The flexibility of electrical loads in the EU-27 residential building stock

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Abstract—With the increasing uptake of heat pumps and photovoltaics within the European building stock, demand-side management becomes an increasingly discussed option to balance the volatile share of renewable electricity generation. But what is the potential short-term flexibility of electricity loads in residential buildings within EU countries? And if this potential is used, how would it affect the overall electricity consumption profiles? To answer these questions, we look at so-called ”prosumagers”. In this work, prosumagers are considered to be households that use a heat pump and minimize their energy costs through optimization using an hourly electricity price signal (day-ahead wholesale electricity price plus grid fees), keeping the indoor temperature in a specific bandwidth. Results show that prosumaging households can support the grid and decrease electricity demand at high electricity prices. At the same time, electricity peak demand could rise up to 12% in some EU countries in the future, if all households react to the same hourly electricity price.

Index Terms—demand response, heat pumps, building stock, optimization

I. Introduction

Decarbonization efforts and declining renewable electricity generation costs have been driving up the amount of fluctuating, renewable electricity generation in the grid. To deal with the fluctuation increase, demand response (DR) can make an important contribution to the energy transition. DR from the residential building stock using heat pumps (HPs) is considered to have a large flexibility potential. In this work, we investigate the future potential of the building stock in the EU member states to shift electricity demand using real-time pricing. In doing so, we ask the question of how large the actual potential of the residential building stock for short term flexibility is and how the electricity consumption profiles will be affected if all HP-heated buildings shift their demand based on the same price profile on a country level for EU member states. To do so we analyze two price profiles in this study also showing how the end-consumer prices going down to zero in some hours intensify or weaken possible effects on the consumption profiles? To answer these questions the remainder of this paper is structured as follows. First, in section II, an overview of the state of the art on DR in buildings and grid interaction is provided. Section III describes the used methodology, and in section IV, results are discussed, finishing with section V summarizing the findings.

II. Literature Review

DR of residential buildings with HPs has been widely studied, and the potential of the thermal mass as short term storage highlighted [8], [11], [13]–[19]. Other studies have focused on how the flexibility of buildings can be defined [7], [12], [22] and some investigated how this flexibility could affect the electricity grid [2], [8], [10], [20], [21].

The term ”flexibility” is defined and expressed in many different ways in literature, some of which are compared in [9]. Yu et al. [2] give a comprehensive overview of building-related flexibility indicators and distinguish them into key performance indicators describing the interaction with the grid and the independence of a building. In this study we focus on the impact of flexibility on the overall electricity system. Therefore we look at indicators introduced in [10] and [8]. Klein et. al. [10] introduced a so called grid support coefficient (GSC). They carried out an analysis for Germany using the day-ahead price, the residual load, the non-renewable cumulative energy consumption and the fraction of fluctuating renewable energy in the mix to show their approach on a single building. They analyze the impact of all HPs in 2023 and 2030 on the residual load if they are operated ’grid friendly’. Their results show that the residual peak loads are affected in a limited way. At the same time, no undesirable overcompensation of the residual load fluctuations occurred. At times with a low residual load in winter, demand can be significantly improved. Sperber et al. [1] show in their study that large-scale DR to a single electricity price signal can lead to a so-called avalanche effect. An avalanche effect means that through the simultaneous DR action of many buildings, new electricity price- or new demand peaks occur. Furthermore, the DR on a large scale could influence the electricity market significantly, which is not captured by most studies. They did so through an iterative process where the day ahead electricity price is updated based on the flexibility provided by HPs trying to avoid any avalanche effects. Results show that DR of buildings by a unified price incentive (day ahead price from 2019) does not reduce peaks in the residual load.

The above-mentioned studies focusing on the national demand only focus on Germany [1], [10]. Similar to these studies we analyze how prosumaging households change the overall grid demand on a national level for the EU member states. By doing so, we take different building stock typologies, amount of heating systems, and climatic conditions into account.

III. Method

In this study, we combine 3 different models to predict the impact of prosumagers on the national electricity grid demand. The first model is a bottom-up building stock model called Invert EE-Lab [6] which was used in the ECEMF[1] project to generate building stock scenarios up to 2050 for all EU member states. The properties of all building archetypes for each country calculated by the Invert model are used as input in this work. In the scenario used for this study the building stock is modeled under the assumption of a strong future electrification and high efficiency which translates into high annual renovation rates (average 3.1% from 2019 to 2050). The average final energy demand for heating in the residential building sector will decrease by 56% by 2050.

The second model is the Balmorel model [3], [4], an energy system model that was used to calculate the electricity prices on an hourly level for the years 2030, 2040, and 2050 in every EU member state. In the Balmorel model a high share of renewable generation was assumed for the future scenarios which results in spot prices close to and equal to zero at times of high renewable generation. The underlying CO_2 price is 69 €/toCO_2, 212 €/toCO_2 and 529 €/toCO_2 for the years 2030, 2040 and 2050. In times of low renewable generation and high load on the other side, flexibility options at higher costs like dispatchable generation units, storage discharge, or import set the marginal price, which results in relatively high spot prices. For the base-year we use the day ahead price from the ENTSO-E platform in 2019. With these prices we created two price scenarios. The first scenario has no grid fees, showing negative prices in 2019 and zero prices in the other years. In the second scenario 20 cent/kWh grid fees were added. This way we can observe the effects of zero end-consumer prices on the load shifting behavior.

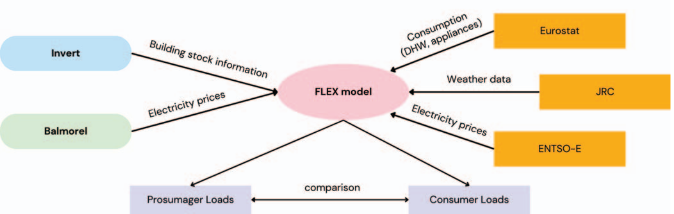

Fig. 1: Overview of the model combination and input data

The first two models provide the input data for the third model (FLEX) (visualized in Figure 1) which calculates the electricity demand of the HP heated residential building stock. The FLEX model is a bottom-up, operation optimization and simulation model for residential buildings which calculates the hourly energy demand of a building for two cases:

1) the building is a consumer or prosumer and energy demand (heating, hot water and electricity) is satisfied independently of the hourly electricity price. The indoor temperature is kept above a certain set point. Storages (thermal water tanks), are charged with local PV generation if installed.
2) the building is a so-called prosumager and the operation of the HP is optimized to minimize electricity costs based on an hourly real-time price. Indoor temperature is kept above a certain set point but can be increased by 3°C to pre-heat the building. Storages are operated to minimize costs as well.

The resulting electricity grid demand profiles of each building can then be compared for these two cases, giving insight into the possible load-shifting behavior of HP-operated buildings. The simulation and optimization are carried out for every building archetype and multiplied by the number of buildings this archetype represents. This way, the electricity demand profiles are upscaled to the building stock level.

The FLEX model uses a linear optimization approach to calculate the optimal operation of the HP in each building with the objective of minimizing energy costs:

$$min \sum_{t=1}^{t=8760} P_{\text{grid, t}} * p_t \tag{1}$$

with p representing the hourly electricity price and P_{grid} being the electricity demand drawn from the grid. The grid demand is the sum of the electricity demand of appliances, the HP and the air conditioning (AC) (if installed), minus the PV generation if a rooftop PV is installed.

$$P_{\text{grid, t}} = P_{\text{appliances, t}} + P_{\text{HP, t}} + P_{\text{AC, t}} - P_{\text{PV, t}} \tag{2}$$

The electricity demand for the HP (P_{HP}) is calculated through the fraction of the heating demand and hot water

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[1] EU H2020 project: https://www.ecemf.eu/

and their respective coefficient of performance (COP) with the subscript k indicating the different heating needs which include: room heating, heating the buffer tank, DHW usage and heating the DHW tank.

$$P_{\text{HP, t}} = \sum_k \frac{Q_{\text{heating, k, t}}}{COP_{\text{heating, k, t}}} \tag{3}$$

The source temperature is the outside temperature for air source HPs and a static 10°C for ground source HPs. The sink temperature of each building is dependent on the buildings heating system (radiators or floor heating) and the insulation level. To charge the buffer or hot water tank the sink temperature is raised by 10°C to include losses in the heat exchangers. Hot water is provided at a temperature of 55°C.

$$COP = \eta \cdot \frac{T_{sink}}{T_{sink} - T_{source}} \tag{4}$$

HPs are sized to be able to provide the necessary heating power in the coldest hour of the day to keep the indoor temperature above the set point. Buffer tanks are sized with 30 l per kW thermal power of the HP. Tanks for domestic hot water are sized with 100 l per person. Battery storages are ignored within this work as the roll out of stationary batteries would include multiple assumptions for each country.

The FLEX model provides two electricity grid demand profiles for the residential building stock which uses HPs. The first profile is the consumer/prosumer profile where households do not react to the electricity price (reference profile) and the second profile is the prosumager profile, where the HPs react to the hourly electricity price in each country. We are using these profiles to calculate the change in demand at low and high electricity times and check what the change in demand through prosumaging can have on the national electricity demand. We do that for all EU member states except Malta and Cyprus due to insufficient data for these two countries.

Le Dreau [8] introduced a flexibility factor for the heating demand based on the hourly price using the first and fourth price quartiles (low and high price time). A higher flexibility factor means that more energy is consumed at low prices. We use the same definition of this factor just for the electricity grid demand (P) instead of the heating demand.

$$Flexibility factor = \frac{\int_{\text{low price}} P_t \quad dt - \int_{\text{high price}} P_t \quad dt}{\int_{\text{low price}} P_t \quad dt + \int_{\text{high price}} P_t \quad dt} \tag{5}$$

Klein et. al. [10] introduced an abolute GSC (GSC_{abs}) and a relative GSC (GSC_{rel}). The GSC_{abs} describes the grid friendliness of a certain consumption profile while the GSC_{rel} is a rescaled version (between -100 and 100) of the GSC_{abs} to make it comparable between different profiles. GSC_{abs} is calculated by weighting the electricity consumption with the price and dividing it by the consumption times the average price ($\overline{p}$). The "best case" for GSC_{abs} would be if the total consumption within the time frame would only be consumed during the hours with the lowest price and the "worst case" is calculated by assuming consumption during the hours with the highest price. The electricity price and the residual load are strongly correlated [10], [11] thus a low GSC_{rel} is seen as grid friendly. In this study, we calculated the GSC_{rel} for the electricity demand of the residential building stock with and without prosumagers.

$$GSC_{abs} = \frac{\sum_{t=1}^{24} P_{\text{grid, t}} \cdot p_t}{\sum_{t=1}^{24} P_{\text{grid,t}} \cdot \overline{p}} \tag{6}$$

$$GSC_{rel} = 200 \cdot \frac{GSC_{abs}(\text{worst case}) - GSC_{abs}}{GSC_{abs}(\text{worst case}) - GSC_{abs}(\text{best case})} \tag{7}$$

At last, we investigate the peak electricity demand on a national level and show how the peak demand can increase through prosumaging like in [1]. While [1] focused on the residual load peak we are considering the national electricity demand peak in this study:

$$\hat{P} = max(P_{\text{national, t}}) \quad with \quad t \in (1, 2, ..., 8760) \tag{8}$$

IV. Results and discussion

In Figure 2 the flexibility factors for all EU countries are shown as boxplots. The reference case refers to the case where prosumagers do not exist and no load is shifted. Through prosumaging, the flexibility factor can be increased, more so if zero prices (Price 1) are passed on to the prosumagers. In Figure 3), we see the change in the total EU electricity demand at high and low prices. The demand at high prices (4th quartile) is reduced more than it is increasing at low prices if the electricity price does not go to zero (price scenario 2). With zero prices the demand at high prices can be reduced slightly more, at the same time the increase at prices in the 1st quartile can more than triple compared to price scenario 2. While the change in electricity demand on average national level is below 2%, it is increased around 20-30% in the first quartile and reduced up to 10% in the 4th price quartile for the buildings which perform the DR. The reduction of the overall electricity demand at high prices could indicate a potential to reduce CO_2 emissions. At the same time, the increase in low prices would likely contribute to a higher share of renewable generation in the electricity mix or reduced curtailment of renewable generation. However, the question remains if this additional demand can be completely covered by renewables. To answer this question a spatial analysis of the demand coupled with a grid model would be required.

The GSC_{rel} shown in Figure 4 is lowered in every country by prosumagers meaning that DR can be beneficial for the electricity grid. For price scenario 2 the GSC_{rel}

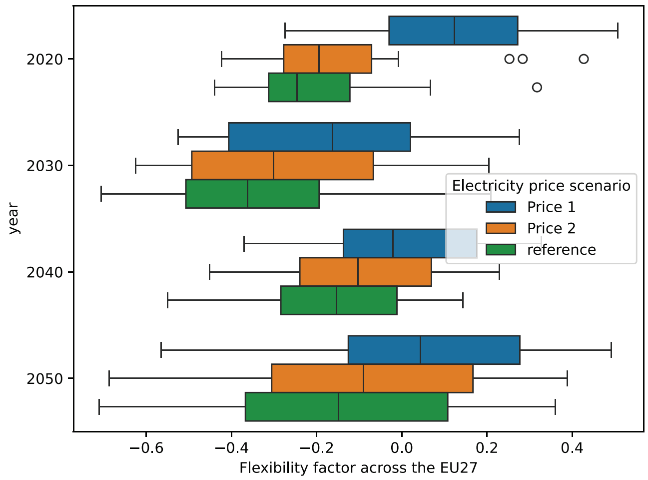

Fig. 2: Flexibility factor over EU27.

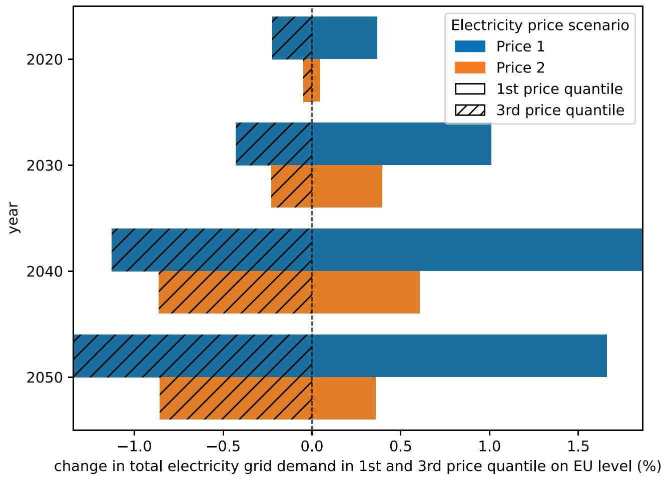

Fig. 3: Average change in the total grid demand in the EU in the 1st and 4th price quartile.

drops even more than in price scenario 1. This means that even though more demand is shifted, negative pricing for prosumagers is less system-friendly than if prices stay positive. With zero prices, very inefficient DR actions are taken which becomes evident when analysing the change in total grid demand. Through prosumagers the grid demand rises by an average of 3% in the first price scenario while it decreases by around 1% in the second. The high losses occurring when electricity can be bought for zero prices have a dampening effect on the GSC_{rel}. Another reason why the end consumer price should not go to zero is given in Figure 5. We can see that in most countries, the national peak demand will rise, especially in Price Scenario 1. The national demand can rise up to more than 14% in 2040 in some countries. Countries with many HPs compared to their overall total electricity demand and with a high electricity price standard deviation experience the highest peak demand increase. In 2050, the rise in national demand is not as extreme as in 2040 due to better insulated buildings and an increase in electricity demand in other sectors. In some countries, the peak demand can also be reduced through prosumaging, however only by a small percentage (<1%).

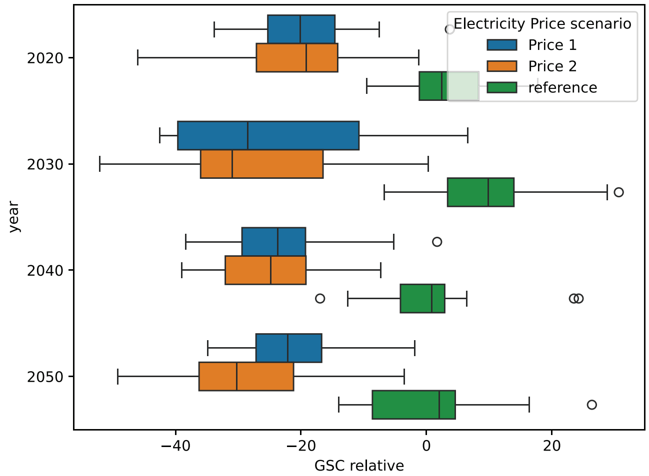

Fig. 4: GSC_{rel} for all countries in the EU.

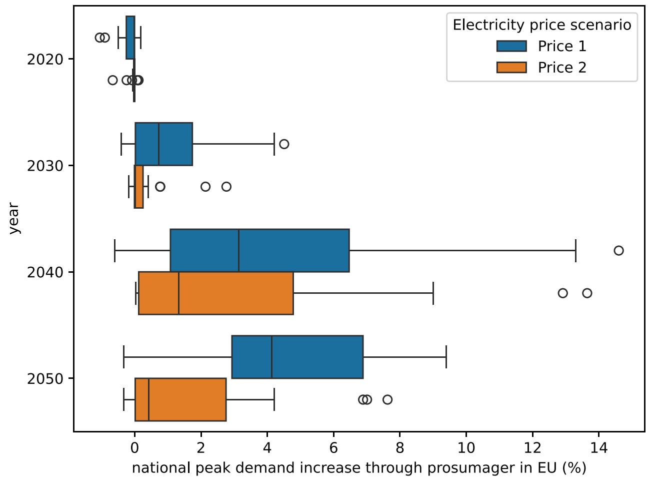

Fig. 5: Increase in national peak demand in the EU.

At the same time, new high peaks could be avoided by introducing different hourly grid tariffs in the regions, better reflecting electricity scarcity and preventing the simultaneous reaction of too many prosumagers to the same price signal. A more effective way to use the building stocks flexibility could be by directly controlling the individual HPs [23], [24]. At the same time, direct control has been identified as a possible barrier to user acceptance [11]. The results presented above vary relatively high within the different countries. A detailed analysis on country level with a spatial distribution of the loads to investigate the possibility of prosumagers to reduce grid congestion through different electricity tariffs will be subject to further research.

A clear limitation of the approach presented is ignoring grid capacities and the spatial distribution of loads. The Flexibility Factor and GSC are supposed to show "grid-friendliness", however without knowing the spatial distribution of the loads, possible grid congestion is not taken into account. Therefore, the authors would describe the meaning of these factors as system friendliness because, regarding the grid, no well-founded statement can be made. Also, with this approach, the active DR is not factored into the electricity price. In [1] it was shown that DR of residential heat pumps can have an impact on the price.

V. Conclusion

In this work we investigated the impact of prosumaging on national electricity grid demand using hourly day-ahead prices. The increase in peak demand could lead to higher needed investments into the electricity grid infrastructure if prosumagers react to the same price profile. Flexibility indicators like the Flexibility Factor and GSC_{rel} suggest that prosumagers are behaving in a system-friendly way. The electricity consumption could be reduced by 0.8% in 2040 and 2050 on EU level at high price periods, which would most likely also reduce CO_2 emissions in the power sector. Simultaneously, the grid demand increases by at least 0.4% at times with low electricity prices, which could indicate a possible reduction of renewable electricity curtailment. The day ahead prices for prosumagers should not go to zero because the excessive demand increase in these hours could lead to higher electricity peak demand on a national level and due to higher losses might be less system friendly than using positive prices.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Software availability

The source code for the FLEX model can be found on GitHub[2].

References

[1] Sperber, Evelyn, Schimeczek, Christoph, Frey, Ulrich, Cao, Karl Kiên, Bertsch, Valentin, "Aligning heat pump operation with market signals: A win-win scenario for the electricity market and its actors?," Energy Reports, vol. 13, pp. 491–513, 2025. DOI: https://doi.org/10.1016/j.egyr.2024.12.028

[2] Yue, Lu, Niu, Jide, Tian, Zhe, Lin, Quanyi, Lu, Yakai, "A three-dimensional evaluation method for building energy systems to guide power grid-friendly interactions during the planning and operational stages," Journal of Building Engineering, vol. 86, pp. 108816, 2024. DOI: https://doi.org/10.1016/j.jobe.2024.108816

[3] Balmorel Community, "Balmorel Code," , vol. , pp. , 2022.

[4] Wiese, Frauke, Bramstoft, Rasmus, Koduvere, Hardi, Pizarro Alonso, Amalia, Balyk, Olexandr, Kirkerud, Jon Gustav, Tveten, Åsa Grytli, Bolkesjø, Torjus Folsland, Münster, Marie, Ravn, Hans, "Balmorel open source energy system model," Energy Strategy Reviews, vol. 20, pp. 26–34, 2018. DOI: 10.1016/j.esr.2018.01.003

[5] Schöniger, Franziska, Morawetz, Ulrich B., "What comes down must go up: Why fluctuating renewable energy does not necessarily increase electricity spot price variance in Europe," Energy Economics, vol. 111, pp. 106069, 2022. DOI: https://doi.org/10.1016/j.eneco.2022.106069

[6] Andreas Müller, "Energy Demand Assessment for Space Conditioning and Domestic Hot Water: A Case Study for the Austrian Building Stock, vol. , pp. 285, 2015. URL: https://www.invert.at/Dateien/Dissertation-AndreasM.pdf

[7] Reynders, Glenn, Diriken, Jan, Saelens, Dirk, "Generic characterization method for energy flexibility: Applied to structural thermal storage in residential buildings," Applied Energy, vol. 198, pp. 192–202, 2017. DOI: https://doi.org/10.1016/j.apenergy.2017.04.061

[8] Le Dréau, J., Heiselberg, P., "Energy flexibility of residential buildings using short term heat storage in the thermal mass," Energy, vol. 111, pp. 991–1002, 2016. DOI: https://doi.org/10.1016/j.energy.2016.05.076

[9] Hall, Monika, Geissler, Achim, "Comparison of Flexibility Factors and Introduction of A Flexibility Classification Using Advanced Heat Pump Control," Energies, vol. 14, pp. 8391, 2021. DOI: https://doi.org/10.3390/en14248391

[10] Klein, Konstantin, Langner, Robert, Kalz, Doreen, Herkel, Sebastian, Henning, Hans-Martin, "Grid support coefficients for electricity-based heating and cooling and field data analysis of present-day installations in Germany," Applied Energy, vol. 162, pp. 853–867, 2016. DOI: https://doi.org/10.1016/j.apenergy.2015.10.107

[11] Klein, Konstantin, Herkel, Sebastian, Henning, Hans-Martin, Felsmann, Clemens, "Load shifting using the heating and cooling system of an office building: Quantitative potential evaluation for different flexibility and storage options," Applied Energy, vol. 203, pp. 917–937, 2017. DOI: https://doi.org/10.1016/j.apenergy.2017.06.073

[12] Kathirgamanathan, Anjukan, Péan, Thibault, Zhang, Kun, De Rosa, Mattia, Salom, Jaume, Kummert, Michaël, Finn, Donal P., "Towards standardising market-independent indicators for quantifying energy flexibility in buildings," Energy and Buildings, vol. 220, pp. 110027, 2020. DOI: https://doi.org/10.1016/j.enbuild.2020.110027

[13] Cuiling Wang, Baolong Wang, Fengqi You, "Demand response for residential buildings using hierarchical nonlinear model predictive control for plug-and-play," Applied Energy, vol. 369, pp. 123581, 2024. DOI: https://doi.org/10.1016/j.apenergy.2024.123581

[14] Reynders, G., Nuytten, T., Saelens, D., "Potential of structural thermal mass for demand-side management in dwellings," Building and Environment, vol. 64, pp. 187–199, 2013. DOI: https://doi.org/10.1016/j.buildenv.2013.03.010

[15] Lind, Johan, Möllerström, Erik, Averfalk, Helge, Ottermo, Fredric, "Energy flexibility using the thermal mass of residential buildings," Energy and Buildings, vol. 301, pp. 113698, 2023. DOI: https://doi.org/10.1016/j.enbuild.2023.113698

[16] Golmohamadi, Hessam, "Stochastic energy optimization of residential heat pumps in uncertain electricity markets," Applied

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[2] https://github.com/H2020-newTRENDs/FLEX under MIT Licence

Energy, vol. 303, pp. 117629, 2021. DOI: https://doi.org/10.1016/j.apenergy.2021.117629

[17] Sperber, Evelyn, Frey, Ulrich, Bertsch, Valentin, “Reduced-order models for assessing demand response with heat pumps – Insights from the German energy system,” Energy and Buildings, vol. 223, pp. 110144, 2020. DOI: https://doi.org/10.1016/j.enbuild.2020.110144

[18] Mascherbauer, Philipp, Kranzl, Lukas, Yu, Songmin, Haupt, Thomas, “Investigating the impact of smart energy management system on the residential electricity consumption in Austria,” Energy, vol. 249, pp. 123665, 2022. DOI: https://doi.org/10.1016/j.energy.2022.123665

[19] Zhang, Yichi, Johansson, Pär, Kalagasidis, Angela Sasic, “Techno-economic assessment of thermal energy storage technologies for demand-side management in low-temperature individual heating systems,” Energy, vol. 236, pp. 121496, 2021. DOI: https://doi.org/10.1016/j.energy.2021.121496

[20] Mascherbauer, Philipp, Martínez, Miguel, Mateo, Carlos, Yu, Songmin, Kranzl, Lukas, “Analyzing the Impact of Heating Electrification and Prosumaging on the Future Distribution Grid Costs,” , vol. , pp. , 2024. DOI: https://doi.org/10.1016/j.apenergy.2024.124997

[21] Yue, Lu, Niu, Jide, Tian, Zhe, Lin, Quanyi, Lu, Yakai, “A simplified assessment method based on Hooke’s law to estimate the grid-friendly ability of buildings,” Renewable Energy, vol. 223, pp. 119931, 2024. DOI: https://doi.org/10.1016/j.renene.2023.119931

[22] Reynders, Glenn, Amaral Lopes, Rui, Marszal-Pomianowska, Anna, Aelenei, Daniel, Martins, João, Saelens, Dirk, “Energy flexible buildings: An evaluation of definitions and quantification methodologies applied to thermal storage,” Energy and Buildings, vol. 166, pp. 372–390, 2018. DOI: https://doi.org/10.1016/j.enbuild.2018.02.040

[23] Elma, Onur and Kuzlu, Murat and Pipattanasomporn, Manisa, ”A Smart Direct Load Control Approach Using Dynamic Voltage Control for Demand Response Programs”, Electric Power Components and Systems, vol. 50, pp. 738-750, 2022. DOI: 10.1080/15325008.2022.2139869

[24] S. Valovcin, N. Abe and B. Massey, ”Using Smart Meter Data to Estimate Demand Reductions from Residential Direct Load Control Programs,” 2022 IEEE International Smart Cities Conference (ISC2), Pafos, Cyprus, 2022, pp. 1-6, DOI: 10.1109/ISC255366.2022.9922481