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The system value of flexible electricity demand in a 100% renewable European energy system

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ABSTRACT

Flexible and energy-intensive technologies such as power-to-X, smart electric vehicle. charging, and energy storage, including thermal storage, are expected to play a critical role in providing system flexibility in renewable energy systems. However, the role and potential of flexible demands in households and industries remain less certain and have not yet been thoroughly investigated. Based on holistic energy system modelling in EnergyPLAN, this study explores the potential of households, industry and electric vehicles to contribute flexibility and the benefits observed at the system level. It is found that there are tangible benefits observed in terms of improved system efficiency, peak power plant operation, and cost savings. Total primary energy savings up to 4.4% (theoretical upper bound, 100% flexible demand on a 4-week basis) are determined. Within a plausible range, savings of 2.0-2.9% are identified in a renewable energy system, compared with only 0.5-0.7% in a baseline system.

Keywords

Renewable energy systems;
Smart Energy Systems;
Flexibility;
Flexible demand;
Load-shifting;
Energy system modelling;
EnergyPLAN

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1. Introduction

Traditionally, energy system flexibility has been sourced from the supply side and the operation of power plants in fossil-fuel-based systems [1]. In renewable energy systems, flexibility can increasingly be realised from sector integrating technologies, e.g., energy storage [2] or large-scale thermal storages [3], power-to-X (PtX), electric vehicles (EVs) [4], pumped hydroelectricity storage [5], or grid-scale battery storage [6]. As renewable energy penetration increases, so does the need for flexibility in system balancing, and with that, the demand side may need to have a more prominent role than before. Flexible demand, specifically within households and industries, constitutes an underexplored opportunity for enhancing system efficiency and resilience, as found in a systematic review of end-user flexibility technologies by Maask et al. [7], and in a study by Lamanna et al. [8], proposing methods for evaluating the flexibility potential of residential consumers.

Several studies have delved into the technical potential of demand side flexibility across different sectors. Söder et al. [9] reviewed demand side flexibility potentials in seven Northern European countries,

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concluding that significant opportunities exist in industrial processes, household electricity and heating, and tertiary sectors. Within households, flexibility can be achieved through, e.g., smart appliance scheduling [10], thermal storage [11], EV charging [12], or residential heat pumps [13]. Golmohamadi et al. [14] review demand side flexibility potentials within the residential sector specifically, highlighting the flexibility potentials from heat pumps, district heating, EV's, and battery systems. The authors also note remaining challenges to actual implementation, with most barriers relating to consumer awareness and market mechanisms, and grid infrastructure and standardisation. Recent work by Peash and Jamal [15] explore different optimisation strategies for residential energy consumption, including automation and integration with smart grids, to automate much of the load shifting and regulation of, e.g., cooling loads.

Gils [16] distinguishes the theoretical potential for demand response, covering all loads physically suited to shifting or shedding, from the technical potential, which is the subset controllable through existing infrastructure. For Europe, Gils estimated a theoretical average load reduction potential of 93 GW and a load increase potential of 247 GW.

Other studies have focused on the economic incentives and consumer engagement of demand side flexibility. Dynamic pricing schemes, time-of-use tariffs, and real-time market signals have been shown to encourage load shifting, where Johannsen et al. showed how redesigning grid tariffs can incentivise flexible power-to-heat operation in district heating (DH) [17] and in energy communities [18], and Gottwalt et al. simulate household behaviour under variable prices [19]. Sneum and Sandberg [20] likewise analysed the behaviour and incentives for flexible DH under different tax and tariff schemes. McKenna et al. [21] demonstrated that price-induced flexibility can reduce system costs and improve renewable integration, though behavioural factors and consumer engagement remain critical. Ilieva et al. [22] proposed a user engagement strategy to involve and engage users in participating in flexible energy practices. Bender et al. [23] explored consumer acceptance in the residential heating sector, finding that convenience and perceived complexity often limit participation despite financial incentives.

Energy system modelling can provide a holistic perspective on demand side flexibility impacts, and studies using tools such as EnergyPLAN [24], TIMES [25], and Balmorel [26] have quantified benefits under different scenarios. Li and Pye [27] assessed demand side flexibility in residential and transport sectors, showing reductions in curtailment and operational costs when flexibility is integrated. Kirkerud et al. [28] modelled Nordic energy systems in Balmorel, highlighting the importance of combining demand side flexibility with supply-side measures.

However, while some prior studies have examined the technical potential of demand-side flexibility and its role in reducing peak loads or effects of dynamic pricing, most analyses have focused on the impacts on the power sector only. Hence, there is limited research on the system-wide impacts of demand side flexibility in fully renewable energy systems with large shares of variable renewable energy (VRE), also referred to as intermittent renewable energy sources. In such systems, the interplay between demand side flexibility and other flexibility sources such as thermal storage, PtX technologies, and district heating becomes critical. As such, there is a continued need for integrated energy system modelling and the quantification of how demand side flexibility interacts with these technologies at scale to assess its marginal contribution when supply-side flexibility is already substantial.

This study applies the EnergyPLAN model to quantify the system-level impacts of incremental demand side flexibility integration in a renewable energy scenario for Europe. We simulate scenarios for the EU-27+UK, modelling varying flexible electricity demands from three key end-use categories: (i) residential electricity demand, (ii) industrial electricity use, and (iii) EV charging. These three end-use categories were selected because, unlike well-studied supply-side and sector-integrating flexibility options such as district heating, thermal storage, and PtX, the flexibility potential in residential consumption, industrial electricity use, and EV charging remains comparatively underexplored. Flexibility is modelled across three shifting windows: 1-day, 1-week, and 4-weeks, allowing for a systematic evaluation of short-, medium-, and long-term demand shifting. Here, flexibility refers to load shifting, excluding mFRR/aFRR, voltage support and load shedding.

The novelty of this study is threefold. First, it quantifies the marginal system value of load shifting in electricity demands and EV charging when included on top of extensive sector-coupling flexibility. Second, it compares this value between a Baseline 2050 (current policies) and a 100% renewable smart energy system scenario for the EU27+UK. Third, it maps how the flexibility related benefits saturate as implementation increases for different shifting windows. The results can

thus inform both technical system design and policy frameworks aimed at enabling and incentivising flexible demand participation.

2. Methods

This section outlines the methodological framework applied to assess the system-level impacts of large-scale demand-side flexibility in a future European energy system. The analysis combines scenario development, detailed representation of flexible electricity consumption, and hourly energy system simulation to evaluate how varying flexibility levels influence overall system efficiency, renewable energy integration, and operational costs.

2.1 Energy system modelling tool

This study applies EnergyPLAN [24], a simulation tool designed for analysing the operation of integrated national or regional energy systems, covering all major energy sectors such as electricity, heating, cooling, industry, transport, and gas infrastructures. The model simulates one full year of system operation with an hourly temporal resolution, an essential characteristic for studying high-renewable energy systems and assessing the integration of VRE sources and demand-side flexibility. The hourly resolution enables detailed representation of VRE fluctuations, storage dynamics, sector-coupling technologies, and, crucially for this study, the temporal shifting of flexible electricity demands.

EnergyPLAN is a deterministic simulation tool that simulate the hourly operation of the energy system using predefined operation strategies. Investment decisions, for example, the installed capacities of generation technologies, are defined by the user rather than the tool. This approach allows for rapid evaluation of complex system configurations, making it particularly suited for scenario-based analyses, sensitivity testing, and cross-sectoral assessments.

An overview of the technology representation, energy flows, and sectoral couplings implemented in EnergyPLAN is shown in Figure 1.

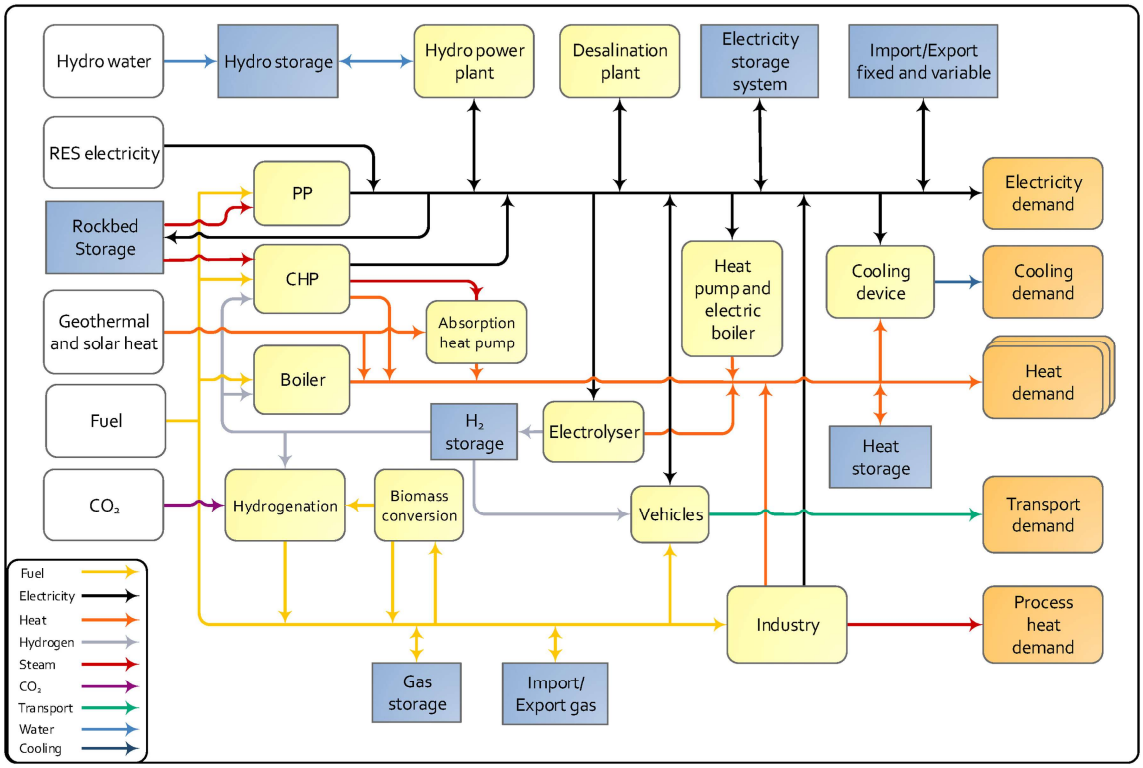


Figure 1: Overall technology and resource model for EnergyPLAN [24].

As illustrated in Figure 1, a number of data inputs regarding energy demands, energy resources, and conversion and storage technologies are needed to simulate an energy system in EnergyPLAN. All primary energy demand sectors are represented, including electricity, heating, cooling, transport and industrial energy demands. A wide range of energy supply technologies are included, ranging from renewable

energy generation technologies such as wind turbines, photovoltaics and hydropower, to dispatchable technologies such as power plants, combined heat and power plants, and heat only boilers. A main strength of the model is the vast opportunities for detailed modelling of sector-coupling, including heat pumps, electrolysers, thermal and electrical storage, and gasification processes. Different system operation strategies can be defined, including dispatch and curtailment priorities, import-export rules and capacity limits such as interconnector limitations. Finally, the economic parameters such as fuel prices, investment costs, and O&M costs are included, enabling a comparison of total system costs across different energy system configurations.

The model outputs include both annual and hourly energy balances, thus capturing system-wide production, consumption, storage operation, electricity import and export, and fuel use [24]. To evaluate system performance, previous studies have employed indicators such as primary energy supply, CO_2 emissions, system costs, curtailment or excess electricity generation, and VRE integration levels [29]. For studies focusing on demand-side flexibility, EnergyPLAN also provides detailed hourly results on flexible demand utilisation across different time frames for demand shifting, as will be further outlined in the following section.

EnergyPLAN has been validated and applied in numerous studies at various scales, from cities [30], regions [31], countries [32] and even to very large-scale or multi-country analyses such as Heat Roadmap Europe [33] or the CEMAC region [34], demonstrating its robustness for long-term energy planning in high-renewable contexts.

2.2 Modelled energy system scenarios

This analysis models and compares two future energy system scenarios for the EU-27+UK. The European Commission (EC)'s "Baseline 2050" scenario, developed as part of the PRIMES "A Clean Planet for All" programme [35], and the "Smart Energy Europe 2050" (SEE) scenario first presented by Thellufsen et al. [36] and developed based on smart energy system principles.

The Baseline 2050 scenario was developed to reflect the EU decarbonization trajectory towards 2050 based on agreed policies and policies proposed by the EC. The Baseline 2050 scenario thus reflects macro-economic projections, fuel price projections, and technology assumptions. Hence, this scenario represents a relatively modest renewable energy expansion and integration effort, resulting to some extent in a transition scenario rather than a fully renewable and integrated energy system scenario.

The Smart Energy Europe 2050 scenario, representing a 100% renewable energy system, is based on smart energy system principles which emphasise energy efficiency first, the modernisation of heating systems including expansion of district heating, and the electrification of transport, among other measures.

In Table 1 a comparison of the main assumptions and model parameters for the two reference scenarios can be seen.

Table 1: Main assumptions for the Baseline 2050 and Smart Energy Europe 2050 scenarios.

Parameter	Baseline 2050	Smart Energy Europe 2050
Conventional electricity demand (PWh/yr)	3.50	3.55
EV electricity demand (PWh/yr)	0.52	0.97
Onshore / offshore wind / PV (GW)	441 / 143 / 441	1,600 / 300 / 1,050
Dammed hydro / nuclear (GW)	154 / 87	154 / 0
Condensing PP (GW, efficiency) / CHP (GWe)	585 (55%) / 86	565 (60%) / 144
DH demand (PWh/yr) / large heat pumps (GWe) / thermal storage (TWh)	0.43 / 0.45 / 0	1.27 / 36 / 1.2
Electrolysers (GWe) / H_2 storage (TWh)	18 / 0.14 TWh	502 / 21.1
Pumped hydro + other electricity storage (GW)	59 + 139	59 + 139
RES share of PES / of electricity production	41.9% / 71.8%	100% / 100.4%
Electricity production, reference (PWh)	4.56	8.30
Interest rate	3%	3%
Fuel prices coal / fuel oil / diesel oil / petrol / Natural gas / biomass / nuclear/uranium (EUR/GJ)	2.9 / 10.4 / 15 / 14.9 / 6.6 / 6.6 / 1.75	Same
Electricity import/export capacity (GW)	0 (closed system)	0 (closed system)

Updates to costs have been implemented for the renewable electricity generators, methanol synthesis process, carbon capture, electrolysers and hydrogen storage compared to the original SEE scenario presented in Thellufsen et al. [36]. An overview of these changes can be seen in Table A1.

For this study, the EU27+UK is modelled as a single node ("copper plate"). Internal transmission constraints are not modelled and electricity exchange with neighbouring regions is not allowed.

All scenarios, including the reference scenarios, include sector-coupling flexibility, such as heat pumps, electric boilers, and thermal storage in district heating, electrolysers with hydrogen storage, and electricity storage. However, the 0% references lack flexibility in the conventional electricity demand and EV charging, which are the demands varied in this study. Consequently, the demand side flexibility modelled is in addition to the other and mostly more established forms of flexibility.

2.3 Flexibility scenarios

In this modelling application, EnergyPLAN enables modelling of 1-day, 1-week, and 4-week flexible electricity demands, i.e., demands that are flexible within the specified time frame and thus available for demand shifting based on what is preferable from a system perspective. Within the time window specified by the user, EnergyPLAN seeks to reduce the fuel consumption of the system, e.g., by shifting electricity consumption to periods with high VRE generation to avoid periods of low VRE generation and thus reduce the operation of power plants.

The scenario matrix below in Table 2 provides an overview of the modelled scenarios, including a reference scenario without any demand flexibility in the residential and industrial sectors. The scenarios explore varying levels of flexibility in electricity demand shifting across three different timeframes: 1 day, 1 week, and 4 weeks. For each timeframe, the flexibility potential is gradually increased from 0% (no flexibility) up to 100% (full flexibility) in 10% increments, allowing for a systematic assessment of the impact of demand-side flexibility on the energy system under different temporal resolutions. All scenarios are modelled both for the Smart Energy Europe 2050 and Baseline 2050 scenarios, and both are modelled with and without including the EV charging demand as flexible demand. This results in a total of 124 scenario simulations.

The scenarios serve to explore the upper limits of system benefits from demand side flexibility from the residential, industrial, and EV electricity demands. In reality, substantial demand shifting within a week or 4-week period is likely only possible for highly selected processes, and not across entire sectors, as explored here. However, the intention of this analysis is to evaluate the theoretical upper limits of system benefits, rather than the practically feasible degree of implementation.

Table 2: Modelled flexibility scenarios, applied to both the Baseline 2050 and Smart Energy Europe 2050 scenarios.

Electricity demands	1-day flexibility	1-week flexibility	4-week flexibility
	0%	0%	0%
- Residential	10%	10%	10%
electricity	20%	20%	20%
demand	30%	30%	30%
- Industrial	40%	40%	40%
electricity	50%	50%	50%
demand	60%	60%	60%
- EV	70%	70%	70%
electricity	80%	80%	80%
demand	90%	90%	90%
	100%	100%	100%

Results from the analysis will first and foremost compare fuel consumption of the energy system in the different scenarios, as an indicator of how system efficiency is influenced by increasing demand side flexibility. Total fuel consumption refers to the total primary energy demand reported in EnergyPLAN, including coal, oil, natural gas, biomass, waste and renewables. This is relevant for further discussions on the relevance and extent to which implementation of such measures should be prioritised in future energy systems.

Secondly, results on the annual system costs are analysed for a comparison of potential cost savings from such demand side flexibility. This includes annual investment costs, fuel costs, and operation and maintenance costs.

Finally, critical excess electricity production (CEEP) is evaluated as an indicator for how increased flexibility can contribute to reducing VRE curtailment. CEEP corresponds to electricity that would be produced by the installed electricity generation capacities, but cannot be used, stored, or exported in the given hour, and as such, in a real system would be curtailed. Altogether, this assessment contributes to the ongoing discussions on the technical and economic feasibility (from a holistic energy system perspective) of establishing measures and

market principles incentivising exploitation of demand side flexibility.

2.4 Representation of flexible demand in EnergyPLAN

In EnergyPLAN, electricity demand consists of a fixed demand following an hourly profile and up to three flexible demands that can be shifted within one day, one week, or four weeks. The fixed demand follows an hourly EU-27+UK electricity demand profile, and EV charging in the reference follows a fixed charging profile. In each flexibility scenario, a share of 0-100% of the conventional demand (and, in the EV variants, the same share 0-100% of EV demand) is moved to one of the flexible demands, so that total annual demand is identical across scenarios and all variants of a system share the same reference. The annual flexible demand is divided into equal energy budgets per period (366 days, 52 weeks, or 13 four-week periods), and each budget must be consumed within its period, so energy is conserved within each window. Within each period, the flexible demand is allocated where it most reduces excess electricity production and power plant operation, which can be subject to a maximum hourly capacity, although for this study, this was not imposed. As an example, 50% 1-week flexibility, translates to 50% of the annual conventional and EV demand is converted to flexible demand. This is then allocated into weekly budgets, where the model can distribute the demand within these weekly windows.

The simulation is deterministic, implying perfect foresight of demand and VRE production within each window. For 1-day flexibility, this correlates to the day ahead market, but for 1-week and 4-week windows, accurate forecasts generally do not exist.

A theoretical average load reduction potential of 93 GW estimated by Gils [16] corresponds roughly to the 20% flexibility scenarios, and the associated shifting times also do not exceed 24 hours. Likewise, the study by Söder et al. [9] estimated the flexibility potential in the Nordic countries of Sweden, Denmark, Norway and Finland, finding flexibility estimates of 15-30 % of the peak load. However, this only included households, industries, and the service sectors, so would likely be higher if also EVs were considered. Hence, a plausible range of the flexibility potential is likely within 10-30% of the demand within 1 day. Flexibility levels above approximately 30%, and the 1-week and 4-week scenarios, should therefore be considered as a sensitivity analysis on upper boundaries of system benefits.

3. Results and Discussion

The following sections present the main findings and resulting system impacts in terms of system efficiency and effects on the utilisation of peak power plants, economic impacts and integration of VRE in scenarios with increasing amounts of demand side flexibility.

3.1 System efficiency and peak power generation

The simulations of SEE and Baseline systems show potential for reducing total fuel consumption and thus increasing system efficiency in the European energy system, as illustrated in Figure 2. Here, the total fuel savings compared to the reference scenario with 0% flexibility in the residential, industrial, and EV electricity demands can be seen. These fuel savings mainly occur as a result of reduced power plant operation, particularly natural gas-fired power plants and CHP plants in SEE, and natural gas and biomass in Baseline, due to increased utilisation of VRE and reduced curtailment. This saves fuel that would otherwise have been used for the operation of the power plants and increases the utilisation of the system's VRE technologies. The total fuel savings achieved amount to upwards of 490 TWh (4.4% of primary energy demand) in the SEE system and 200 TWh (1.6% of total energy demand) in the Baseline system.

Within the plausible range of the potential (10-30%, 1 day), as outlined in Section 2.4, the savings amount to 220-330 TWh (2.0-2.9%) in the SEE system, and 60-90 TWh (0.5-0.7%) in the Baseline system.

The potential for achieving fuel savings depends on several factors and energy system characteristics. Perhaps not surprisingly, a prerequisite is a substantial flexible electricity demand, i.e., demand that can be shifted in time. Including the EV electricity demand only improves fuel savings only at low shares of flexible demand, for example, increasing fuel savings from 190 TWh to 220 TWh in the 10% SEE system. In scenarios with higher shares of flexible demand, the system is saturated and the additional flexibility from the EVs does not improve the utilisation. The results demonstrate that while it is naturally preferable to have more flexible demand, most of the potential is realised with 30% of demand being flexible.

There is also little difference in whether demand is shifted 1 day or 1 week. In the 30% flexible demand scenario for SEE with EVs, the fuel savings amount to 330 TWh for flexible demand within one day, and 350 TWh for flexible demand within one week. Having demand that is flexible over a 4-week period increases

the savings to 430 TWh. 1-day flexibility thus achieves about 75% of the maximum savings (4-weeks) in SEE, compared to 50% in Baseline 2050.

The potential for fuel savings depends on the energy system having substantial installed VRE capacities. A system dominated by power plants that are easily regulated up and down will have limited benefits from flexibility on the demand side, while on the contrary, a system with large VRE capacities, such as wind and solar, will have significant benefits from any source of flexibility, as this will allow for improved utilisation of the variable resources. This is also demonstrated in these results, where the SEE system has large VRE capacities installed, while the Baseline system relies much less on renewable energy and more so on traditional power plants and nuclear energy.

Finally, the realised fuel savings depend on the extent to which other means of flexibility, either on the supply or demand side, exist in the energy system. This could be large power-to-heat capacities such as electric boilers and heat pumps coupled with thermal storage in district heating, or electrolysis capacity, which are both present on a large scale in the SEE system, thus limiting the effect of further flexibility measures, as implemented in this analysis on the demand side in the residential, industrial, and EV sectors.

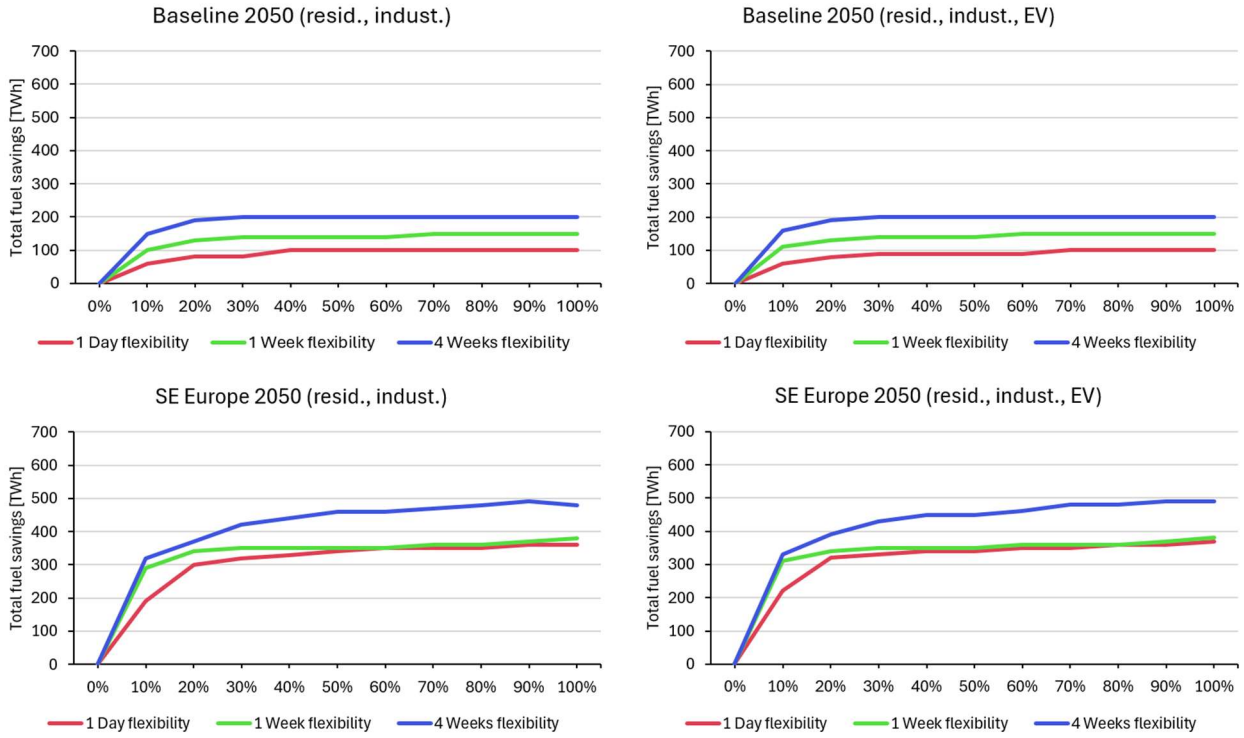


Figure 2: Total fuel savings in "Smart Energy Europe 2050" and "Baseline 2050" scenarios with increasing flexible demand.

Another effect of the increased demand side flexibility can be observed for the peak power plant operation, as seen in Figure 3. The peak power plant capacity constitutes the maximum hourly electricity generation from condensing peak power plants, where a lower amount indicates a more flexible system. For the Baseline system, it can be seen that increasing the amount of flexibility reduces the necessary peak power plant capacity but cannot remove the peak power plant operation. Similarly to the results on primary energy consumption, the effect is most pronounced for the first additions of flexibility (10-30%), and then gradually tapers off. In the SEE system, a similar effect of reducing peak power plant operation is observed, and the peak power plant capacity activated is lower. For the 1-week and 4-week flexibility scenarios, activation of the peak power plants can be entirely avoided from 40-60% flexible demand. This indicates a system with more flexible producers (and consumers), able to exploit this increased flexibility and thereby shift demands to periods of excess VRE production.

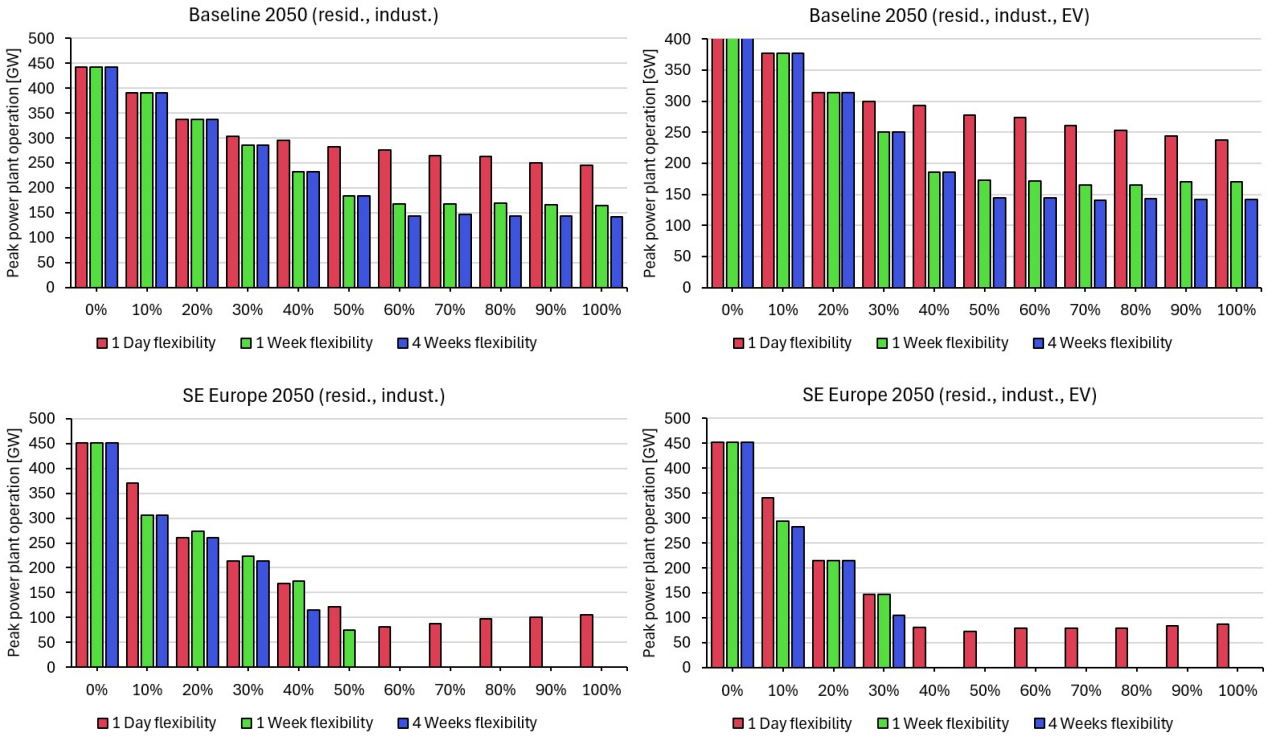


Figure 3: Peak power plant operation in "Smart Energy Europe 2050" and "Baseline 2050" scenarios with increasing flexible demand.

3.2 Economic impacts and cost savings

Figure 4 illustrates the total cost savings achieved in the energy system through the implementation of flexible electricity demands. The most substantial savings are observed in the SEE system with a 4-week flexibility window, which aligns with the scenario's highest fuel savings, fuel costs being the primary driver of total system cost reductions. In this scenario, total system costs amount to 1976 BEUR, corresponding to cost savings of 16 BEUR (0.8% of the total system cost). In the Baseline system with EVs, total system costs amount to 2019 BEUR, corresponding to savings of 8 BEUR (0.4% of the total system cost).

For the plausible range of 10-30% flexibility within a one-day shifting window, the savings range from 7-11 BEUR (0.4-0.6% in the SEE with EV system), and 3 BEUR (0.1%) in the Baseline with EV system.

It is important to note that the supply side of the energy system remains unchanged across all simulations; the installed capacities of power plants and VRE technologies are held constant. However, increased system flexibility, particularly on the demand side, could enable adjustments to the supply side, as demonstrated by the results on the peak power plant operation. The increased demand side flexibility reduced the activated peak power plant capacity, and thus, arguably, the installed capacity could be decreased, leading to further cost savings.

However, such adjustments should be approached with caution, as reducing dispatchable generation capacity may compromise system security and resilience, especially in the face of unforeseen events, emergencies, or extreme weather conditions.

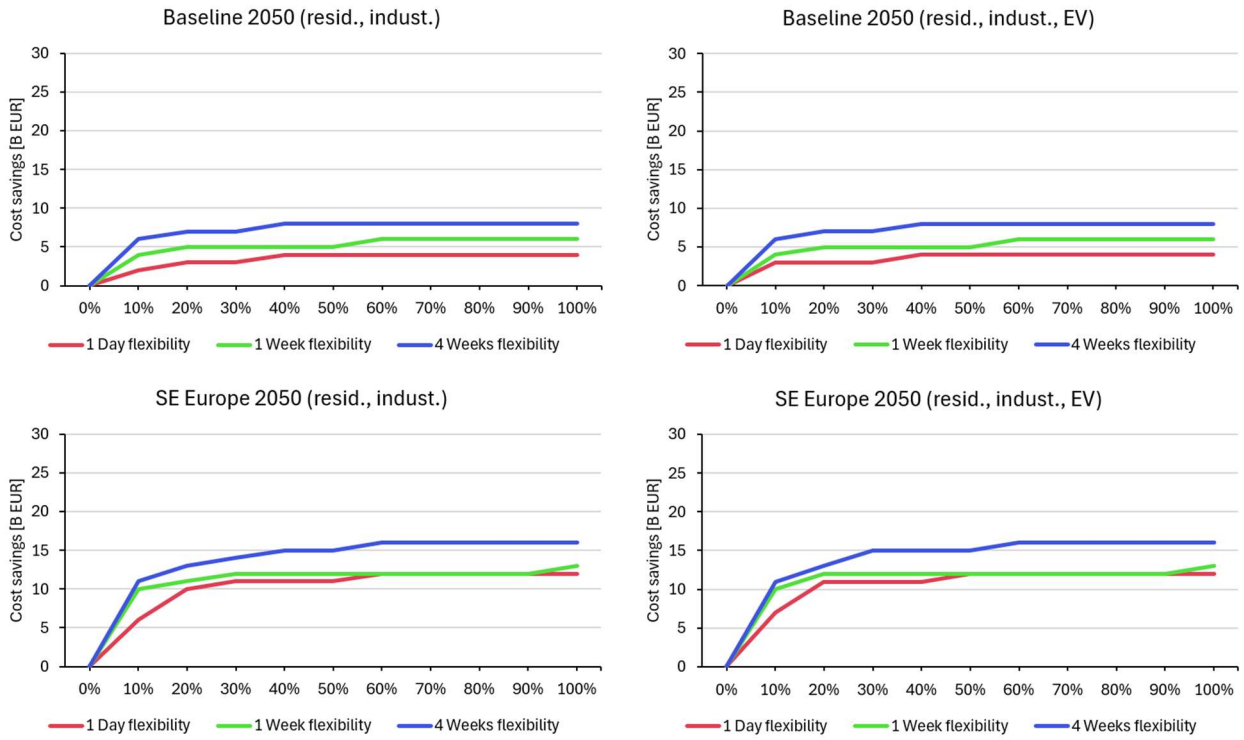


Figure 4: Total cost savings in Smart Energy Europe 2050 and Baseline 2050 systems with increasing flexible demand.

To relate the operational savings to the cost of enabling flexibility, we express them as the annual cost saving per MWh of annual electricity demand made flexible (Table 3). For the first 10% of flexible demand, the value is 15.5–31 EUR/MWh in the SEE system and 6–17 EUR/MWh in the Baseline system, depending on the shifting window. Between 10% and 30%, the marginal value falls to 2–7 EUR/MWh and 0–1.4 EUR/MWh respectively, and beyond 30% it is below 1 EUR/MWh in all cases. These values indicate an upper limit on the annualised cost of enabling flexibility (metering, control, communication, aggregation, process adaptation) that could be recovered through operational system savings alone.

Table 3: Marginal energy system savings in modelled scenarios per MWh of annual electricity demand made flexible.

Case	Marginal 0–10% [EUR/MWh]	Marginal 10–30% [EUR/MWh]	Marginal 30-100% [EUR/MWh]
SEE+EV 1 day	15.5	4.4	0.3
SEE+EV 1 week	22.2	2.2	0.3
SEE+EV 4 weeks	24.4	4.4	0.3
SEE 1 day	16.9	7.1	0.4
SEE 1 week	28.2	2.8	0.4
SEE 4 weeks	31.0	4.2	0.8
Baseline+EV 1 day	7.5	0.0	0.4
Baseline+EV 1 week	10.0	1.2	0.4
Baseline+EV 4 weeks	14.9	1.2	0.4
Baseline 1 day	5.7	1.4	0.4
Baseline 1 week	11.4	1.4	0.4
Baseline 4 weeks	17.2	1.4	0.4

As mentioned, the cost results presented here only reflect operational savings driven by improved system efficiency, specifically reductions in primary energy demand. Several other economic aspects fall outside the scope of this analysis but may significantly influence the overall cost–benefit balance of large-scale demand-side flexibility. On the savings side, increased flexibility could allow for downsizing of peak production units, reserve capacities, or even certain forms of energy storage. Similarly, more flexible demand profiles could reduce the need for grid reinforcements associated with high peak electricity loads.

On the other hand, realising flexibility in practice may introduce additional system and societal costs that are not captured in the modelled scenarios, including costs for grid reinforcements. For households and industries, enabling large-scale flexibility may require investments in smart appliances or other forms of advanced control systems, and for industries, increased production capacity, to allow temporal shifting of industrial processes. For EVs, higher charging flexibility may require more widespread installation of smart chargers and increased capacity of chargers.

3.3 Integration of variable renewable energy and curtailment reduction

In EnergyPLAN, CEEP refers to electricity that would be generated within the system but cannot be used, stored or exported. This typically arises from surplus production by VRE sources such as wind and solar. In a real-world energy system, such excess electricity would generally be curtailed to maintain grid stability and prevent frequency imbalances, and thus the energy is "wasted". Therefore, CEEP serves as an indicator of a system's ability to effectively integrate VRE, and reductions in CEEP generation thereby indicate improvements to the efficiency of the system.

High levels of CEEP suggest either limited system flexibility or an overcapacity of VRE relative to the system's ability to absorb and distribute it. Figure 5 presents the CEEP levels across the simulated energy system scenarios in percentage of the total electricity production. Unsurprisingly, the Baseline system produces very little CEEP due to a lower total electricity production, and particularly lower installed VRE capacity. Further reductions in CEEP as a result of increased demand side flexibility are therefore minor, and CEEP can even be entirely avoided in the scenarios with 4-week flexibility.

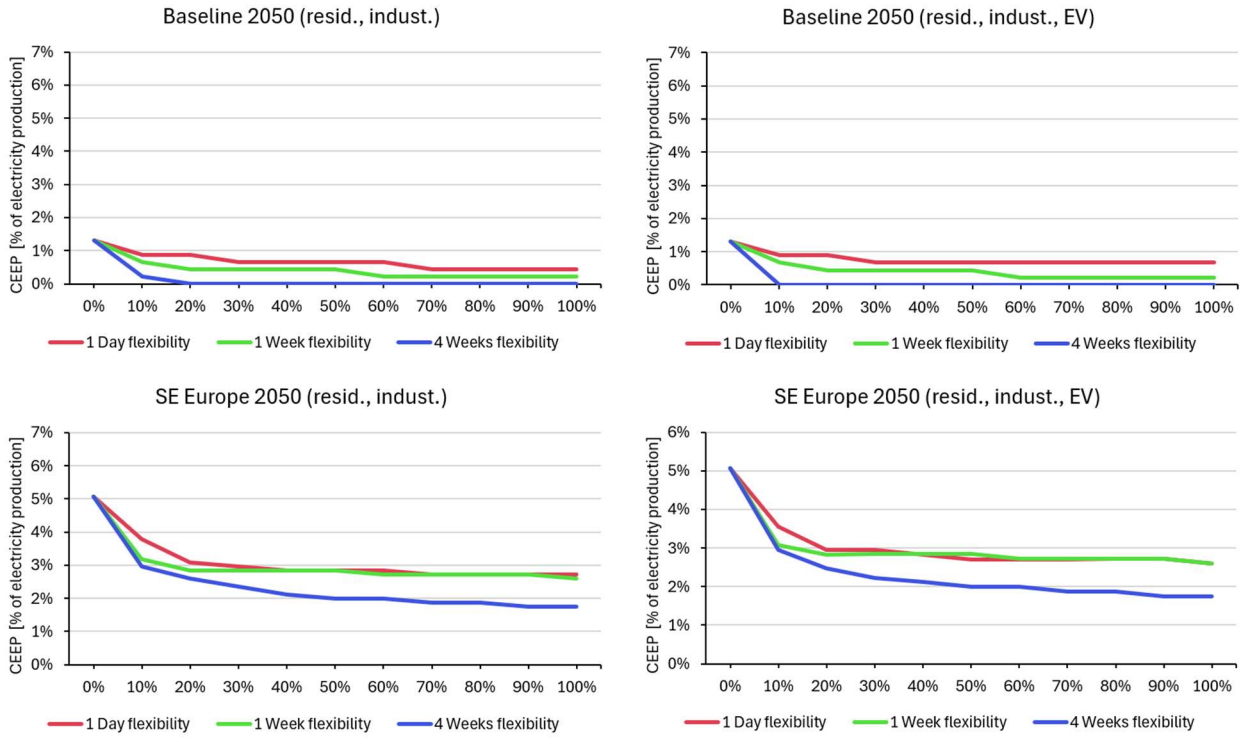


Figure 5: Critical excess electricity production (CEEP) as a percentage of the total electricity production in Smart Energy Europe 2050 and Baseline 2050 scenarios with increasing flexible demand.

On the contrary, the Smart Energy Europe 2050 scenario has a much larger installed VRE capacity and a larger electricity production, resulting in a CEEP generation of 5.1% of the total electricity production, which is reduced to 2.6-2.7% (1-day and 1-week) and to 1.7% (4-week). In the SEE system CEEP cannot be entirely avoided solely from increasing flexible demand, a result of the large VRE capacities installed where surplus during high wind and PV periods exceed the full flexible demand window.

Across the different timeframes, CEEP reductions are achieved, with most benefits being obtained from the first 10-30% of flexibility, while further additions only result in minor to no further reductions. Secondly, while having the flexibility to distribute the electricity demand across an entire 4-week period is naturally most beneficial, as seen in Figure 5, there are no large differences between the three timeframes, indicating that the flexibility to shift demand even just one day is valuable from a system operation and efficiency perspective. These results also underline the mutually beneficial relationship between system flexibility and VRE generation, where there are little to no benefits from flexibility in a traditional, combustion-based energy system, while in renewable energy systems, flexibility further enables VRE integration and improves system efficiency.

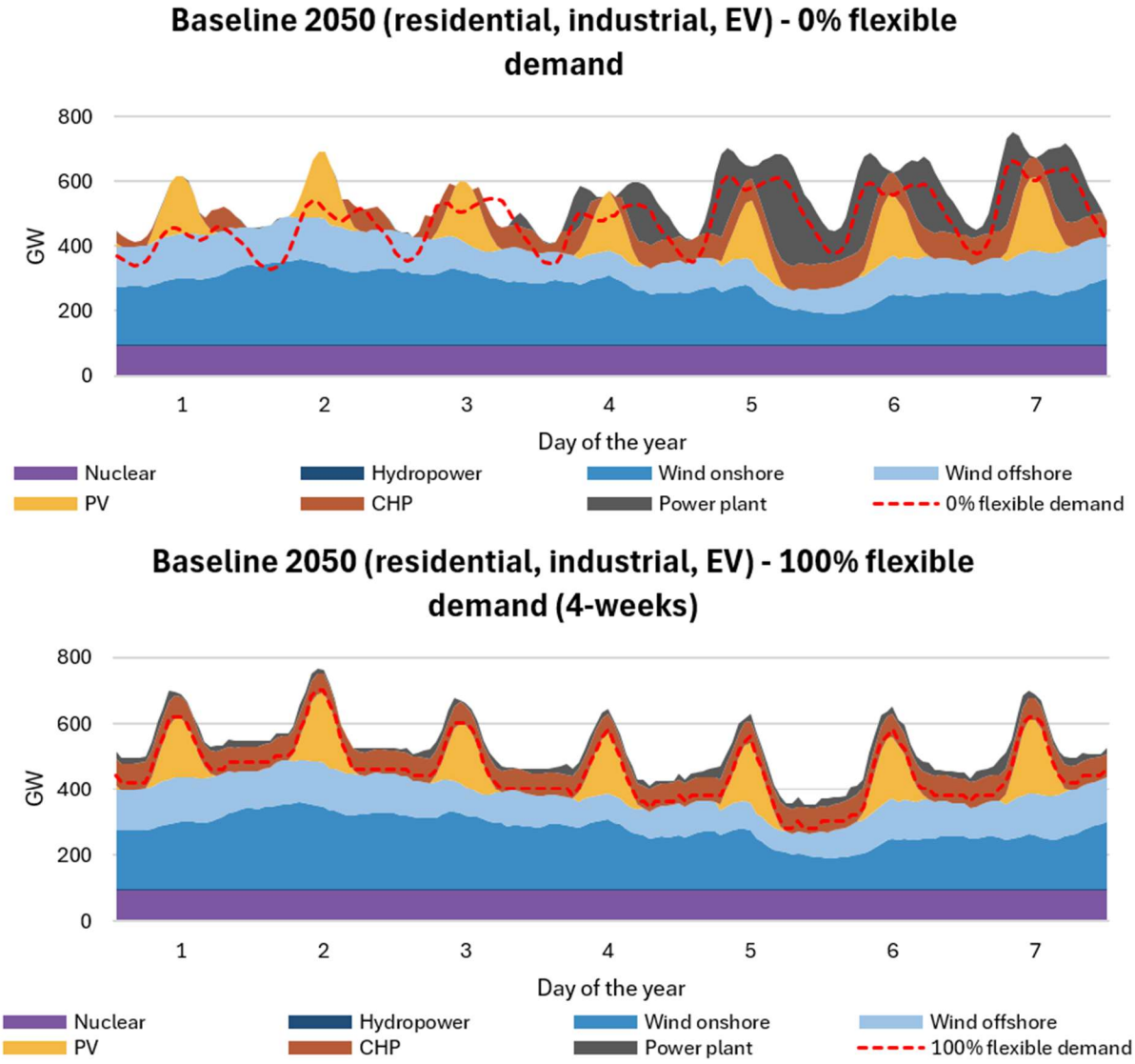


Figure 6: Temporal distribution of electricity demand and production for the first week of January in the "Baseline 2050" scenario with 0% and 100% 4-week flexible electricity demand.

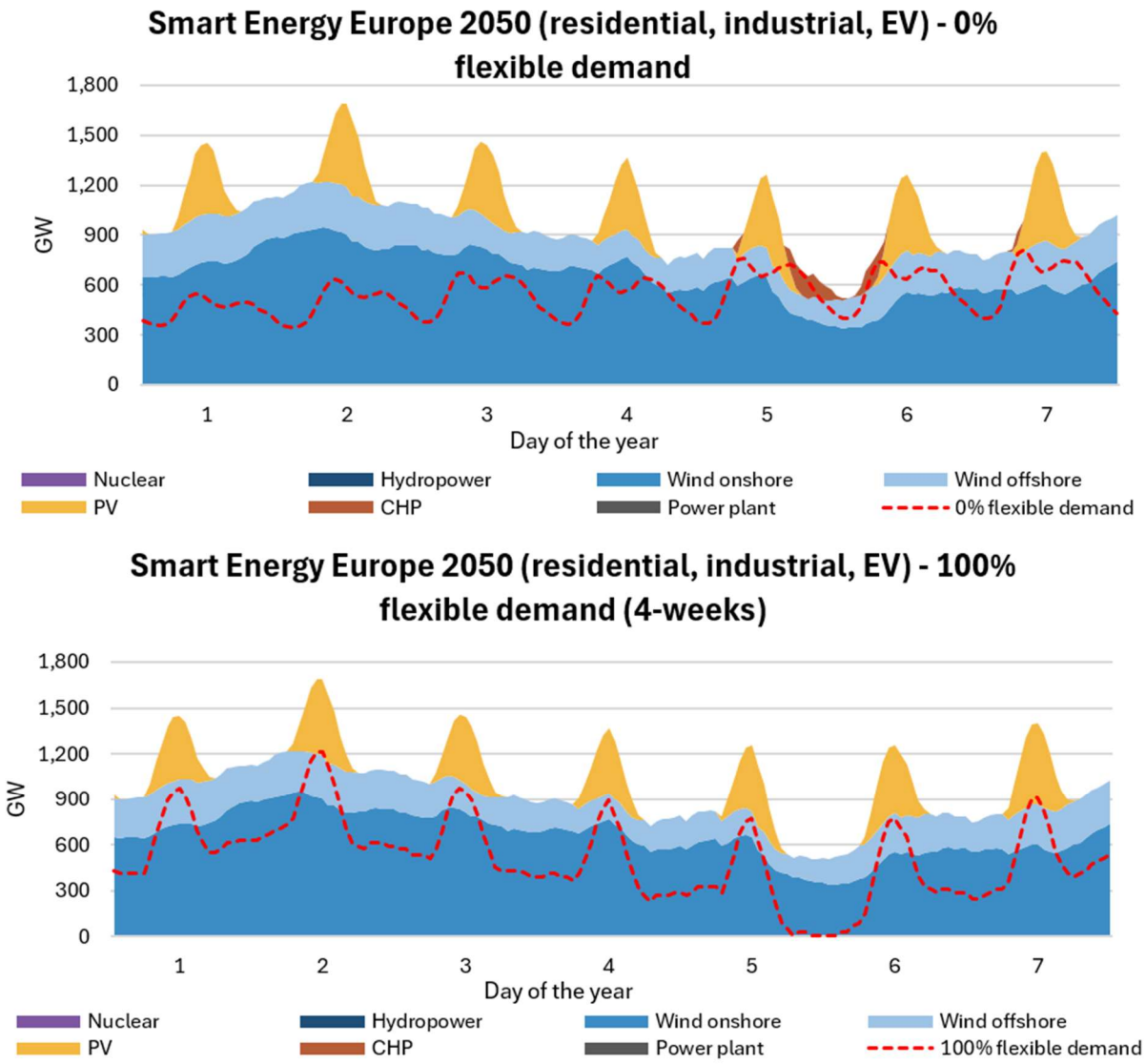


Figure 7: Temporal distribution of electricity demand and production for the first week of January in the "Smart Energy Europe 2050" scenario with 0% and 100% 4-week flexible electricity demand.

Figure 6 and Figure 7 depict the hourly operation of the simulated energy systems during the first week of January for both the SEE and Baseline systems. Each system is shown under two conditions: with 0% flexible demand and with 100% flexible demand over a 4-week horizon, considering residential, industrial, and EV electricity demands.

In both scenarios, EnergyPLAN shifts electricity consumption to align with periods of high VRE generation, primarily coinciding with periods of PV production. However, due to the significantly larger VRE capacity in the "Smart Energy Europe 2050" scenario, this system is better equipped to take advantage of flexible demand. Conversely, during periods of low VRE output, electricity consumption is minimised wherever possible to reduce reliance on dispatchable generation.

In the example week the "Baseline 2050" scenario continues to rely substantially on power plants, CHP units, and nuclear energy, while the "Smart Energy Europe 2050" scenario avoids their use entirely during the same period in the scenario with 100% flexibility. This outcome highlights the combined impact of high VRE penetration and flexible demand (alongside other supply side flexibility measures) in enhancing system efficiency and reducing reliance on conventional generation.

Technically, the results have shown how demand

side flexibility can improve energy efficiency by enhancing the integration of VRE and reducing reliance on dispatchable generation. Economically, this additional flexibility contributes to modest reductions in total system costs (at most 0.8%), primarily through fuel savings and more efficient utilisation of existing production capacity.

When viewed in the context of the large-scale energy system modelled, covering the EU-27 plus the UK, the overall impact of demand-side flexibility is relatively modest, with fuel savings of approximately 2.0-2.9% of primary energy demand in the plausible range (10-30%, 1-day) and up to 4.4% in the theoretical upper-bound case. This underscores the importance of complementing demand-side measures with other forms of system flexibility.

Large-scale energy storage, district heating systems, and PtX technologies such as electrolysis play equally, if not more, critical roles. These technologies offer substantial flexible energy consumption and storage capacities, which are essential for balancing supply and demand in systems with high shares of VRE.

4. Conclusion

This study explored the role of flexible demands in improving the performance of future renewable energy systems, focusing on additional flexibility potentials within households, industry, and electric vehicle charging.

The results show that demand-side flexibility can contribute to reduced primary energy demand, modest cost savings, reduced peak operation of power plants, and increased integration of VRE in renewable energy systems. Flexibility was modelled for 1-day, 1-week, and 4-week periods, and while longer time durations do increase the system benefits, about 75% (SEE) and 50% (Baseline) of the potential for cost and primary energy reductions is realised already with the ability to shift demand within one day. The most substantial benefits are obtained from the initial additional flexibility, and the effects gradually taper off. Additional benefits in terms of energy and cost savings beyond 30% of the electricity demand are very limited or non-existent. This coincides with the plausible range of flexible demand, where 67-69% (SEE) and 38-45% (Baseline) of the primary energy and cost savings are realised within one day and at 30% flexible demand.

The impact of demand side flexibility is different for traditional and renewable energy systems; traditional energy systems generally lack the large amounts of variable energy generation capacity which, on the other hand, dominates renewable energy systems. This reduces the value of additional flexibility obtained from households and industry in traditional energy systems compared to renewable energy systems, where in the latter, demands can effectively be shifted to periods of excess VRE production. Despite this, even in scenarios with large amounts of VRE generation and sector integration, the energy system effects remain limited due to the prevalence of other technologies and measures for significant flexibility contributions. For the first 10% of flexible demand, the value is 15.5–31 EUR/MWh made flexible in the Smart Energy Europe scenario and 6–17 EUR/MWh in the Baseline scenario, but between 10% and 30% the marginal value falls to 0–7 EUR/MWh, and beyond 30% it is below 1 EUR/MWh in all cases.

Substantial system-wide benefits are achieved through other large flexibility measures such as thermal storages in district heating and PtX technologies. These technologies offer greater capacity for energy shifting and storage and are essential for balancing supply and demand in systems with high shares of variable renewable energy. Therefore, while demand side flexibility should remain a valuable component of a broader flexibility strategy, its implementation should be pursued in combination with sector integrating measures, not as a substitute, in future fully renewable energy systems.

The findings are subject to a few limitations. The system savings determined do not include costs for enabling the flexibility, such as costs for grid reinforcements due to new load peaks caused by electricity demand shifting. Furthermore, the modelled scenarios did not consider internal transmission constraints, which could be a limiting factor to the realisation of demand shifting.

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Appendix

The table below presents the technical and cost specifications of the reference scenario adopted in this study. Compared to the SEE scenario developed in [36], the following technologies have been updated:

- Renewable electricity generators, including onshore wind, offshore wind, PV
- Renewable methanol synthesis process, including both biomass hydrogenation and CO_2 hydrogenation
- Carbon capture
- Green hydrogen production through electrolysers
- Hydrogen storage

Table A1: Cost inputs for updated technologies in the reference scenario (updated SEE scenario).

Technologies	**Unit**	**Investment [GEUR/unit]**	**Lifetime [year]**	**Fixed O&M [% of CAPEX]**	**Note**
Onshore wind	GWe	1.11	30	1.92	Based on [37].
Offshore wind	GWe	1.68	30	2.89	Based on [37].
Photovoltaic	GWe	0.34	40	2.4	Based on [37].
Carbon capture	$GtCO_2$	233	27.5	3.9	Based on [38]. Assumes 50% point sources (post-combustion) and 50% DAC (solid adsorption).
Methanol synthesis: biomass hydrogenation	GW	2.26	20	7	Based on [39].
Methanol synthesis: CO_2 hydrogenation	GW	0.955	30	3	Based on [39].
Electrolyser	GWe	0.5	25	5.75	Based on [39]. Assumes an even mix between AEC, PEM and SOEC.
Hydrogen storage	TWh	3.68	30	4.85	Assumes 5% tank hydrogen storage and 95% underground storage [40].