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Estimating the Potential of Residential Heat Pumps to Reduce Surplus Electricity using the Flexible Demand Tool in EnergyPLAN

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ABSTRACT

Energy system flexibility is necessary to accommodate the expansion of variable renewable electricity. The EnergyPLAN tool is useful for simulating energy systems with high shares of variable renewable energy sources by representing supply and demand side technologies and verifying the balance of the system with an hourly resolution. This paper proposes a methodology to investigate the potential and availability of the flexible electricity demand of residential (individual) heat pumps providing heating, cooling, and domestic hot water to reduce surplus (excess) generation. The methodology was applied to a theoretical scenario of the Hungarian electricity system as a case study. The theoretical flexible demand achieved an average monthly reduction of 30% in surplus power. At its peak in February, the reduction reached nearly 50% of the surplus power. However, during the most critical period (May), it dropped to just 7% due to the limited availability of flexible demand. Given the significant variation and the fact that the surplus was not eliminated in any month, the value of flexible demand under the conditions of the case study may be limited. The key practical takeaway from this paper is the methodology for representing the availability of flexible demand from residential heat pumps, which is applicable to country-level EnergyPLAN models.

Keywords

Flexible demand;
EnergyPLAN;
Individual heat pump;
Integration;
Excess electricity.

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1. Introduction

Renewable energy expansion and the electrification of key segments of demand such as transport and heating are valuable measures to improve energy efficiency and move towards sustainability. New electricity-consuming equipment will alter demand patterns and may provide opportunities for demand-side flexibility [1,2]. This flexibility, accessed through demand-side management (DSM), can contribute to the integration of variable renewable energy sources (VRES) by accommodating fluctuations in generation [3]. The increasing popularity of electric vehicles (EVs) and residential (individual) heat pumps (HPs) providing heating are examples of new loads that are more energy-efficient than the fossil fuel-based technologies that they replace [4,5].

Ongoing changes, such as renewable energy expansion and electrification, add complexity to energy system analyses and the planning of a low- or zero-carbon future. The EnergyPLAN [6] is a computerized tool designed for simulating energy scenarios with high shares of VRES and verifying the electricity balance in one-hour steps over the course of an entire year. The indicators most frequently analyzed with EnergyPLAN are primary energy consumption, CO_2 emissions, costs, and excess electricity generation (surplus) [7]. The usefulness and validity of the EnergyPLAN tool for complex system analyses have been demonstrated in its popularity among renewable energy research; as of mid-2022, 315 peer-reviewed articles had EnergyPLAN as part of their methodology [8].

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List of acronyms

D:	Dwellings in the flexible demand scheme
$d_{cooling}$:	Number of days which cooling is required
DHW:	Domestic hot water
DSM:	Demand-side management
EL_{hp}:	Heat pump average energy use [kWh/year]
$EL_{flex,day}$:	Flexible electricity demand within one day [kWh]
EV:	Electric vehicle
FE:	Flexible electricity demand [TWh]
$FE_{heating}$:	Flexible electricity demand value for the heating season simulation [TWh]
FE_{mid}:	Flexible electricity demand value for the mid-season simulation [TWh]
$FE_{cooling}$:	Flexible electricity demand value for the cooling season simulation [TWh]
FP:	Flexible power [MW]
HP:	Heat pump
NECP:	National energy and climate plan (mandatory planning document in EU countries)
PHP:	Flexible power capacity of a residential heat pump
PV:	photovoltaic
SCOP:	seasonal coefficient of performance
SH:	space heating
VRES:	variable renewable energy sources
WAM:	With Additional Measures (a more ambitious scenario of NECPs)

Section 2 provides a brief review of selected articles focusing on flexible demand. Section 3 details the methodology and the case study area. The results and discussion are covered in Section 4, while Section 5 highlights the key practical takeaways from the research.

2. Literature Review

Demand-side management is a broad field of research comprehending disciplines such as engineering, resource and environmental management, economics, education, and social science. The term was first introduced in the literature during the 1970s [13]. Meng et al. [14] listed 2118 research papers published between 1987 and 2022 on demand-side management, which has been increasing, particularly since 2014, revealing a growing interest in the field. Based on their comprehensive review, Meng et al. [14] suggested a few key themes of DSM research including (i) efficiency of the power system; (ii) thermal energy management; (iii) microgrid management; (iv) demand response; (v) energy consumption patterns and modeling; (vi) energy storage; and (vii) electric vehicle charging schedule. These key themes are crucial for integrating VRES, particularly (iv) demand response.

Demand response requires flexibility to adjust the electricity demand in response to both anticipated and unanticipated variability in power supply [15]. The literature shows that flexible demand through the electrification of residential heating can be valuable for reducing the surplus generation of wind turbines [16,17], but also to reduce the marginal cost of renewable electricity generation [16] while creating a cost-effective alternative to fossil heating [18]. Consequently, heat pumps can increase the share of electricity consumption that is covered by wind turbines while facilitating wind energy investments and reducing fuel consumption, system costs, and carbon emissions. Nevertheless, the main benefit of utilizing flexible demand could be the reduction of system peak load [19].

There are hundreds of energy system analyses that use the EnergyPLAN modeling tool [8], however, the number of analyses using the EnergyPLAN model and incorporating the flexible demand option is much smaller. Several studies have analyzed the potential of EVs through smart charging and vehicle-to-grid strategy [9–12]. However, fewer studies have focused on modeling the potential flexibility of residential HPs with heat storage. A search of the terms “flexible demand” and “EnergyPLAN” on article titles, abstracts, and keywords using the Scopus database returns only five research papers [1,20,21,22,23]. The five papers, along with four other studies [24,25,26,27] not identified by those keywords, are summarized below.

Kwon and Østergaard [1] applied flexible demand to reduce the interconnection capacity of a future Danish energy system. They calculated the potential flexible demand considering three sectors (residential, commercial, and industrial) and two criteria (the potential to store energy and the potential to control services). The criteria suggest that the best sources of flexibility are services that are automatically controlled or have energy storage, while the least flexible are those that require human intervention and lack storage. The results showed that flexible demand can avoid the investment of 1-2 GW expansion of the transmission line capacity. However, nearly 30% of the classical electricity demand would need to be flexible within one month. They concluded that this time frame and the amount of flexible energy are not feasible, limiting the value of flexible demand for the system.

Sare et al. [20] examined the role of electric vehicles with smart charging, flexible demand, and vehicle-to-grid technology in the future 100% renewable energy system of the Dubrovnik region. Their results highlighted that EVs help optimize a 100% renewable energy system by reducing critical excess electricity generation. This study did not specify the electricity values utilized in the flexible demand tool.

Novosel et al. [21] investigated the influence of desalination plants on the energy system of Jordan with simulations up to 2050. Their model incorporated flexible electricity demand (for desalination) and high shares of variable renewable energy. The flexible input varied from 3.31 TWh/year to 36.36 TWh/year depending on the scenario. The maximum effect of the flexible power (i.e., the maximum amount of power that can be increased or decreased in a given hour in the EnergyPLAN simulation) ranged from 1000 MW to 8000 MW depending on the scenario. Results showed that flexible demand and renewable energy utilization can reduce system costs and CO_2 emissions.

Marczinkowski and Barros [22] developed six EnergyPLAN-based models to study the transition to sustainable energy on Madeira Island. These models used the smart charging tool but did not incorporate the flexible demand tool. Their results showed that curtailment could be reduced to zero when smart charging, vehicle-to-grid, and storage are considered [22].

The model developed by Luo et al. [23] compared the potential flexibility in three regions: Denmark, the Netherlands, and Sichuan (China). The flexible demand considered within one day was 2.28 TWh for Denmark, 8.65 TWh for the Netherlands, and 15.11 TWh for Sichuan.

The model developed by Cruz et al. [24] incorporated flexible demand within three different time frames (one day, one week, and four weeks). The maximum effect (i.e., the maximum amount of power that can be increased or decreased in each hour in the EnergyPLAN simulation) chosen for the model was 10% of the peak power demand (2264 MW), and the total selected flexible electricity demand was 10% of the annual consumption (15.6 TWh). Cruz et al. [24] considered three options (flexibility within one day, one week, and four weeks) by normalizing the average demand for each period. In this paper, only one option (flexibility within one day) was considered, as it is assumed that the hot water storage tank in the house can provide flexibility within one day, but not beyond that.

Bianco et al. [25] simulated various HP penetration scenarios ranging from 10% to 50%. They determined that a 20% level is optimal for minimizing system costs. They suggested that HP in buildings can reduce primary energy consumption and pollution emissions.

Vivian et al. [26] explored the potential of coordinating a pool of HPs in a residential neighborhood in Germany to reduce the power peaks at the distribution level. Their simulations revealed the possibility of reducing daily peaks by 21% with the management of space heating alone and up to 35% when hot water tanks are part of the optimization strategy.

Magni et al. [27] suggested that implementing 1 million flexible electric heating system at the national level could reduce annual surplus by up to 1 TWh. They also suggested that replacing non-flexible power stations with flexible ones can help reduce surplus electricity. This implies that, when evaluating the role of flexible demand, it is essential to consider not only renewable capacity and the demand-side of the system but also the generation capacity mix.

While the articles mentioned above describe comprehensive energy system models, the limited number of articles focusing on the flexible demand tool in the EnergyPLAN motivated the research. Therefore, this paper aims to (1) develop a refined methodology for incorporating the availability of the flexible demand of residential heat pumps alongside traditional electricity demand in an EnergyPLAN model, and (2) apply this flexible demand to an existing model to assess its impact on surplus electricity from variable renewable energy sources. Advancing these two objectives, the paper may serve as an introductory guide for integrating flexible residential HP demand within the EnergyPLAN framework.

3. Materials and Methods

The EnergyPLAN tool [6] offers the possibility to specify the amount of flexible demand in three different time frames; flexible within one day, one week, and four weeks (Figure. 1). The user can input the amount of flexible electricity demand (in TWh) and the maximum effect (in MW). The user can choose one, two, or all three categories (or neither of the three). The category "flexible demand within one day" was used in this model. In practice, this means that EnergyPLAN will allocate the demand specified to a time that optimizes the match with the variable electricity generation within 24 hours. The "maximum effect" of the flexible power means the aggregated connection to the grid and the maximum potential to change the system load in each hour of the day. If the options "flexible demand within one week" or "flexible demand within four weeks" were used, the software would allocate the flexible demand within these two timeframes, meaning a better match between supply and demand as these can be understood as larger storage capacities, however, these are not common in the residential level. A thorough description of the logic that EnergyPLAN uses for allocating flexible demand can be found in [6].

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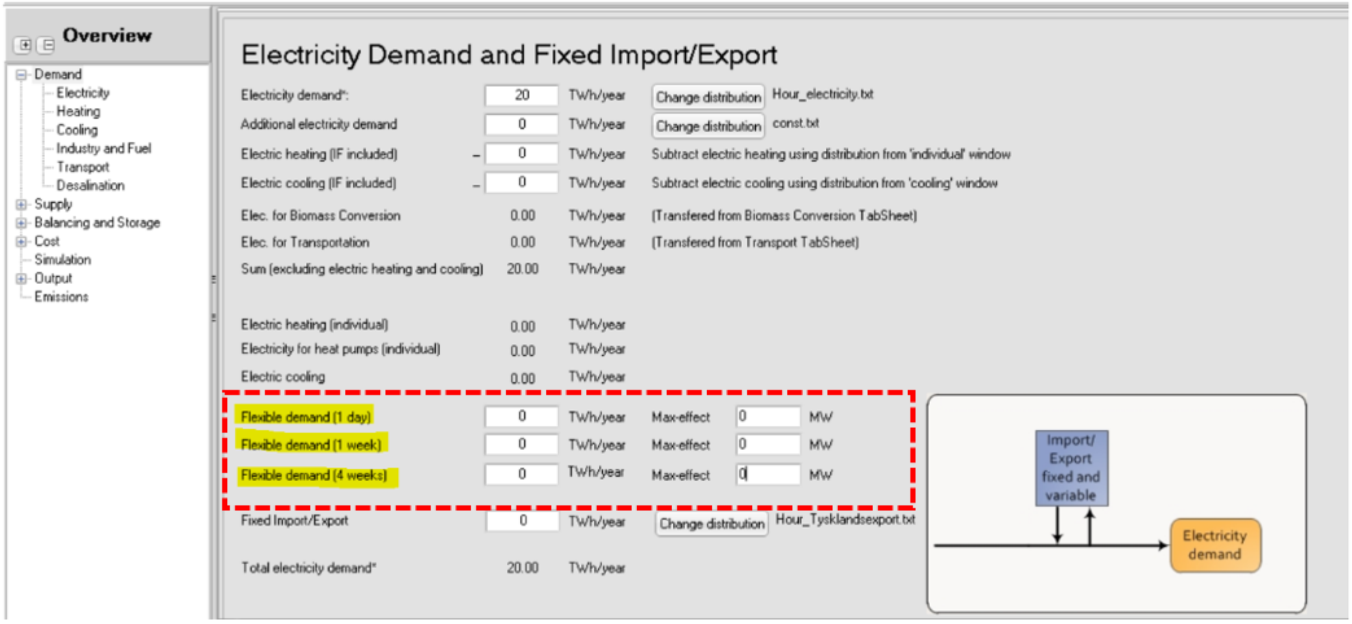


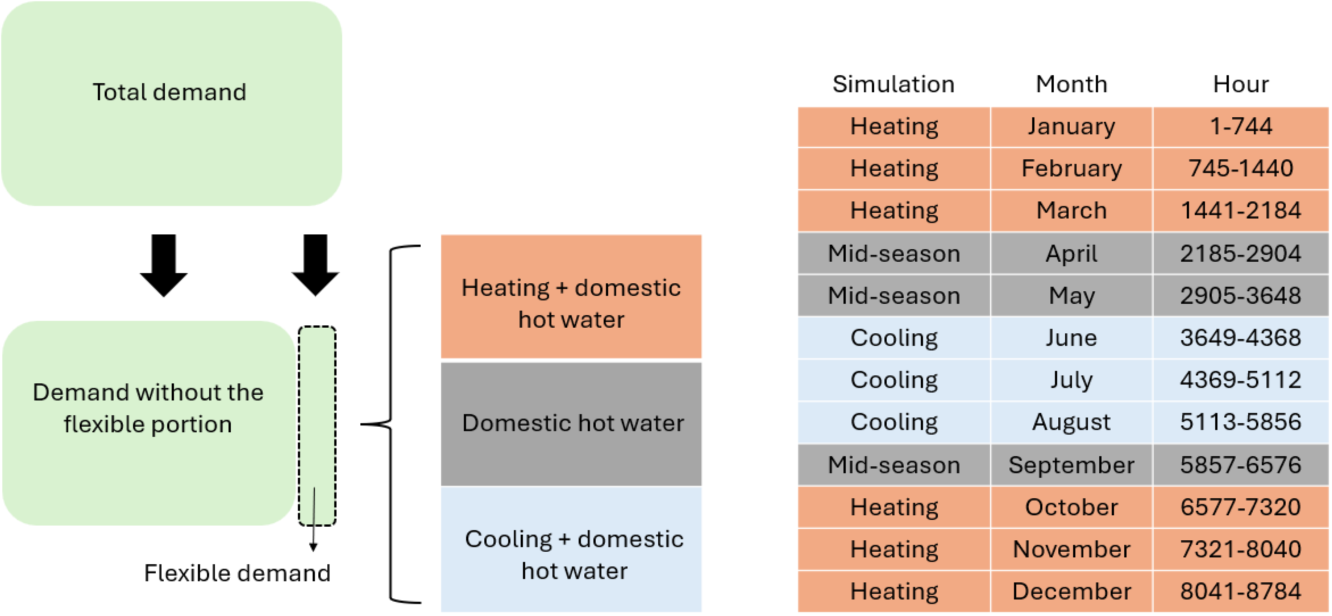
Electricity demand*:	20	TWh/year	Hour_electricity.txt		
Additional electricity demand	0	TWh/year	const.txt		
Electric heating (IF included)	– 0	TWh/year	Subtract electric heating using distribution from 'individual' window		
Electric cooling (IF included)	– 0	TWh/year	Subtract electric cooling using distribution from 'cooling' window		
Elec. for Biomass Conversion	0.00	TWh/year	(Transfered from Biomass Conversion TabSheet)		
Elec. for Transportation	0.00	TWh/year	(Transfered from Transport TabSheet)		
Sum (excluding electric heating and cooling)	20.00	TWh/year			
Electric heating (individual)	0.00	TWh/year			
Electricity for heat pumps (individual)	0.00	TWh/year			
Electric cooling	0.00	TWh/year			
Flexible demand (1 day)	0	TWh/year	Max-effect	0	MW
Flexible demand (1 week)	0	TWh/year	Max-effect	0	MW
Flexible demand (4 weeks)	0	TWh/year	Max-effect	0	MW
Fixed Import/Export	0	TWh/year	Hour_Tysklandsexport.txt		
Total electricity demand*	20.00	TWh/year			

Figure 1: The EnergyPLAN user interface with the flexible demand options marked in red and yellow [6].

EnergyPLAN does not offer the possibility to specify what portion of the flexible demand is available each month of the year. This means that it is impossible to input the potential flexible demand in the summer and the potential during winter; the user can only enter one value used for the whole year which is evenly distributed [28]. Therefore, a new approach was created to incorporate the seasonal availability in the model.

To incorporate the effects of heating, cooling, or domestic hot water (DHW) production, this paper proposes a model composed of three simulations (Figure. 2). The first simulation concerns the flexible demand available during the heating season, the second simulation refers to the flexible demand available during the months when neither heating nor cooling is needed (mid-season), and the third simulation concerns the flexible demand available when space cooling is mostly used (summer months). The specific months can be adapted in the model by selecting the desired hours in the output file generated by EnergyPLAN.

As an initial step, the days were divided according to the following. It was considered that heating is used in January, February, and March by selecting the results for the hours 1 to 2180 and in October, November, and December by using the results for the hours 6577 to 8784. To include the month of April, for example, the user would want to consider hours from 2185 to 2904. Similarly, other months could be included or excluded. The values for the mid-season simulation (when neither heating nor cooling is needed) refer to the EnergyPLAN results from hour 2185 to 3648 and from hour 5857 to 6576. The initial values for the cooling



Simulation	Month	Hour
Heating	January	1-744
Heating	February	745-1440
Heating	March	1441-2184
Mid-season	April	2185-2904
Mid-season	May	2905-3648
Cooling	June	3649-4368
Cooling	July	4369-5112
Cooling	August	5113-5856
Mid-season	September	5857-6576
Heating	October	6577-7320
Heating	November	7321-8040
Heating	December	8041-8784

Figure 2: Adaptation of the EnergyPLAN model to consider seasonal availability of flexible demand.

simulation refer to the EnergyPLAN results from 3649 to 5856. This adaptation is based on subchapter 3.3 of the author's thesis [29], with the research further expanded in this paper. Before each simulation, the values of flexible demand are adapted according to the following calculations.

In the simulation of the heating season, the flexible demand ($FE_{heating}$) per year was estimated considering the consumption for space heating (SH) and DHW and the number of dwellings participating in the demand response program. The flexible electricity demand per year was estimated by multiplying the assumption on the flexible demand in one day ($EL_{flex,day}$) during the heating season per dwelling per day and multiplying this value by 366 days (a leap year is the standard in all EnergyPLAN simulations). Then the flexible value was multiplied by the number of dwellings (D) participating in the demand response program (Equation 1).

$$FE_{heating} = EL_{flex,day} \times 366\ x\ D \tag{1}$$

This means that the energy consumption of the heat pump can be redistributed within 24 hours. The problem of thermal discomfort was not explicitly addressed in the simulations, instead, it was assumed that the building's inertial and the hot water storage tank could make the shift possible without causing discomfort in this time frame.

The total flexible power (FP) was estimated based on the electrical power capacity (kW) of the residential heat pumps (P_{HP}) considering an average building. The capacity value was multiplied by the number of dwellings participating in the theoretical demand response program (Equation 2).

$$FP = P_{hp} \times D \tag{2}$$

In the mid-season simulation, the flexible electricity demand FEmid per year was estimated considering that 15% [30] of the total HP electricity consumption (EL_{hp}) in one year is for DHW production. The two values were multiplied by the number of dwellings (Equation 3). The total flexible power (FP) was assumed the same as in the heating simulation for simplification.

$$FE_{mid} = EL_{hp} \times 0.15 \times D \tag{3}$$

In the cooling season simulation, the flexible electricity demand ($FE_{cooling}$) was calculated by adding the flexibility of the mid-season simulation to the value estimated for the cooling demand portion. The cooling demand value was calculated by dividing the assumption on the average electricity demand consumption ($EL_{cooling}$) for cooling by the number of days in which cooling is needed (d_{cooling}) and by taking 25% of the result as an assumption of the amount of demand that could be flexible. The 25% flexibility value was based on Hu and

Xiao [31]. The values were multiplied by 366 days (leap year) and the number of dwellings (D). Equation (4) summarizes the calculation. The total flexible power () was assumed the same as in the other two simulations for simplification.

$$FE_{cooling} = (EL_{cooling}/d_{cooling} \times 0.25 \times 366 \times D) + FE_{mid} \qquad (4)$$

3.1. Case Study

The methodology was applied to incorporate a level of flexible demand into an existing EnergyPLAN model. This model used as a case study describes an energy scenario for Hungary in 2033 [32] and all the necessary files to run the simulation are available to the user to download (see reference entry [33]). In this scenario, wind turbines and solar photovoltaics (PV) generate the equivalent of 50% of the annual demand. The scenario has been hypothesized with the purpose of analyzing the flexibility problem with domestic HPs; residential HP ownership is assumed to be 50% of the dwellings in the country, totaling 2075287 dwellings [34]. This is purely a theoretical and optimistic scenario for the estimations at the national level as there are no policies in place that suggest that achieving this level of ownership is possible by 2033. All values necessary for using Equations 1-4 are shown in Table 1 with their respective sources. The maximum flexible power capacity (MW) is considered the same for all simulations because the value per dwelling was adopted the same for simplification.

The analysis compares surplus in a system with and without the flexible electricity demand of residential HPs. Table 2 presents the main parameter of the EnergyPLAN model without flexible demand. The difference between this system and the one with flexible demand is the addition of the $FE_{heating}$ value in the field “Flexible demand” (1 day) and the value in the field “Max-effect” in the EnergyPLAN interface. The flexible demand is subtracted from the total demand of the model to conserve the total demand in both models. The process was repeated using the values of FE_{mid} and $FE_{cooling}$, and the results of the simulation were recorded.

The supply side of the system consists of flexible power stations (modeled as PP2, a group of thermal power stations that generate only electricity, unlike the PP1 group which generates both heat and power), non-flexible power stations (modeled as a nuclear power plant with constant output in the EnergyPLAN structure), and variable renewable electricity generation from wind turbines, solar PV, and river hydro. The non-flexible power stations are not necessarily nuclear power

Table 1**:** Parameters for considering flexible demand in the model based on Equations 1-4. The assumptions consider the year 2033.

Parameter	Unit	Description	Value	Source
EL_{hp}	kWh/year	Average consumption of the HP providing heating and hot water in one year	1470	model assumption based on [35,36]
$EL_{flex,day}$	kWh/day	The flexible electricity demand per day during the heating season	3.37	[35]
D	dwellings	An assumption on the number of dwellings participating in the theoretical demand management program	2075287	[34] and projections
P_{HP}	kW	Average electrical power capacity of residential heat pumps considering a SCOP of 3.4.	1.50	[35]
$EL_{cooling}$	kWh/year	Average demand for cooling in one year	670	model assumption based on [36]
$d_{cooling}$	days	An assumption on the average number of days in which cooling is needed	90	model assumption
$FE_{heating}$	TWh/year	Flexible demand per year in the heating simulation	2.56	model calculation
FE_{mid}	TWh/year	Flexible demand per year in the mid-season simulation	0.46	model calculation
$FE_{cooling}$	TWh/year	Flexible demand per year in the cooling simulation	1.87	model calculation
FP	MW	Total flexible power (maximum effect). The same value was applied to the three simulations	3113	model calculation

Table 2: EnergyPLAN input parameters in the two models.

	Units	**Model without flexible demand [32]**	**Model with flexible demand**		
			Heating	**Mid-season**	**Cooling**
Electrical energy demand	TWh/year	45.58	42.53	45.12	43.72
Electrical energy for transportation	TWh/year	4.67	4.67	4.67	4.67
Flexible demand (1 day), HP	TWh/year	–	2.56	0.46	1.86
Total flexible power (maximum effect), FP	MW	–	3113	3113	3113
Total demand	TWh/year	50.25	50.25	50.25	50.25
Flexible power stations (PP2 in EnergyPLAN nomenclature)	MW	3372	3372	3372	3372
Non-flexible power stations (nuclear PP with constant output)	MW	944	944	944	944
Wind turbines	MW	6765	6765	6765	6765
Photovoltaics	MW	7650	7650	7650	7650
River hydro	MW	59	59	59	59

plants, they are just modeled using the nuclear power plant tab in the EnergyPLAN tool. In this case study, however, they represent the nuclear power station in Hungary. The total capacity of thermal power stations considered in the model was 4375 MW based on the 2019 Hungarian NECP's scenario called With Additional Measures - WAM [37] and the capacities of wind turbines and photovoltaics are based on a more ambitious alternative scenario described in [32]. The simulations used three years of weather data (to describe variable renewable electricity output) [38]. The distribution files of the model are available at [33]. The hourly profile of heating, cooling, and DHW demand of residential buildings were based on the comprehensive analysis of smart meter data in Hungary developed by [36]. The profiles suggested in their work were compiled in a file compatible with EnergyPLAN, which is also available at [33].

The results of the case study are presented as surplus electricity for one year, broken down by month.

4. Results of the case study

Validating an EnergyPLAN model of the electricity system is a complex task [8]. One way to assess the validity of the model is by comparing its output to that of a reference system. In this study, the model is a theoretical scenario for 2033 that cannot be directly compared to a reference. However, the scenario was built up from the electricity system of 2021, therefore this was considered the reference for comparison. The developed EnergyPLAN model (of 2021) was able to replicate 2021 system, with the following limitation: the surplus energy in the model was overestimated by 6% compared to the reference system.

Table 3 shows the surplus electricity (TWh/year), hourly average surplus power (which is the average of the surplus when surplus is present in MW), and maximum surplus power (MW) registered in the simulations. Adding flexible demand reduced yearly surplus energy by nearly 20%. The monthly average power recorded during surplus events was reduced by approximately 19%, while the peak surplus was only reduced by about 7%.

The 19.6% annual reduction in surplus energy refers to the best-case scenario, assuming that all the equipment (an ownership rate of 50% of dwellings in the country) would be available for demand management. In reality, not all consumers would choose to participate in the program. Given the large number of consumers that would need to participate to achieve such a reduction, a more significant result could arguably be a yearly reduction of at least 30%. Given the number of residential consumers required, there seems to be a small impact of using their flexibility to reduce surplus and

Table 3: Comparison of the electricity system with and without the flexible demand scheme. Results were obtained using three years of weather data [38].

	System without flexible demand (reference)	System with the flexible demand scheme	Difference	
			Absolute values	**%**
Surplus electricity (TWh/year)	2.40	1.93	–0.47	–19.60
Average surplus power (MW)	272	220	–52	–19.11
Maximum surplus power (MW)	4507	4192	–315	–6.98

other forms of flexible demand such as the strategic management of EV charging should be incorporated.

Figure. 3 compares the surplus in the electricity system without flexible demand (black bars) and the system with flexible demand (green bars) revealing significant differences (values in red) between the months.

The difference was caused by the utilization of heating, cooling, or DHW only (periods when there is no need for heating or cooling). The monthly average reduction is 23%. When heating is needed, the average reduction of surplus energy was 27% (difference between system with and without flexible demand). During the warmer months when cooling is required, the average reduction was 33%. During the months when neither is required the average reduction was 6%. The most significant reduction during the warmer months can be attributed to the compatibility between electricity generation from solar PV and the demand for cooling. It is important to note that "passive cooling" can partially replace "active cooling", reducing electricity consumption. Therefore, it should be encouraged in the context of sustainable energy. The strategy of using flexible demand (green bars, Figure. 3) is most effective in August followed by November, and least effective in April and May. The low efficiency observed in April and May is concerning, as these months experience the highest levels of surplus generation.

The reduction in surplus during the heating season (particularly December, January and February) is smaller than the cooling season because the generation from solar PV, which causes the most surplus, is also smaller during this period. The reduction in April and May is small due to the significant amount of electricity generated by solar PV and wind turbines during this period and the limited flexible demand available, as no heating or cooling is required.

Figure. 4 shows the average surplus power in each month, representing the average of each hour that surplus power is present. The solid line refers to the electricity system without flexible demand (reference) and the dashed line refers to the system with flexible electricity demand for comparison. The reduction in surplus

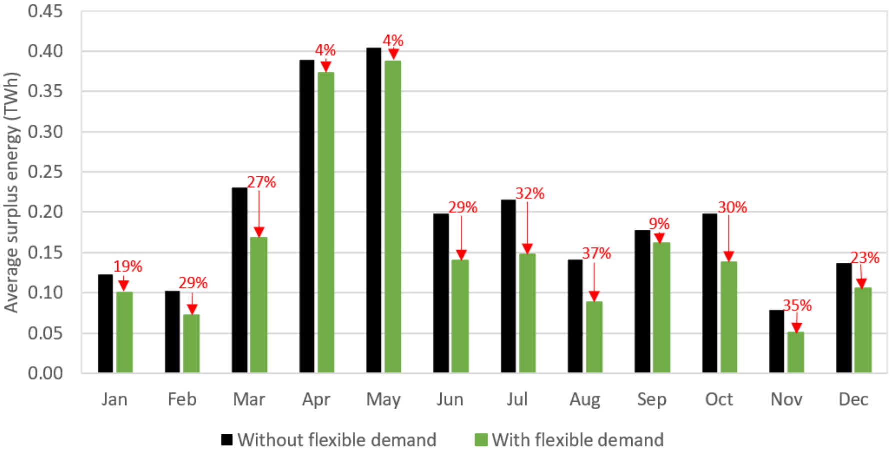


Figure 3: Monthly surplus energy in the reference system (without flexible demand) compared to the system with flexible demand. The arrow and text in red refer to the difference between the two cases.

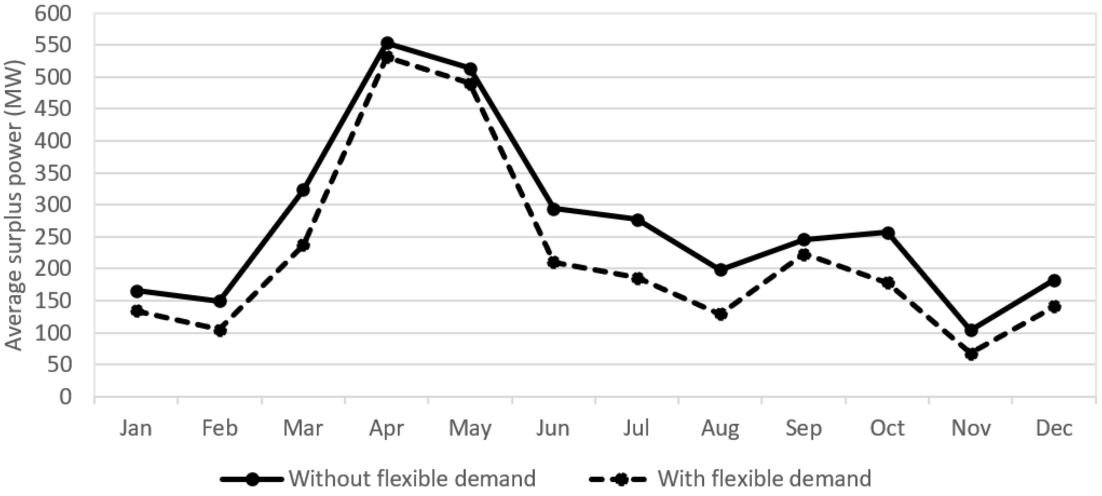


Figure 4: Average surplus power in the electricity system without flexible demand (reference) compared to the system with flexible demand.

(difference between two lines) is more significant during the time that cooling is needed. The strategy of using flexible demand has a significant impact in March and October because the conditions are favorable for solar PV electricity generation while there is flexible demand available due to the utilization of heating.

Figure. 5 illustrates the maximum surplus power (peak) recorded in each month. The solid line represents the system without flexible demand, while the dashed line represents the system with flexible demand for comparison. The highest surplus power (in both systems with and without flexible demand) occurred in March, April, and May, followed by June, July, and August which is explained by favorable solar PV electricity generation conditions. When comparing the system with and without flexible demand, the least significant reduction occurred in May (7%), due to large amounts of solar PV electricity in the system. The maximum surplus in May is 13% greater than the reference capacity of transmission lines (approximately 4000 MW [37]). Considering May as the worst-case scenario, the system with flexible demand could reduce the need to expand the transmission line capacity by 7%.

The monthly average reduction of maximum surplus is 30%. Therefore, the ability to reduce the maximum surplus power is the most effective aspect of the flexible demand strategy examined.

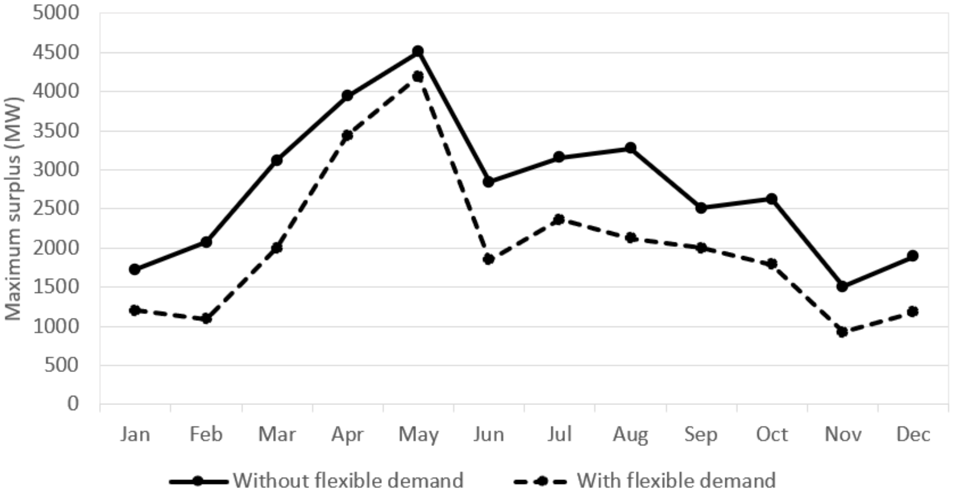


Figure 5: Maximum surplus power in the electricity system without flexible demand (reference) compared to the system with flexible demand.

Figure. 6 demonstrates how the flexibility scheme can shift consumption, using the first week of January, April, and August as examples. The solid line is the demand in the reference system and the dashed line is the demand when the flexibility scheme is incorporated. The blue areas represent the total variable renewable electricity supply for each hour. It can be observed the dashed line attempted to follow the blue area in hours of peak supply to reduce surplus if flexible demand is available. Therefore, it cannot follow exactly the blue line because there is no sufficient flexible demand to do so in the case study. The dashed line followed the solar PV peak output (midday), but reduced the demand in other hours during the day to instead increase the demand during the night to match the generation from wind turbines. This is noticeable in January, as there is a high amount of wind power generation, whereas the peak of solar PV is less significant compared to August. In the week of April represented in Figure 6, there is no shift in demand because no heating or cooling is considered for this month which reduces the flexibility of the demand side. As shown in Figure. 3, 4, and 5, this month is problematic for this particular reason; there is no available flexible demand, but there is a lot of supply from solar PV and wind turbines resulting in a surplus. In August, the flexibility scheme mostly shaped the demand according to solar PV output, but it also increased the demand at night to match wind power.

These calculations are performed by EnergyPLAN, which allocates the flexible portion of demand to match supply, while respecting the specified value of flexible demand within one day. This means that the input of the field “Flexible demand (TWh/year)” in EnergyPLAN is automatically divided by 366 days (the software always

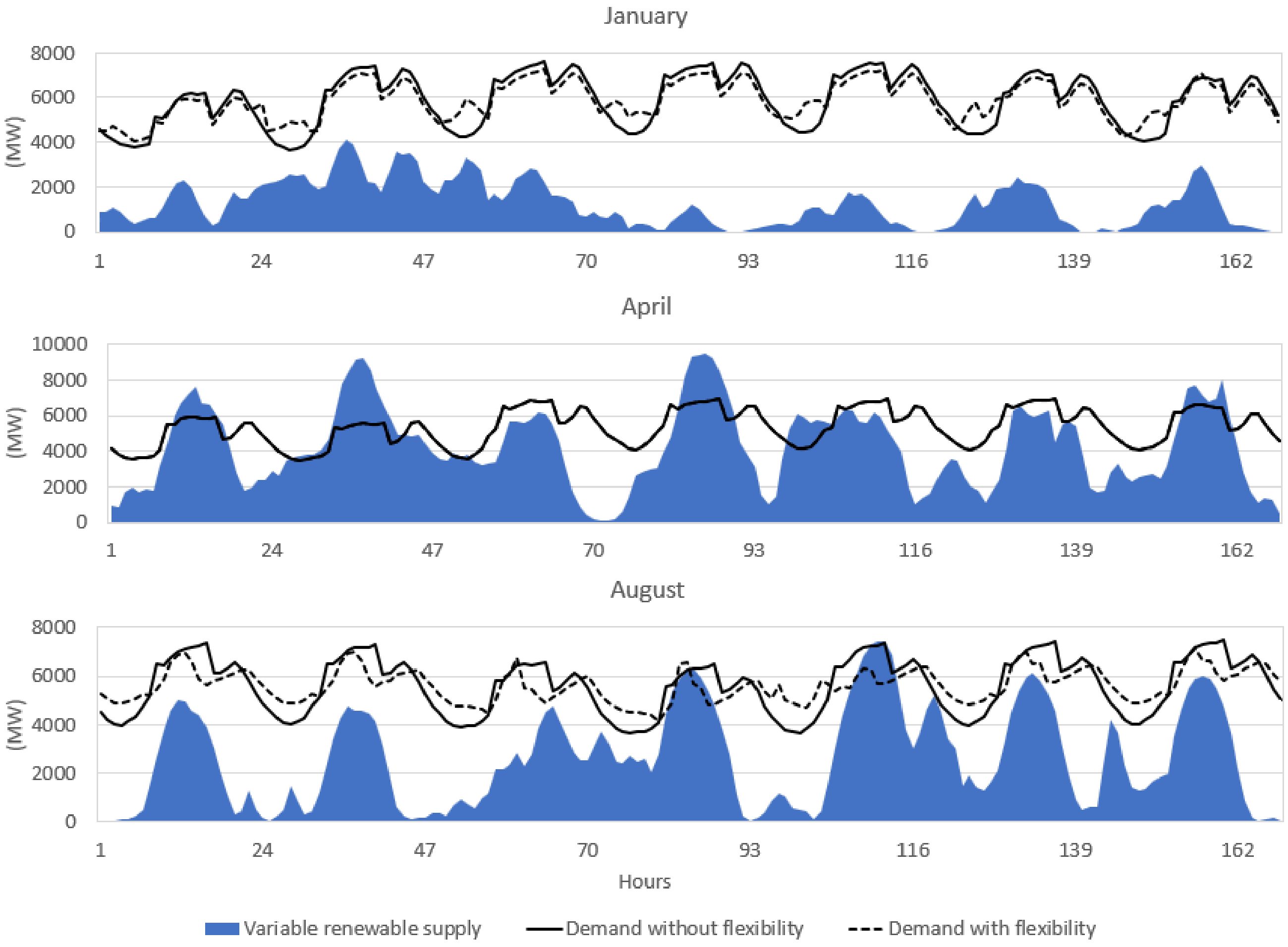


Figure 6: The shift in demand with the flexibility tool in the first week of January (heating season), April (mid-season), and August (cooling season).

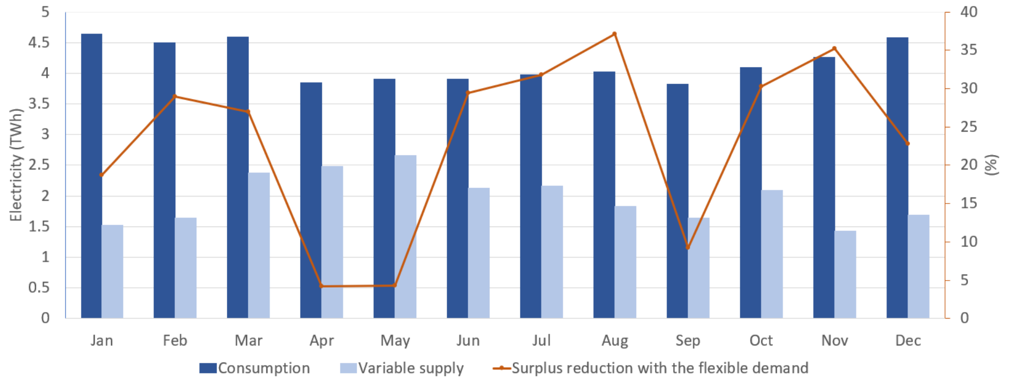


Figure 7: Consumption, variable renewable supply, and the potential surplus reduction of the flexible demand scheme (orange line) compared to the reference system without flexible demand.

considers a leap year) and the result is the value to be allocated to any hour within the same day.

Figure. 7 shows the energy consumption (represented by the dark blue bar) and amount of variable supply from renewable sources (represented by the light blue bar). It also shows the percentage reduction (represented by the orange line) compared to the system without flexible demand. The high variable supply in April and May made the scheme less effective in those months, however, Figure. 7 reveals that the consumption has a bigger impact on the effectiveness of the scheme since April, May, and September also had the lowest consumption and lower flexible demand. Consequently, the effectiveness of the scheme depends more on the amount of flexible demand than the amount of variable supply.

Figure. 8 illustrates the aggregated supply from all thermal power stations in the system with flexible demand (dark blue bar) and without flexible demand (dark orange bar). It also shows imports from neighboring countries in the system with flexible demand (light blue bar) and without flexible demand (light orange bar), calculated automatically by EnergyPLAN based on demand and installed generation capacity. The supply shown in Figure. 8 would be the main source of carbon emissions in the electricity system since the other sources of domestic electricity generation are wind turbines, solar PV, and hydropower. EnergyPLAN results indicate that the flexibility scheme has limited influence on the output required from thermal power stations; the system with flexible demand reduces the yearly generation from thermal power stations by only 0.2% compared to the system without flexible demand.

The output of thermal power stations slightly increased with the flexible option in January, February, July, November, and December (Figure. 8) because the non-flexible power stations were not able to reduce their output and because the imports were reduced in those same months, except July when imports slightly

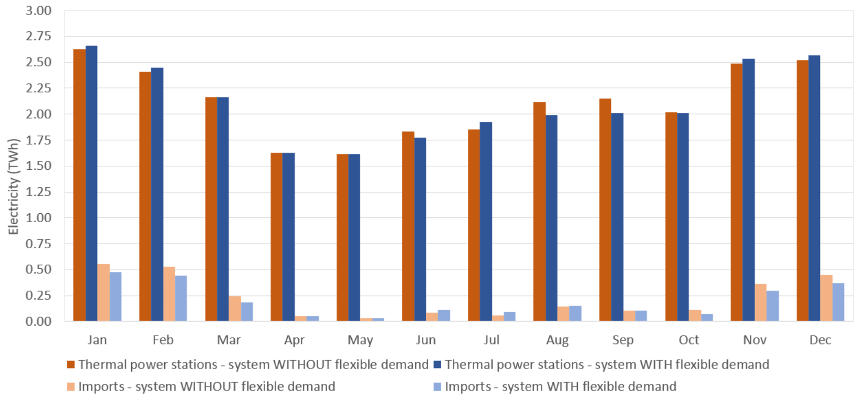


Figure 8: Supply from all thermal power stations and imports from neighboring countries in the system, with and without flexible demand.

increased. Regarding imports, the flexible option reduced the yearly imports by 12%. Overall, the flexible option reduced the output of thermal power plants by 0.1 TWh/year and imports by 0.3 TWh/year, which were replaced by locally available renewable supply.

4.2. Comparison to the literature

The literature on renewable integration through demand flexibility provides several examples for comparison.

Based on the study by Hedegaard and Münster [19], which analyzed the future Danish energy system in 2030, the potential peak reduction is the most important benefit of the flexible demand from HPs as this capacity is comparable to a medium-sized power station. The expected peak reduction in May (316 MW) is similar to their findings (300-600 MW), but the most significant reduction, 1145 MW in August, is nearly double the value estimated by Hedegaard and Münster [19].

The study of the Belgium energy system by Magni et al. [27] suggested that electric heating equipment in 1 million houses could reduce yearly surplus by up to 1 TWh. This value is four times the potential estimated in the present research (considering the number of houses proving flexible demand). One of the reasons is that HPs are more energy efficient than electric resistance heaters which were included in their analysis. Another reason is the conservative assumptions made in the present paper which considers an increasing demand, in reality, demand has decreased in 2023 in both the EU [39] and the USA [40], despite millions of new EVs and HPs. Compared to the work of Magni et al. [27] the results of the present study may underestimate the potential of flexible demand. On the other hand, Magni et al. [27] highlighted that their estimation should be considered as “an upper limit of the available flexible resources through demand response”. The findings for the most critical months (April and May) could still be relevant because even if the efficiency of the flexible demand strategy to reduce surplus was four times higher the effect in these months is still limited in comparison to the other months.

Results showed that the peak reduction capacity of flexible demand varies from 7 to 47% depending on the season. The average peak reduction is 30% which aligns with the findings of Vivian et al. [26] who found a reduction of up to 35% of peak power considering HPs and hot water storage.

It should be highlighted that in both cases compared (with flexible demand and without flexible demand) HPs were part of the system. Even without the flexible aspect, HPs already contribute to the integration of wind energy, which reduces the impact in comparing the system with and without flexible demand [19].

4.3. Limitations of the model and obstacles to exploring flexible demand

One of the key limitations of the study is the simplification of the electrical system modeled with EnergyPLAN. This tool aggregates the total capacity of power stations; therefore, the detailed operation of individual units is not captured. Since EnergyPLAN uses flexible demand to balance demand and supply, two other key limitations appear; the flexible demand must be positive at any time and should be below the stipulated capacity constraint. Another tool (e.g., MATLAB) would have to be used to overcome some of the limitations of EnergyPLAN.

As highlighted by Neves et al. [28], the EnergyPLAN model, and many other models, has limitations in representing flexible demand with a level of detail. The adaptation presented in this paper is only one small improvement to modeling the availability of flexible demand. The electricity demand of HPs could be further detailed by considering different climates and specific building demands with archetypes. While the seasonal availability of the flexible demand was developed into three periods (winter, summer, and autumn/spring), this separation is only reasonable for some regions.

The present study also focused exclusively on residential heat pumps. Still, other types of residential equipment and consumers can provide flexibility to the demand side of the energy system [1].

It should be noted that the utilization of heat pumps will impact the local electricity market by increasing the winter peak (possibly by 20-70%) according to the analysis of Kavvadias et al. [41], which may lead to a supply shortage.

As another example, Alla et al. [42] examined the maximum share of HP utilization in a case study focused on the Italian market. They found that the 2019 system could accommodate a level of HP penetration ranging from 10% to 50%. For a potential system of 2030, the level was estimated at only 5% to 10% due to changes in the market and more restrictive conditions. The amount of flexible demand modeled in the present case study would only be achieved if many consumers participated in the demand response program. Since it is unlikely that 50% of all residential consumers would participate in the program, the flexibility of HPs is unlikely to solve the surplus problem alone and other tools need to be considered to store surplus energy.

The utilization of flexible demand has a few obstacles. One of the obstacles to utilizing the flexible demand is that an energy management system (equipment that reacts to price or other automated signals) needs to be implemented in the dwellings participating in the demand response program. Another obstacle is that the owners of the HPs need to be willing to participate in the program. McKenna et al. [43] found that residential consumers may be willing to participate if there are benefits, such as reduced electricity bills. However, the financial incentives for residential users to contribute to system flexibility are often limited [19,44]. Moreover, the current regulatory framework and design of the electricity market do not support load aggregators in trading flexible demand [45,46].

5. Conclusions

EnergyPLAN is frequently used in scenario studies focusing on energy systems with a high share of VRES. Despite the large number of research papers that use the tool as part of their methodology [8], only a few papers mention using the flexible demand option that EnergyPLAN offers. The paper addressed this knowledge gap by utilizing the EnergyPLAN model's flexibility option and introducing a methodology to assist users in modeling the flexibility potential of residential HPs. The methodology can be readily applied to an existing model after performing the calculations described in this paper.

The methodology introduces a novel approach by representing the flexible demand of residential HPs across three distinct seasons—heating, cooling, and mid-season—rather than relying on a single value, as is typical in the standard model. This seasonal differentiation represents the availability of flexible demand and offers a more nuanced way to utilizing the flexibility option in the EnergyPLAN model.

Using this methodology, the paper evaluates the potential of residential HPs to reduce surplus electricity in a hypothesized scenario of the Hungarian electricity system. The reductions in surplus were greatest during the cooling season, followed by the heating season, and finally the mid-season. Moreover, the scheme proved more effective in mitigating maximum surplus power (MW) than surplus electricity (TWh/year). When comparing the volume of variable renewable energy supply to the availability of flexible demand, the latter had a more significant impact on the scheme's effectiveness. The scheme also showed limited impact on the output required from thermal power stations; output slightly increased in hours that non-flexible power stations could not adjust their generation. Compared to findings from other studies, the reduction in surplus electricity (TWh/year) may be underestimated, while the reduction of maximum surplus power (MW) could be overestimated in the cooling season.

A limitation of the methodology is the level of detail of the energy demand of an average dwelling. Future research could address this issue by dividing the country into regions based on heating and cooling requirements or by using building archetypes to estimate demand and the potential flexibility of HPs more accurately.

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