $d_r(s, t)$, so as to maximize consumer surplus (1) under the

¹²See Weissbart and Blanford [69] for detailed information on this scenario.

market-clearing condition $d_r(s, t) \leq \sum_j y_{jr}(s, t) + TR_r(s, t)$. It is straightforward to show that price-responsive consumers increase consumption up to the level of electricity offered ($\sum_j y_{jr}(s, t) + TR_r$) so that the market-clearing condition always binds (e.g., Helm and Mier [33]).

Trading is restricted by transmission line capacity. To alleviate this constraint, the central planer invests $C_{r,r'}^{tr}(\cdot)$ to install transmission line capacity, $q_{r,r'}^{tr}(t)$, between regions r and r' . The transformation of electricity into energy services is determined by the level of energy efficiency. The central planer invests $C_{ir}^{ee}(\cdot)$ in each region to improve the energy efficiency of sector i by $q_{ir}^{ee}(t)$. The aggregated energy efficiency capacity, $Q_{ir}^{ee}(t)$, depreciates at rate δ^{ee} . Using these investment costs, we can formulate the central planner's objective as

$$\max_{\mathbf{q}, \mathbf{y}} W = \sum_t \sum_r \left(\sum_s CS_r(s, t) + \sum_j \pi_{jr}(t) - \sum_i C_{ir}(\cdot) - \sum_{rr'} C_{r,r'}^{tr}(\cdot) \right) \quad (2)$$

$$\text{such that } 0 = \pi_{jr}(t), \quad (3)$$

$$0 = \sum_j y_{jr}(s, t) + TR_r(s, t) - d_r(s, t), \quad (4)$$

$$0 \leq IM_{r,r'}(s, t) + EX_{r,r'}(s, t) \leq Q_{r,r'}^{tr}(t), \quad (5)$$

$$0 \leq \bar{E}(t) - E(t), \quad (6)$$

$\pi_{jr}(t)$ denotes technology-specific profits of firms in a specific region. The central planner maximizes welfare as the sum of consumer surplus and producer surplus, minus costs of energy efficiency improvements and costs of transmission line capacity expansion. \mathbf{q} is the vector that contains capacity decisions (generation, energy efficiency, and transmission line capacity) for all periods in each region, and \mathbf{y} is the vector of all production decisions. Constraint (3) is the zero-profit condition of firms. Constraint (4) is the market-clearing condition that reflects consumer surplus maximization. Constraint (5) ensures that imports and exports are non-negative and do not exceed transmission line capacity. Finally, constraint (6) ensures that the emission reduction target is met.

3. Implementation of Demand Response in the Numerical Model

We quantify the future equilibrium of the European power market by using the model framework introduced in Section 2 and implementing short-term (demand shedding and shifting) and long-term demand response (endogenous investments in energy efficiency and exogenous technical progress in energy efficiency) in the combined dispatch and investment EU-REGEN model (see Weissbart and Blanford [69]). The EU-REGEN model includes all the EU countries (EU28)—except for the island countries Malta and Cyprus—and, additionally, Switzerland and Norway. These countries are grouped into 13 regions as shown in Table A.10 in Appendix A. The base year is 2015 and the time horizon in this analysis is 2050. Dispatch and investment decisions are optimized in five-year steps, resulting in eight time periods. Similar to the spatial aggregation, the model reduces the number of intra-annual segments within each period to 121 for computational reasons. The choice of time segments is based on an algorithm that finds the extreme moments in all possible one-, two-, and three-dimensional spaces of wind, solar, and demand. For the purpose of this paper, time segments are weighted by mapping them to original hours based on minimizing the Euclidean distance.¹³ This mapping of segments to original hours allows us to still capture the temporal sequence of hours.

The model comprises 25 technologies (15 dispatchable and 10 intermittent technologies). EU-REGEN abstracts from intraregional electricity distribution and considers only the electricity exchange between regions. In each period, new transmission capacity can be added between neighboring regions or regions with an already existing transmission link. Moreover, the EU-REGEN model allows for the geological storage of CO₂ (CCS). In the model, capacity for CCS can be added through investment in new capacity or conversions

¹³Note that this weighting algorithm differs from the one in Weissbart and Blanford [69] where time segments are weighted so as to minimize the sum of squared errors between the aggregated averages and the hourly averages for wind, solar, and demand profiles.

of existing power plants.¹⁴

Finding a market equilibrium under the assumption of perfectly competitive markets and without short-term demand response is a cost-minimization problem and thus can be solved as a linear program. Adding short-term demand response to this model changes the structure of the underlying algebraic problem in regard to the new objective of maximizing welfare. The objective function can become quadratic or exhibit other kinds of nonlinearities. The most general way of solving such a problem is complementary programming. Karush-Kuhn-Tucker conditions are derived as the necessary first-order conditions for finding an optimum. The respective complementary variables are defined for each equilibrium condition (e.g., Takayama and Hashimoto [61]). However, solving a detailed (i.e., large number of constraints) problem through complementary programming is not feasible given that a complementary variable has to be defined for each equilibrium constraint. Takayama and Uri [62] emphasize that under certain conditions, a market equilibrium can be found by using quadratic programming, which requires (among other things) that the underlying problem be convex and the resulting market matrix positive semidefinite and, thus, symmetric (de Jonghe et al. [15]). If these conditions are fulfilled, the market equilibrium can be found by solving the problem as an equivalent quadratic program by means of efficient algorithms that are tailored to solving convex problems (e.g., CPLEX). However, these conditions seriously constrain an extensive analysis of the impact of short-term demand response. Hence, in this paper, formulation of demand response in the numerical implementation must be adjusted with regard to those technical constraints.

¹⁴For parsimony, we introduced only the most important constraints in Section 2. More detailed information about the EU-REGEN model structure, the underlying data set, and additional constraints can be found in Weissbart and Blanford [69].

3.1. Short-Term Demand Response

As a benchmark we abstract from short-term demand response by taking a cost-minimizing approach and obtain reference values for energy service demand (denoted by $x_{r,0}(s, t)$), electricity demand (denoted by $d_{r,0}(s, t)$), and electricity prices (denoted by $p_{r,0}(s, t)$). These reference values account for production decisions and investments in generation and transmission capacity. We use these reference values as fixed points to specify demand shedding and demand shifting in our model.

Demand shedding leads to more (or less) consumption, whereas demand shifting is just the intertemporal reallocation of demand, that is, all shifts equalize over the respective period. Shedding accounts for the response to changing prices in a specific segment in comparison to a benchmark, that is, consumers decide to consume more (less) if the price is lower (higher). Shifting accounts for the response to changing prices in specific segments in comparison to prices in other segments, that is, consumers decide to shift some of their demand from segments with high prices to segments with low prices (and the other way around).¹⁵ Note that shifting is temporarily limited and demand cannot be shifted for longer than a couple of hours.

Demand Shedding. As benchmark for demand shedding, we use the reference values determined by the reference run described above. Remembering that ϵ_i^s is the ability to shed, we obtain

$$x_{ir}(p_r(s, t)) = x_{ir,0}(s, t) + \epsilon_i^s \frac{x_{ir,0}(s, t)}{p_{r,0}(s, t)} (p_r(s, t) - p_{r,0}(s, t)). \quad (7)$$

Here, $x_{ir,0}(s, t)$ is the reference demand that serves as fixed point and the second term is shed demand. The price difference, $p_r(s, t) - p_{r,0}(s, t)$, is the willingness to shed. The fraction determines the overall level and ϵ_i^s constrains the total amount shed. Observe from

¹⁵Regarding shedding, households might decide to switch on lights or the television when actual prices are low (or switch off when prices are high). Regarding shifting, households might decide not to use the dishwasher right now, but instead wait for a couple of hours until the price is lower.

Equation (7) that ϵ_i^s is defined as an own-price elasticity of demand. Thus, the magnitude of the increase is determined by an exogenously given price elasticity, which is obtained from empirical studies (e.g., [46]).¹⁶

Demand Shifting. Figure 1 illustrates the effect of demand shifting between the specific segment s and another segment s' . We use the superscript sh to denote outcomes after the shifting process. Demand (gray curves show inverse demand, $p(x(\cdot))$) is the same in both segments, but supply (black curves show inverse supply, $p(y(\cdot))$) is lower in s than in s' , which leads to higher prices in s . Consumers exploit the price difference $p(s) - p(s')$ and shift demand from s to s' , yielding lower prices in s but higher ones in s' so that the price difference becomes smaller. This process is illustrated by the arrows and the parallel shifted demand curves (dotted gray curves show inverse demand after shifting, $p^{sh}(x(\cdot))$). There are two countervailing effects. First, demand is reduced in s (and increased in s') by Δx , which is the total amount of demand shifted. Second, demand is increased in s by $\Delta r(s)$ (and reduced in s' by $\Delta r(s')$) due to consumer response (demand shedding) to lower prices in s (and higher prices in s').

In the numerical model, we determine the change in demand due to shifting by using the ability to shift ($\epsilon^{s,s'}$). Using average reference demand from s and s' , denoted by $\bar{x}_{ir,0}(s, s', t)$, and the average reference price, denoted by $\bar{p}_{r,0}(s, s', t)$, we obtain

$$\begin{aligned} x_{ir}(p_r(s, t)) &= x_{ir,0}(s, t) + \epsilon_i^s \frac{x_{ir,0}(s, t)}{p_{r,0}(s, t)} (p_r(s, t) - p_{r,0}(s, t)) \\ &\quad + \sum_{ss} \epsilon_i^{s,ss} \frac{\bar{x}_{ir,0}(s, ss, t)}{\bar{p}_{r,0}(s, ss, t)} (p_r(s, t) - p_r(ss, t)), \end{aligned} \quad (8)$$

where ss defines a subset of segments that does not contain a specific segment s .¹⁷ The second line reflects demand shifting. $p_r(s, t) - p_r(s', t)$ is the price difference that determines

¹⁶For illustration, assume $\epsilon_i^s = -0.1$, $x_{ir,0}(s, t) = 50$ GW, $p_{r,0}(s, t) = 50$ EUR/MWh. If the current price is lower than the reference price, e.g., $p_r(s, t) = 40$ EUR/MWh, the consumer increases consumption by 1 GW. The relative price difference is -20% and, thus, the consumed quantity increases by 2% .

¹⁷Note that $\bar{x}_{ir,0}(s, s', t) := \frac{1}{2} (x_{ir,0}(s, t) + x_{ir,0}(s', t))$ and $\bar{p}_{r,0}(s, s', t) = \frac{1}{2} (p_{r,0}(s, t) + p_{r,0}(s', t))$.

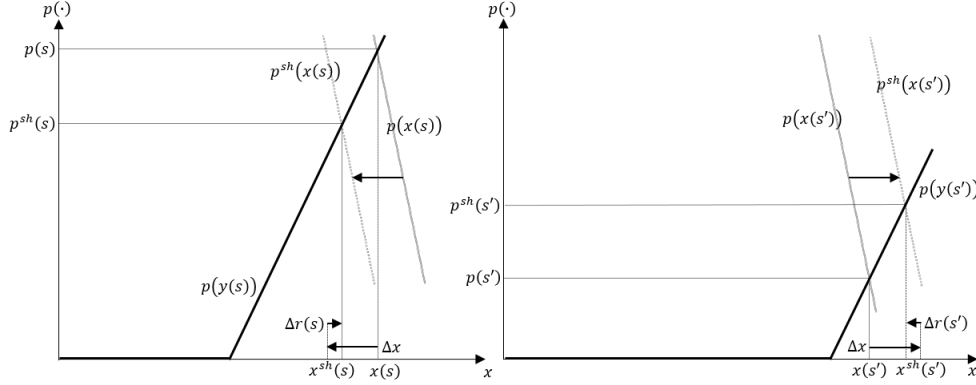


Figure 1: Demand shifting from periods with low supply to periods with high supply

the willingness to shift. The fraction ensures that shifts equalize over the entire period t , that is, the whole second line would vanish when summing up over all time segments. Finally, $\epsilon_i^{s,ss}$ constrains the total amount that can be shifted.¹⁸

Setting up the objective by using the specification of energy service demand in Equation (8) results in a complementary programming problem, which, as argued above, is numerically not tractable for the large number of constraints that are necessary to describe a multi-region electricity system. To be able to use a solution algorithm tailored to solving convex problems, such as CPLEX, we need to derive inverse (energy service) demand for each segment that depends only on the demand in this segment. Note that (from Equation (8)) energy service demand depends on the price in segment s but also on the prices in all segments with $\epsilon_i^{s,ss} \neq 0$. Given that we have one equation for each segment and the same number of unknown variables, this is, in principle, possible. However, the resulting objective violates the necessary convexity (the market matrix

¹⁸For illustration, suppose that shifting is possible between segments 1 and 2. Prices are 100 EUR/MWh in segment 1 and 0 EUR/MWh in segment 2. Moreover, suppose that $\epsilon_i^{1,2} = -0.01$, $\bar{p}_{r,0}(1,2,t) = 50$ EUR/MWh, $\bar{x}_{ir,0}(1,2,t) = 50$ GW. The total amount shifted from segment 1 to segment 2 is 1 GW, which accounts for 2% of the average reference demand between these two segments.

is not positive semidefinite anymore) so that the problem is numerically not tractable. We avoid this problem by using an approximation of energy service demand. We use $p_{r,0}(s', t)$ instead of $p_r(s', t)$ because the best guess for prices in other segments is the reference price. Using $x_r(s, t) = \sum_i x_{ir}(s, t)$, $x_{r,0}(s, t) = \sum_i x_{ir,0}(s, t)$, and the shortcuts $\Gamma(s, t) = -\sum_i \epsilon_i^s \frac{x_{ir,0}(s, t)}{p_{r,0}(s, t)}$ and $\Gamma(s, s', t) = -\sum_i \epsilon_i^{s, s'} \frac{\bar{x}_{ir,0}(s, s', t)}{\bar{p}_{r,0}(s, s', t)}$, we obtain the (approximated) inverse demand by

$$p_r(x_r(s, t)) = \frac{(x_{r,0}(s, t) - x_r(s, t)) + \Gamma(s, t) p_{r,0}(s, t) + \sum_{ss} \Gamma(s, ss, t) p_{r,0}(ss, t)}{\Gamma(s, t) + \sum_{ss} \Gamma(s, ss, t)}, \quad (9)$$

which is a linear function of $x_r(s, t)$. Furthermore, we need to impose the constraint $\sum_s \sum_{ss} \Gamma(s, ss, t) (p_r(s, t) - p_{r,0}(ss, t)) = 0$ to ensure that demand shifts—even under the approximation of energy service demand—still equalize over all segments.

3.2. Energy Efficiency

Consumers obtain utility from energy services but need to buy electricity. These can be treated as equivalent as long as there is a fixed transformation ratio from electricity into energy services. Energy efficiency improvements increase that ratio so that less electricity is required to consume the same amount of energy services.

This is illustrated by Figure 2. The demand for electricity, d , and energy services, x , is depicted on the x-axis; the price of electricity is shown on the y-axis. The black curve depicts inverse supply ($p(y)$) and the solid gray curve inverse energy service demand ($p(x)$), which are both time independent. Initially, demand for electricity (dashed gray curve, $p(d(0))$), is slightly lower than energy service demand. Improvement in energy efficiency does not change demand for energy services but electricity demand is reduced by ΔQ^{ee} (see the arrow and the dotted gray curve, $p(d(t))$). This reduces the price and consumers negate the effect of energy efficiency improvements by consuming more energy services and, thus, more electricity. $\Delta r^{ee} = \Delta Q^{ee} - (d(0) - d(t)) = x(t) - x(0)$ is the rebound and $\Delta r^{ee} / \Delta Q^{ee}$ is the corresponding *rebound effect* of energy efficiency improvements. Finally,

by including the rebound effect, the price drops from $p(0)$ to $p(t)$.¹⁹ Finally, observe that energy efficiency improvements increase welfare due to lower production costs (gray area on the left) and due to the rebound, that is, increased energy service consumption (gray area on the right).

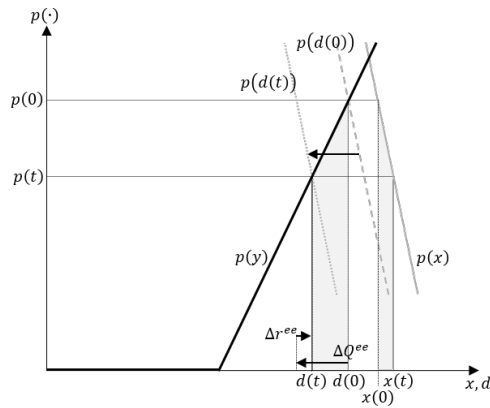


Figure 2: Demand shifting from periods with low supply to periods with high supply

To keep the numerical model tractable, we assume that energy efficiency is measured in absolute terms. We specify sector-specific electricity demand by

$$d_{ir}(s, t) = x_{ir}(s, t) - \gamma(t) Q_{ir}^{ee}(t). \quad (10)$$

$Q_{ir}^{ee}(t)$ is the aggregated capacity of energy efficiency improvements that obtains endogenously from investments. $\gamma(t)$ is the performance factor of the respective energy efficiency measure. The development of $\gamma(t)$ over time reflects exogenous technological progress in energy efficiency. We take this approach so as to account for the fact that exogenous progress depends on endogenous investments in energy efficiency.

¹⁹The magnitude of this rebound critically depends on the shape of (inverse) demand and supply. However, in a partial equilibrium setting, rebound never overcompensates the initial savings and thus never leads to “backfire” (see Lemoine [47]).

4. Calibration of the Numerical Model

In the following we describe the quantification of parameters relevant for depicting demand response in the EU-REGEN model.²⁰ Regarding the abilities to shed (ϵ^s) and shift demand ($\epsilon^{s,s'}$), we use existing estimates that vary widely depending on the specific sector, country, sample period, and estimation method (see Labandeira et al. [46], Jamil and Ahmad [40], Huntington et al. [36]). The overview in Huntington et al. [36] indicates that the residential sector generally has better ability to shed demand than do the industry, transport, or commercial sectors. This analysis uses estimates from the meta-analysis conducted by Labandeira et al. [46]. As a default assumption, we set the ability to shed demand to the values shown in Table 1. Moreover, as indicated in Huntington et al. [36] and Taylor et al. [63], the ability to shift (called cross-price elasticity in those works) seems to be moderate in comparison to the ability to shed. Thus, we assume that the abilities to shift occurs in the four previous and subsequent cross-hours and is 10% of the ability to shed (see Table 1).²¹

Table 1: Abilities to shed and shift demand

	Ind	Res	Com	Tra
$\epsilon^{s,s}$	−0.15	−0.2	−0.1	−0.1
$\epsilon^{s,ss}$	−0.015	−0.02	−0.01	−0.01

To approximate the existing level of energy efficiency, we assume that each region’s current level is represented by a relative measure (denoted by ζ_r) reported in the *Odyssee Database* (see Enerdata [17]). We assume that demand for electricity and energy services is the same in 1990 and all differences after 1990 reflect energy efficiency improvements.

²⁰See Weissbart and Blanford [69] and Weissbart [68] for the general calibration of the EU-REGEN model and the underlying data set for the supply side.

²¹This assumption ensures that the symmetry and positive semi-definite requirements (see Section 3) are satisfied.

We obtain the initial level of energy efficiency from $EE_r(2015) = \zeta_r \bar{d}_r(1990)$, where $\bar{d}_r(1990)$ is the annual electricity demand in 1990. We assume that the performance factor increases by 5% with every new vintage. For parsimony, we assume a default performance of $\gamma(2015) = 1$, which will be varied in Section 5 to test the sensitivity of our results to this assumption. Table B.11 in Appendix B shows the resulting 2015 base levels and the values for ζ_r and $\bar{d}_r(1990)$. The industrial and residential sectors appear to have experienced an especially significant improvement in energy efficiency since 1990. The United Kingdom has the highest (absolute) level of energy efficiency across all sectors, followed by Germany and France. For demand growth projections by country, we use numbers from the *e-HIGHWAY 2050 Project* (see e-HIGHWAY 2050 [16], Weissbart and Blanford [69]), which expects an EU-wide demand growth of 34% in the period 2015–2050. We apply this growth rate to energy service demand and obtain the resulting electricity demand from endogenous energy efficiency improvements.

Data availability is less than optimal when it comes to the costs of endogenous energy efficiency investment. We use Germany as the reference and approximate the costs function by a stepwise function that is characterized by five quality classes. Each class has an upper size limit and average investment costs. We base our assumptions on the costs proposed by Steurer [59], Huntington [35, 34]. For the *industrial* sector, we use the energy efficiency supply curve for the German industrial sector from Steurer [59]. Huntington [35, 34] shows that the opportunity costs of energy efficiency are lower in the residential sector than in the industry sector. Hence, we scale the energy efficiency industry supply curve from above by a factor of 0.5. Furthermore, we adjust the size of the energy efficiency classes in proportion to the 2015 German residential electricity demand relative to the electricity demand of the German industrial sector. We use the same approach (scaling by a factor of 0.5 and proportional class sizes) for *transport* and *commercial*. Table 2 shows class sizes as well as costs for Germany.

We assume the same costs for all other regions and determine the size of each quality

Table 2: Energy efficiency supply classes for Germany

Class	Size (GW)	Ind	Res	Com	Tra	Res, Com, Tra
		Costs (EUR/kW)	Size (GW)			Costs (EUR/kW)
1	2	2,500	1,23	1,40	0,11	1,250
2	3	6,000	1,85	2,10	0,16	3,000
3	1	10,000	0,62	0,70	0,05	5,000
4	1	17,000	0,62	0,70	0,05	8,500
5	1	30,000	0,62	0,70	0,05	15,000

class by using the sector-specific demand of the other regions relative to the sector-specific demand in Germany. The existing level of energy efficiency is distributed over quality classes in ascending order, meaning that all the existing level is located in quality class 1. If the existing level exceeds the size of a quality class, the remaining is assigned to next class. This allows determining the remaining energy efficiency potential and its costs for each sector in a region.²²

5. Results

We begin our presentation of results by characterizing the long-run equilibrium of the European power market under different assumptions of demand response. Next, we quantify role of energy efficiency plays in climate policy. We end by discussing how the optimal level of energy efficiency (EE) changes under varying assumptions. For parsimony, we use the term *energy efficiency investments* to refer to accumulated additions.

²²Note that we assume that the already existing level of energy efficiency only impacts the remaining energy efficiency potential. Moreover, we assume that the existing level of energy efficiency does not depreciate.

5.1. Long-Run Market Equilibrium under Responsive Demand

Energy Efficiency. Under responsive demand (i.e., with the default assumptions outlined in Section 4), the optimal (EU-wide) level of energy efficiency gradually increases until 2030, peaks in 2040, and then depreciates to 42 GW in 2050 (see Table 3), resulting in an annual electricity demand reduction of 394 TWh (11%) in 2030 and 429 TWh (10%) in 2050.²³ In relation to the 2015 level of energy efficiency, the 2030 level represents a further 69% increase in energy efficiency.²⁴ Interestingly, there is a massive build-up in the first investment period (2020), indicating that the level of energy efficiency is below its socially optimal level.

Table 3: Initial level of energy efficiency (2015) and investments

Region	2015	2020	2025	2030	2035	2040	2045	2050
<i>Europe</i>	60.4	32.3	38.7	41.8	44.1	44.2	44.0	42.3
<i>Britain</i>	10.5	0.0	0.5	0.5	0.5	0.5	0.4	0.4
<i>Eastern Europe-SE</i>	3.6	3.0	4.1	4.1	5.2	5.2	5.2	5.0

Regarding future investments, we observe a heterogeneous spatial distribution. Up to the (EU-wide) level peak in 2040, the northeast region (Eastern Europe-NE) does the best at increasing its energy efficiency level by 5.8 GW (583%), followed by the southeast region (Eastern Europe-SE, 5.2 GW, 143%), the southwest region (Eastern Europe-SW, 5.5 GW, 281%), and Italy with 4.7 GW (124%). For Scandinavia, Britain, and North Germany, it is optimal to make only minor or no investment. Table 3 shows the detailed development for Britain (United Kingdom and Ireland) and Eastern Europe-SE (Bulgaria, Greece, and Romania). The case of Britain can be explained, to a certain extent, by the

²³Note that the reduction in electricity demand in 2050 is larger than that in 2030, even though energy efficiency capacity slightly decreases, due to the exogenous technological progress in energy efficiency described in Section 4.

²⁴See Table B.11 in Appendix B for regional- and sector-specific figures for the initial level of energy efficiency, and Table C.12 in Appendix C for the regional-specific development over time.

already high level of energy efficiency and a high quality of wind resources.²⁵ Our results indicate that it is optimal to improve energy efficiency mainly in regions that are either on the border of the (spatial) European power market or do not have access to high-quality wind (e.g., Eastern Europe-SE).²⁶ In Eastern Europe-SE, we observe a catch-up effect in 2020. The further development is driven by low-quality wind resources and the absence of links to other regions due to its position on the spatial fringe. Note that solar irradiation in Eastern Europe-SE is high, but does not influence energy efficiency investment. The diurnal solar irradiation pattern is not a substitute for the constant demand reduction from energy efficiency, whereas the seasonal wind pattern is a substitute.

With respect to sectoral distribution, the industrial sector (28 GW) and the residential sector (20 GW) have much higher initial levels of energy efficiency than to the commercial (11 GW) and transport (1 GW for transport) sectors.²⁷ However, the equilibrium energy efficiency level by demand sector shows that it is chiefly the residential, commercial, and transport sectors that engage in investments. The transport and commercial sectors have a low existing level of energy efficiency and thus can still make energy efficiency improvements at relatively low cost. The residential sector increases its energy efficiency more than the industrial sector due to lower investment costs (see Table 2).

Short-Term Demand Response. Short-term demand response reduces residual peak load (i.e., the time segments with the highest electricity demand net of intermittent renewables such as wind and solar) by 8% in 2015 and by almost 33% in 2050.²⁸ We decompose this reduction by comparing the outcome with one where there is no investment in energy

²⁵The United Kingdom has the highest initial level of energy efficiency, followed by Germany (9.5 GW) and France (6.2 GW). See Table C.12 in Appendix C for more details.

²⁶In particular, when looking at Scandinavia and North Germany, it is obvious that access to high-quality wind resources prevents investments in energy efficiency.

²⁷See Table B.11 in Appendix B.

²⁸Note that no capacity investments take place in 2015, but capacities can be decommissioned and responsive demand influences (residual) peak and off-peak load.

efficiency. The contribution of energy efficiency is one-third of the total reduction and the share of shedding and shifting accumulates to two-thirds. For the residual off-peak load (i.e., the time segments with the lowest residual load), short-term demand response contributes to an increase of this moment by almost the same amount as the residual peak load decreases.

Capacity and Generation Path. We now turn to the long-run equilibrium of generation and capacities. Responsive demand particularly impacts substitution among technologies on the supply side. The impact of demand response can be found by comparing market outcomes under a *full demand response* scenario to those under a *no demand response* scenario, which is illustrated in Figure 3. The figure shows the development of annual generation for relevant technologies under full demand response (left) and no demand response (right). Under full demand response, wind power is the major technology, with an annual generation share of 24% in 2030 and 40% in 2050. Wind power is accompanied by an increasing contribution from gas power (6% in 2030, 19% in 2050), and solar PV (3%, 11%). In 2050, under no demand response, the accumulated share of wind and solar PV decreases from 51% to 35%, whereas the share of gas increases from 19% to 25%. Demand response is a substitute for flexible generators such as gas turbines. When consumers are able to react to changing prices, less gas capacity is needed to balance intermittent generation from renewables. Moreover, the balancing does not come at a higher cost so that the relative competitiveness of wind and solar PV increases. Furthermore, coal-powered technologies (brown and hard coal) stay active longer under responsive demand because substituting gas power is less competitive in the presence of responsive demand.

Interestingly, in neither scenario is there investments in CCS on the basis of coal and gas. However, bio power in combination with CCS (BECCS) does not enter the European power market under responsive demand, whereas under no demand response BECCS will

be build at the end of the time horizon.²⁹

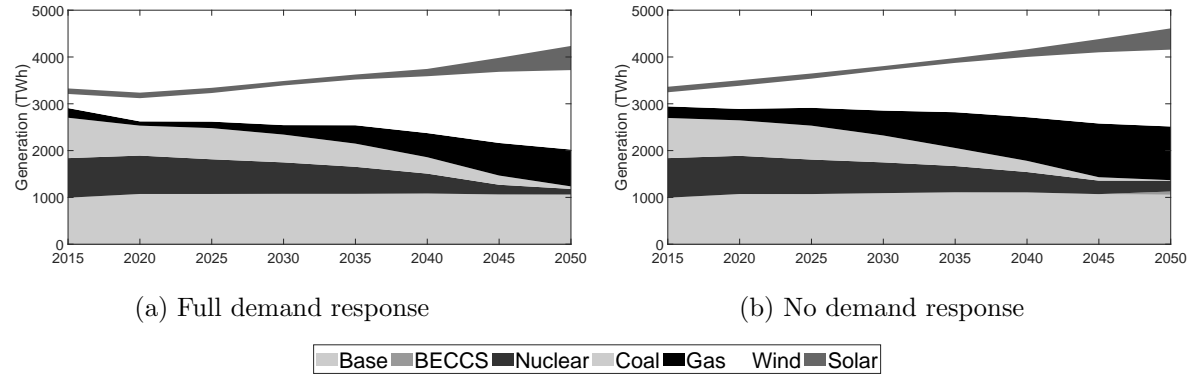


Figure 3: Long-run generation path with and without demand response

The effect of responsive demand is also visible on the capacity investment path. Again, comparing the outcomes of a full demand response scenario and no demand response scenario (see Figure 4) shows that responsive demand not only promotes higher generation (e.g., due to avoided curtailment) but also the build-up of wind and solar PV in the long run. The 2050 wind power capacity rises by 5% with responsive demand and the stock of solar PV capacity experiences an increase of 23%. In analogy to the generation path, the further capacity build-up of both technologies is compensated by reduced stocks of mainly gas power as well as nuclear and BECCS.

It is important to emphasize that responsive demand leads to higher utilization rates of generation capacity. For example, wind power capacity is lower under full demand response up to 2040, although its generation is higher (see Figure 3). Moreover, the 2050 capacity stock across all technologies is 9% lower with responsive demand. Observe that under responsive demand, more than 70 GW of gas capacity is decommissioned immediately in 2015. Gas capacity decreases further as the share of wind and solar PV generation in the system increases (compare Figures 4 and 3). This effect mainly comes from short-term

²⁹See the Subsection 5.2 on decarbonization.

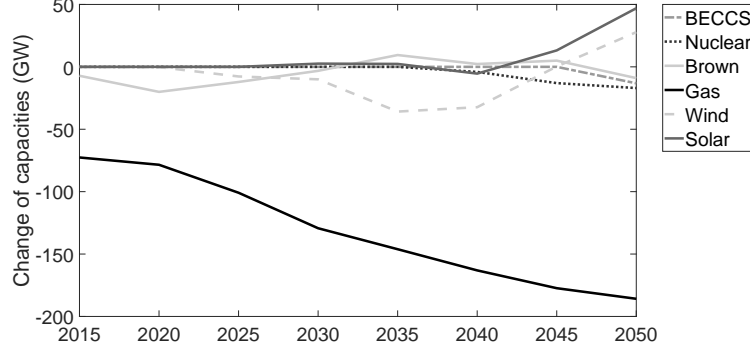


Figure 4: Change of generation capacity path with full demand response

demand response. The effect of energy efficiency investments on this development is small (33.5 GW in 2030 and 31 GW in 2050).

Electricity Prices. The switch to more capital-intensive renewable energy technologies and energy efficiency further impacts expenditures on the supply side, and the equilibrium electricity prices. Whereas until 2050, capital expenditures experience only a minor decrease with responsive demand, the sum of incurred variable costs decreases by 22%.

To decompose the effects of short-term demand response and energy efficiency improvements on price levels, we compare the weighted average electricity prices over all regions under four scenarios: *no demand response*, *EE investments only*, *short-term response only*, and *full demand response* (see Table 4). Intuitively, the price is highest under no demand response; we thus chose this scenario as the reference and set the level to 1. Observe that the average electricity price is decreasing with demand response. Energy efficiency improvements play a dominant role for prices in 2020 and 2025. The build-up of energy efficiency capacity (see Table 3) leads to a price drop of 13% in 2020, which is phased out over time. From 2030 on, the impact of short-term demand response is dominant. In 2050, short-term demand response accounts for almost two-thirds of the price decrease, whereas energy efficiency delivers only one-third, which is in line with the impact shares of short- and long-term demand response on residual peak load.

Table 4: Change of electricity prices under demand response

Scenario	2015	2020	2025	2030	2035	2040	2045	2050
<i>EE investments only</i>	1.00	0.87	0.93	0.93	0.95	0.98	0.97	0.99
<i>Short-term response only</i>	0.99	0.98	0.96	0.95	0.95	0.96	0.95	0.95
<i>Full demand response</i>	0.98	0.87	0.89	0.90	0.92	0.92	0.92	0.92
in Britain	1.00	0.95	0.91	0.90	0.95	0.90	0.91	0.89
in Eastern Europe-SE	1.00	0.65	0.67	0.70	0.78	0.85	0.91	0.91

All regions experience a long-run price decrease, which is in line with Gambardella et al. [23]. The northern regions experience the strongest impact due to their common characteristic of high-quality wind resources.³⁰ In the case of Britain, responsive demand can reduce the 2030 equilibrium price by 5% and for 2050 by another 6%. The lowest decrease is in the southwestern region (4% in 2050). For Eastern Europe-SE, prices drop due to the build-up of energy efficiency (see Table 3). However, in the long-run (relative) prices are increasing again and, finally, are higher than those in Britain because the higher wind potential in Britain leads to more intra-annual price differences so that the effect of short-term demand response is higher.

Rebound Effect. As described in Subsection 3.2, energy efficiency investment leads to a *rebound effect* due to reduced prices.³¹ Lower prices do not occur only due to energy efficiency improvements but also due to the dynamic adjustment of capacities. To distill the rebound effect from energy efficiency investments, we need to determine the change in electricity demand due to the dynamic adjustment of capacities and short-term demand response. To do so, we determine demand under the *short-term response only* scenario that fully abstracts from energy efficiency investments.³² The rebound is determined by

³⁰See Table D.13 in Appendix D for a regional differentiation of prices under full demand response.

³¹Note from Section 1 that we cover the direct (or partial equilibrium) rebound effect only and abstract from the indirect (or general equilibrium) one.

³²Note that, under this scenario, there is still the initial level of energy efficiency.

calculating the expected savings, and subtracting the observed decrease in electricity demand over time. We compare this result with the rebound under the *full demand response* scenario. The rebound due to energy efficiency investments is given by the difference between these two scenarios. To calculate the final rebound effect, we just need to divide the rebound by calculated savings (see Figure 2). Table 5 shows a rebound effect from energy efficiency investments of 9% in 2030 as well as in 2050.

Table 5: Decomposition of the rebound effect

Scenario	Category	2030	2050
<i>Short-term only</i>	Full rebound from lower prices (TWh)	61	99
	Full rebound from lower prices (TWh)	103	137
<i>Full demand response</i>	Rebound from EE investments (TWh)	41	37
	Rebound effect from EE investments (%)	9	9

In the following, we focus on the rebound effect from energy efficiency investments. Observe that the rebound effect remains constant over the covered time horizon. The magnitude of this effect is rather small compared to the empirical results of other studies (e.g., [66, 12, 67]). The reason for the difference is threefold. First, our analysis does not capture the general equilibrium rebound effect. However, Boehringer et al. [8] suggest that the general equilibrium part of the rebound is rather small (16.5% for electricity in the EU) in comparison to the partial one (57%). Second, empirical studies rely on engineering projections, which might overestimate the true savings (see [21, 3]). Third, the size of the rebound effect is driven by the sensitivity of short-term demand response. For example, higher price elasticities of demand lead to greater quantity adjustments. In Table 6, we verify this for 2050 by using doubled to fivefold abilities to shed and shift (see Table 1 for the default values).³³ Doubling the abilities leads to a more than doubled rebound effect, whereas the fivefold abilities result in a rebound effect of 29%. The qualitative

³³For example, doubling the ability of the industrial sector would lead to $\epsilon^{s,s} = -0.3$ and $\epsilon^{s,ss} = -0.03$.

result—that the rebound effect is larger when gradually increasing the abilities—is not surprising. More interestingly, even with fivefold abilities to shed and shift, we cannot confirm that the rebound effect is of much relevance for the long-run equilibrium of the European power market.

Table 6: Sensitivity of the rebound effect in 2050

Ability levels $\epsilon^s, \epsilon^{s,s'}$	1×	2×	3×	4×	5×
<i>Rebound from EE investments</i> (TWh)	37	81	104	115	125
<i>Rebound effect from EE investments</i> (%)	9	19	24	27	29

5.2. The Role of Energy Efficiency for Decarbonization

Abatement Channels. In Section 5.1, we show that energy efficiency investments reduce annual electricity demand by 10% in 2050. Now, we want to shed further light on energy efficiency by analyzing its role in decarbonization. We quantify the contribution of different abatement channels—intermittent renewables such as wind and solar, energy efficiency, fuel switching, and nuclear power—to decarbonization of the European power market. We do so by comparing the market outcomes under a *climate policy* (80% emission reduction target in our default version) and under the *absence of a climate policy* (no reduction target).³⁴ Figure 5 shows the shares of different abatement channels. The uppermost line represents emissions under the absence of a climate policy. Emissions increase from 1,040 MtCO₂ in 2015 (by 15%) to 1,200 MtCO₂ in 2050. The lowest line shows emissions under a 80% reduction target, so that emissions reach a level of 290 MtCO₂ in 2050. The area in between the uppermost and lowest line represents emission reductions due to a climate policy. We find that the majority of emission reductions comes from intermittent renewables (53% in

³⁴The absence of a climate policy does not necessarily mean that there will be no investment in energy efficiency, renewables, or gas power as well as no utilizing of short-term demand response.

2050) and fuel switching (36%).³⁵ Observe that emissions drop in 2020 due to investments in energy efficiency, even without a climate policy. Energy efficiency investments increase even further until they peak in 2040 (see Table 3). However, in analogy to the results in Section 5.1, energy efficiency plays a minor role for meeting the reduction target in the long run (11% in 2050). The reason is that energy efficiency investments are beneficial even without a climate policy. Energy efficiency helps with the total burden of reduction and alleviates the emission target (observe that until 2030 there is almost no difference between the policy and the no policy scenario). This allows a technology mix with higher emission intensity so that coal power stays longer active (see Figure 3).³⁶

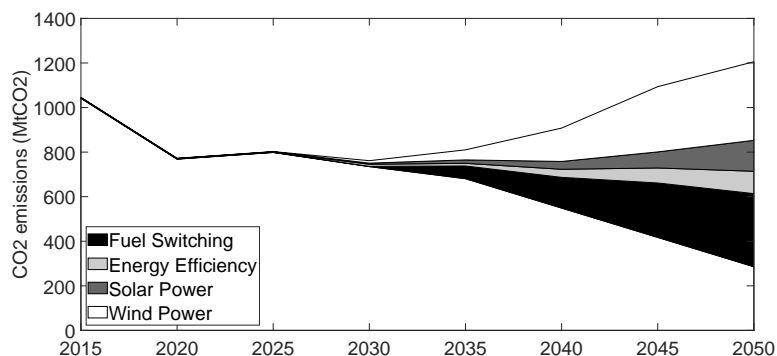


Figure 5: Contribution of different abatement channels to climate policy goals

To distill the effect of short-term demand response on a climate target, we conduct the same exercise as in the previous paragraph while omitting short-term demand response. The contribution of intermittent renewables to emission reductions falls to 49% (compared

³⁵Note that we define fuel switching as the change in the emission intensity of fossil-fuel-based generation technologies due to switching to fuels with a lower carbon content (either natural gas instead of coal or biomass instead of natural gas) or power plants with a higher conversion efficiency.

³⁶The mechanism is similar to the finding of Böhringer and Rosendahl [9] that an emission reduction target in combination with a quota for renewables promotes the dirtiest technology, meaning that coal stays and gas leaves the market. In our model, we do not have a green quota but, rather, a central planner investing in energy efficiency.

to 53% with short-term demand response). This is compensated for by an increased role for fuel switching (49%). Thus, when defining the contribution of short-term demand response to decarbonization (under a reduction target) as the increased role of renewable energies, it contributes 4%. The mechanism behind is discussed in Subsection 5.1: the non-existence of a cheap flexibility option (short-term demand response) reduces the relative competitiveness of intermittent renewables in comparison to gas power. Without short-term demand response, energy efficiency plays an even smaller role (2%), either due to energy efficiency investments that are beneficial even without a climate target or due to substituting effects with gas power.

Marginal Abatement Costs. The impact of a climate policy in economic terms is captured by the marginal abatement costs, which are carbon prices in our model. As shown in Table 7, the marginal abatement costs increase over time with a tight climate target. This holds for *no demand response* as well as for scenarios with demand response. Responsive demand has its merits in reducing the costs of the technology that abates on the margin. The marginal abatement costs are significantly lower with *full demand response* (51 compared to 73 EUR/tCO₂ for no demand response). However, energy efficiency and short-term demand response are equally important for lowering the marginal abatement costs. We calculate this by using scenarios that either abstract from short-term demand response (*EE investments only*) or from investments in energy efficiency (*short-term response only*). The results are shown in Table 7. Interestingly, the interaction of both mechanisms holds potential for reducing the marginal abatement costs. Gas power serves as base load generator as well as a flexible generator to balance the supply of renewables such as wind and solar. Now, energy efficiency reduces the need for base load gas power in the *EE investments only* case but, still, gas power is needed due to its flexibility. In contrast, with *short-term response only*, gas power is less needed as a flexibility option, but is still required as base load generator. Thus, gas power is still crucial for the marginal abatement technology. This prevents stronger price drops with regard to energy efficiency investments

Table 7: Marginal abatement costs (EUR/tCO₂)

Scenario and climate target	2015	2020	2025	2030	2035	2040	2045	2050
<i>No demand response</i> (80%)	0	0	0	8	14	26	46	73
<i>EE investments only</i> (80%)	0	0	0	2	4	18	34	65
<i>Short-term response only</i> (80%)	0	0	0	3	8	19	36	64
<i>Full demand response</i> (80%)	0	0	0	1	1	12	27	51
<i>No demand response</i> (95%)	0	2	10	17	25	44	76	91
<i>Full demand response</i> (95%)	0	0	0	3	13	25	58	82

or short-term demand response. However, combining both demand side measures has a subadditive effect because the need for gas power drops tremendously.

When looking at a tighter climate target (i.e., a 95% reduction target), the ability of responsive demand to reduce the marginal abatement costs diminishes. While demand response reduced the carbon price in 2050 by 29% under a 80% reduction target, demand response accounts for a reduction of only 10% under a 95% target (see Table 7). Moreover, the marginal abatement costs increase significantly, for three reasons. First, the tighter climate policy is pushing almost all coal and a significant share of gas generation (and capacity) out of the market. More expensive abatement technologies (BECCS, nuclear) must be used. Second, the tighter climate target has a feedback effect on the ability to reduce carbon emissions with intermittent renewables. The ability to shed and shift demand stays constant but less gas capacity reduces the system flexibility and thus the ability to balance the intermittent supply of wind and solar so that the subadditive effect from the less stringent climate target above vanishes. Third, more expensive energy efficiency measures will be used to allow for increased carbon intensity of the remaining generation-mix.

5.3. Robustness of Investments in Energy Efficiency

We identified energy efficiency as one way of reducing carbon emissions, but its final impact on demand (10% reduction) and emission reduction (11%) is small compared to that of intermittent renewables and fuel switching. The assumptions about costs and

performance of the latter two are based on a broad literature (e.g., Schroeder et al. [57]), whereas the assumptions of short-term demand response and energy efficiency are less well established.³⁷ For example, the energy efficiency supply curve is grounded on Steurer [59] (for the industrial sector), whereas reduced costs for other sectors rely on Huntington [35, 34]. Moreover, there is an ongoing debate about the size of the energy efficiency gap (Gillingham and Palmer [25]) and the reasons for it (Fowlie et al. [21], Allcott and Greenstone [3]). Thus, we now relax assumptions made in Section 4 about depreciation rate, initial performance factor, and exogenous technological progress of energy efficiency in order to look into the sensitivity of energy efficiency investments.³⁸

Table 8: Sensitivity regarding depreciation rate

Depreciation rate δ^{ee} (%)	0	1	5	10	15
<i>EE investments until 2030</i> (GW)	44.05	43.97	42.47	41.78	39.56
<i>Electricity demand reduction</i> (%)	11.59	11.58	11.22	11.17	10.64

Sensitivity Regarding Depreciation Rate. Note that the carbon constraint is tightening from 2030 to 2050 (80% target). However, we see that this has no influence on energy efficiency investments. For example, between 2030 and 2050 there are almost no new investments in energy efficiency. We test the robustness of this result by varying the depreciation rate (δ^{ee}). Table 8 shows the results. Note that the electricity demand reduction refers to a situation without any (additional) energy efficiency investments. Increasing or decreasing the default depreciation rate of 10% leads to minor adjustments in investment but does not change the overall picture. Energy efficiency constantly leads to a reduction in electricity demand of around 10%. Also the lack of a build-up between 2030 and 2050 remains.

³⁷Note that assumptions about short-term demand response have already been tested in Table 6.

³⁸We refrain from showing sensitivity of energy efficiency potentials and costs because the effect of varying the performance factor is analogous. For example, doubling the performance factor has the same effect as doubling the energy efficiency potential by class while assuming half costs.

Table 9: Sensitivity regarding performance parameter

Initial performance parameter γ	0.2	0.5	0.7	1.0	1.2	1.5
<i>EE investments until 2030 (GW)</i>	4.71	29.14	33.57	41.8	42.66	47.58
<i>Electricity demand reduction (%)</i>	0	4	6	11	14	19

Sensitivity Regarding Performance Parameter. In Section 1, we discuss the energy efficiency gap and provide an overview of arguments on this topic. One explanation for the existence of the energy efficiency gap is the uncertain impact of one unit of investment (compared to engineering projections) (e.g., Hassett and Metcalf [31]). Within the framework of this paper, this can be captured through the delivered impact of energy efficiency, that is, the performance factor ($\gamma(t)$; see Equation (10)). Values smaller than 1 represent a reduced performance, for which there is empirical evidence (e.g., Allcott and Greenstone [3], Fowlie et al. [21]). Varying this parameter shows the effect of the delivered impact of energy efficiency on its equilibrium level (see Table 9). For low performance values, there is no investment in energy efficiency.³⁹ For $\gamma > 0.15$, the central planner starts investing in energy efficiency; however, the results show that a level of $\gamma \geq 0.35$ is required to achieve any significant investment in energy efficiency. Assuming a better energy efficiency performance and hence going beyond the default value of 1, leads to a minor increase in the optimal energy efficiency level. As a consequence, the actual electricity demand reduction is minor for small values of γ and increases to 19% when reaching an energy efficiency performance of $\gamma = 1.5$. Observe that the robustness of the economic viability of energy efficiency investments is strongly dependent on their delivered impact. The results identify a threshold of 0.35 before there will be any significant investment in energy efficiency, which is close to the calculated value of true savings in [21].

³⁹Note that the variation discussed in this paragraph refers to the value of γ in 2015. We still assume the 5% increase of γ over time due to exogenous technological progress.

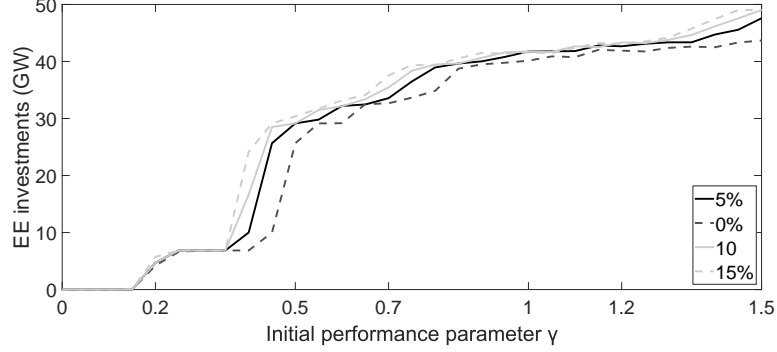


Figure 6: EE investments for varying performance and technological progress in 2030

Sensitivity Regarding Technological Progress. As a default assumption, the performance parameter increases by 5% every five years. The impact of this exogenous technological progress is tested by varying the initial performance (γ in 2015) between 0 and 1.5, and omitting the increase of γ over time or using even higher rates (10% and 15%). The resulting equilibrium levels of energy efficiency for 2030 are shown in Figure 6. Observe that the level of energy efficiency investments depends very little on the assumed exogenous technological progress. However, higher progress rates tend to increase energy efficiency investment. In particular, for values around 0.35 the assumed progress has an influence, but for our default assumption of $\gamma = 1$ there is almost no difference.

6. Conclusions

In this article, we developed a framework for implementing short-term demand response and energy efficiency in a multi-region partial equilibrium power market model. We use this framework to determine the optimal level of energy efficiency investment and its implications for the transition of the European power market under a climate target.

Some of the extant literature emphasizes that the interaction between short-term demand response and energy efficiency might lead to much lower energy demand reductions due to the rebound effect. We calculate a rebound effect from energy efficiency investment

of 9% in 2050, so that electricity demand is finally reduced by only 10%. This outcome is robust with respect to the depreciation rate, performance, and the assumed rate of exogenous technological progress in energy efficiency. Higher rebounds are calculated for more sensitive short-term demand response. Having in mind that the empirical literature indicates that the short-term sensitivity of electricity demand is rather low (e.g., Labandeira et al. [46]), rebounds higher than 30% are extremely unlikely and the future role of the rebound effect, at least in the power sector, seems to be *overplayed*.⁴⁰

We show that the merits of demand response in supply side adjustment also need to be considered. Short-term demand response and energy efficiency enhance the role of wind and solar power, and change the composition of the stock of dispatchable technologies. Energy efficiency reduces demand and thus the need for base load generators so that nuclear capacity diminishes. Short-term demand response offers flexibility in integrating intermittent renewables and hence diminishes the role of gas power; bio power with CCS vanishes completely. Coal power stays active even longer because energy efficiency alleviates the emission reduction constraint for the supply side, which allows for a higher emission intensity across the remaining technologies and hence increases the relative competitiveness of coal power.

Energy efficiency plays a heterogeneous role across regions. This depends on a country's spatial position in the European power market, the quality of its wind resources, and the existing level of energy efficiency. We observe a catch-up effect for regions with energy efficiency below its socially optimal level. For regions at the spatial fringe of the European power market, it is harder to balance intermittent generation via transmission, so that they have to rely more on energy efficiency investments. Wind power serves as a substitute for energy efficiency investments, whereas access to high-quality solar power does not dampen investments in energy efficiency. The constant demand reduction from energy efficiency is

⁴⁰Gillingham et al. [24] use this wording for the estimated rebound effect in the US car sector.

more similar to the seasonal supply pattern of wind and deviates fundamentally from the diurnal solar irradiation pattern.

Investments in energy efficiency contribute 11% toward meeting the 80% emission reduction target of 2050 (compared to 1990). Here, renewables (53%) and fuel switching (36%) play dominant roles. Energy efficiency investments and short-term demand response reduce the carbon price almost equally (reduction of 8 or 9 EUR/tCO₂, respectively). We find subadditive effects when the measures are combined (reduction of 22 EUR/tCO₂), so that the final carbon price is at 51 EUR/tCO₂ in 2050. Energy efficiency reduces the base load and, thus, generation of gas power. In turn, gas power remains crucial to the marginal abatement technology because it offers the necessary flexibility to integrate intermittent renewables. As soon as short-term demand response is also adding to the ability to deal with intermittency, instead of gas power playing this role, the carbon price drop is reinforced.

Under a tighter climate policy (95% emission reduction), carbon prices are less influenced by demand response (drop from 91 to 82 EUR/tCO₂). The subadditive effect vanishes because the tighter climate target not only limits the generation of gas power but also its role as a flexibility option. This makes it necessary to rely on more expensive abatement and flexibility technologies such as bio power with CCS.

This article is a first step toward a consistent integration of the impacts of demand response on the equilibrium outcome of power markets. However, conclusions come with some caveats. First, the integration of demand shifting requires an approximation to keep the model numerically tractable. Second, we are able to derive a first estimate for the energy efficiency supply curve, but its representation is stylistic and its quantification is based on a scant extant research. Third, our framework captures only the effects of a partial equilibrium setting. Fourth, we abstract from storage as another—in addition to gas power, transmission, and short-term demand response—major flexibility option and from investments in the ability to respond to prices in the short-term (e.g., smart meters,

smart devices).

However, these caveats should motivate future work on this topic. For example, the energy efficiency supply curve could be more carefully analyzed so as to elaborate on the role of energy efficiency in decarbonization and avoid exaggerated expectations. Better data quality on potentials and costs of energy efficiency measures—and also with respect to temporal demand profiles and elasticities by sectors and regions—would lead to more precise results. Similar research could be conducted with frameworks that cover economy-wide effects (as done in Abrell and Rausch [1] for transmission infrastructure). Finally, including investments in storage and in short-term demand response would allow analyzing the effect of different flexibility options, in particular, for the integration of intermittent renewables and, in general, for the decarbonization of the power sector.

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Appendix A. Spatial Resolution of the EU-REGEN Model

Table A.10: Composition of model regions

Region	Countries
<i>Britain</i>	United Kingdom, Ireland (UK, IE)
<i>France</i>	France (FR)
<i>Benelux</i>	Belgium, Luxembourg, Netherlands (BE, LU, NL)
<i>Germany-N</i>	Northern Germany (GER)
<i>Germany-S</i>	Southern Germany (GER)
<i>Scandinavia</i>	Denmark, Finland, Norway, Sweden (DK, FI, NO, SE)
<i>Iberia</i>	Portugal, Spain (PT, ES)
<i>Alpine</i>	Austria, Switzerland (AT, CH)
<i>Italy</i>	Italy (IT)
<i>Eastern Europe-NW</i>	Czech Republic, Poland, Slovak Republic (CZ, PL, SK)
<i>Eastern Europe-NE</i>	Estonia, Latvia, Lithuania (EE, LV, LT)
<i>Eastern Europe-SW</i>	Croatia, Hungary, Slovenia (HR, HU, SI)
<i>Eastern Europe-SE</i>	Bulgaria, Greece, Romania (BG, EL, RO)

Appendix B. Electricity Demand Assumptions

Table B.11: Existing energy efficiency level and energy service demand projection

	EE indicator				2015 EE capacity (GW)				Demand (TWh)		
	Ind	Res	Com	Tra	Ind	Res	Com	Tra	1990	2015	2050
<i>AT</i>	0.16	0.32	0.30	0.09	0.32	0.42	0.34	0.03	42	60	84
<i>BE</i>	0.35	0.30	0.06	0.16	1.18	0.45	0.08	0.02	57	87	121
<i>BG</i>	0.56	0.21	0.19	0.12	1.31	0.25	0.11	0.02	37	28	34
<i>CH</i>	0.15	0.25	0.29	0.15	0.18	0.47	0.47	0.04	44	55	97
<i>CZ</i>	0.37	0.21	0.20	0.02	1.12	0.23	0.15	0.01	46	64	71
<i>DE</i>	0.13	0.31	0.16	0.17	3.02	4.12	2.03	0.27	453	553	661
<i>DK</i>	0.25	0.23	0.08	0.12	0.24	0.26	0.10	0.00	28	35	43
<i>EE</i>	0.52	0.23	0.09	0.16	0.16	0.02	0.02	0.01	6	7	12
<i>EL</i>	0.29	0.28	0.07	0.41	0.41	0.29	0.06	0.01	28	60	67
<i>ES</i>	0.22	0.26	0.28	0.14	1.60	0.89	0.92	0.06	126	275	529
<i>FI</i>	0.11	0.09	0.05	0.06	0.41	0.21	0.06	0.00	44	89	84
<i>FR</i>	0.17	0.28	0.11	0.11	2.20	3.13	0.80	0.11	286	459	661
<i>HR</i>	0.29	0.18	0.13	0.11	0.20	0.09	0.04	0.00	13	20	24
<i>HU</i>	0.34	0.13	0.33	0.23	0.54	0.13	0.28	0.03	32	36	60
<i>IE</i>	0.40	0.37	0.32	0.15	0.20	0.18	0.12	0.00	12	28	41
<i>IT</i>	0.23	0.10	0.03	0.13	2.93	0.60	0.16	0.10	215	324	527
<i>LT</i>	0.63	0.16	0.10	0.21	0.39	0.03	0.05	0.01	12	9	37
<i>LU</i>	0.28	0.19	0.44	0.09	0.09	0.01	0.06	0.00	5	8	8
<i>LV</i>	0.47	0.34	0.08	0.29	0.17	0.05	0.06	0.01	11	7	27
<i>NL</i>	0.33	0.37	0.17	0.12	1.21	0.67	0.40	0.02	71	114	170
<i>NO</i>	0.21	0.29	0.14	0.13	1.08	1.00	0.33	0.01	96	150	112
<i>PL</i>	0.52	0.18	0.00	0.25	2.51	0.42	0.00	0.15	96	126	160
<i>PT</i>	0.25	0.37	0.22	0.29	0.31	0.25	0.15	0.01	23	49	75
<i>RO</i>	0.40	0.39	0.00	0.42	0.80	0.27	0.00	0.10	35	46	64
<i>SE</i>	0.17	0.41	0.40	0.13	1.04	1.79	1.18	0.04	120	136	127
<i>SI</i>	0.26	0.23	0.43	0.11	0.18	0.06	0.04	0.00	9	14	14
<i>SK</i>	0.47	0.36	0.52	0.15	0.81	0.15	0.28	0.02	25	29	28
<i>UK</i>	0.31	0.34	0.33	0.14	3.54	3.60	2.82	0.08	274	356	389
<i>Total</i>					28.15	20.04	11.11	1.16	2247	3224	4327

Appendix C. Regional Energy Efficiency Capacities

The 2015 value is the initial level of energy efficiency based on the approximation described in Section 4. The values for the years 2020–2050 show the accumulated investments. Note that the latter values already account for depreciation.

Table C.12: Regional energy efficiency capacities (GW)

Region	Level		Accumulated investments					
	2015	2020	2025	2030	2035	2040	2045	2050
<i>Britain</i>	10.5	0.0	0.5	0.5	0.5	0.5	0.4	0.4
<i>France</i>	6.2	3.6	3.6	3.6	3.6	3.6	3.6	3.4
<i>Benelux</i>	4.2	2.4	3.3	3.3	3.3	3.3	3.3	3.2
<i>Germany-N</i>	5.2	0.6	1.0	2.1	2.1	2.1	2.0	1.8
<i>Germany-S</i>	4.3	0.8	1.2	2.1	2.1	2.1	2.0	1.8
<i>Scandinavia</i>	7.7	0.0	0.0	0.0	0.4	0.4	0.4	0.3
<i>Iberia</i>	4.2	4.3	4.3	4.3	4.3	4.3	4.3	4.2
<i>Alpine</i>	2.3	3.3	4.3	4.3	4.3	4.3	4.3	4.2
<i>Italy</i>	3.8	4.7	4.7	4.7	4.7	4.7	4.7	4.6
<i>Eastern Europe-NW</i>	5.9	3.5	3.5	3.5	3.5	3.5	3.5	3.4
<i>Eastern Europe-NE</i>	1.0	2.2	3.6	4.7	5.6	5.8	5.8	5.3
<i>Eastern Europe-SW</i>	1.6	3.6	4.5	4.5	4.5	4.5	4.5	4.4
<i>Eastern Europe-SE</i>	3.6	3.0	4.1	4.1	5.2	5.2	5.2	5.0

Appendix D. Regional Equilibrium Prices

The change in relative prices in 2015 for some regions is caused solely by adjustment due to short-term demand response and only leads to price changes in France and Eastern Europe-NE.

Table D.13: Change of regional equilibrium prices with responsive demand

	2015	2020	2025	2030	2035	2040	2045	2050
<i>Britain</i>	1.00	0.95	0.91	0.90	0.95	0.90	0.91	0.89
<i>France</i>	0.97	0.85	0.89	1.00	0.94	0.94	0.91	0.93
<i>Benelux</i>	1.00	0.90	0.96	0.96	0.94	0.95	0.92	0.93
<i>Germany-N</i>	1.00	1.00	0.96	0.95	0.94	0.93	0.93	0.92
<i>Germany-S</i>	1.00	1.00	0.95	0.96	0.93	0.93	0.92	0.91
<i>Scandinavia</i>	1.00	0.92	0.91	0.88	0.87	0.93	0.91	0.91
<i>Iberia</i>	1.00	0.98	0.94	0.97	0.94	0.93	0.93	0.92
<i>Alpine</i>	1.00	0.83	0.89	1.00	0.93	0.96	0.93	0.90
<i>Italy</i>	1.00	1.00	0.92	0.97	0.96	0.94	0.93	0.93
<i>Eastern Europe-NW</i>	1.00	1.00	0.93	0.88	0.92	0.92	0.91	0.91
<i>Eastern Europe-NE</i>	0.93	0.76	0.65	0.77	0.83	0.88	0.90	0.90
<i>Eastern Europe-SW</i>	1.00	0.81	1.00	1.00	0.83	0.88	0.94	0.96
<i>Eastern Europe-SE</i>	1.00	0.65	0.67	0.70	0.78	0.85	0.91	0.91

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