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Flexibility Potential in the Austrian Building Sector

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Abstract. What would happen if 15% of the Austrian building stock in 2030 – both refurbished and newly-built – would use flexible heating/cooling systems to offer their flexibility on a market? How much annual residual loads from volatile renewable energy sources (RES) could be absorbed? Our simple agent-market model says: ~5% of annual national RES surpluses and around 2% of annual national RES residual loads. The efficiency of storing this electricity thermally through TABS and heat pumps is approximately 70%, co-benefits are higher indoor temperatures in winter and lower indoor temperatures in summer. In this model, buildings are agents offering additional electricity consumption from pre-emptive HVAC operation, effectively using the building mass as storage, their energy demand is modelled in a simple thermal RC model. The grid flexibility demand is derived from future residual load scenarios and the offered flexibility depends both on signal parameters, mainly signal frequency and duration, and on key building parameters indoor temperature comfort bounds, building mass and thermal envelope quality.

Keywords: Energy Flexibility, Building Stock, Demand-Side-Management

1. Introduction

Austria's climate goals call for a 100% renewable electricity supply by 2030 and climate neutrality by 2040 [1]. The significant expansion of (volatile) renewable energy sources necessitates increased dispatch flexibility [2], [3], [4]: Despite an expected decrease in annual residual load until 2030, temporal residual load fluctuation are projected to remain similar to 2020 in magnitude and frequency [5]. Approximately 39% of the Austrian building stock (residential) needs to be renovated, to reach national and European climate goals, the renovation rate must increase rapidly and strongly by 2030 and 2040 [6].

“Building as a battery” means converting electricity into an increase/decrease in building core and indoor temperature, storing the electricity thermally with heat-pumps and low-temperature heating/cooling systems such as thermal activated building systems (TABS) [7]. The efficiency and cost-effectiveness of these systems is high [8], but subject to a number of constraints [9]. Their operation is unidirectional: The thermal storage can only be charged actively but discharge is a passive operation constantly happening over time. The charging and discharging speeds depend on building properties, differ between building types and determine the optimal frequency and duration of flexible operation: Highly efficient buildings can absorb and increase their demand for just a few hours before reaching comfort bounds, yet are able to maintain adequate temperatures for days to weeks in comparison to less insulated buildings [10].

This paper presents a dynamic dispatching model including a centralized flexibility “buyer” (surplus electricity, DSM signal) and over 1000 independent providers or “sellers” of flexibility (buildings) representing approximately 14% of the future Austrian building stock. The study explores the possible extent and efficiency of load shifting from TABS, considering different qualities of the building sector as well as different demand signal characteristics. Ultimately, the paper aims to quantify the potential of the TABS systems in the building sector for strategic grid-support utilization in the year 2030.

2. Methods

2.1 Building model

The method contains three parts: First, future building stock was modeled with a typological approach. Estimates Renovation rates and Qualities were based on established literature [4], [6] and summarized in 36 building types, categorized by geometry, thermally active building mass, quality of thermal hull and building main usage.

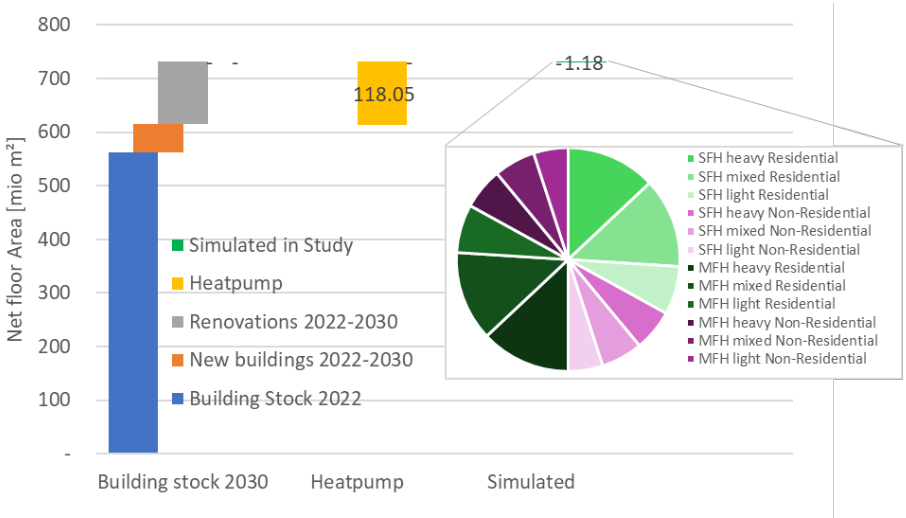

Figure 1. *Building stock 2030, with 16% net floor areas heated and cooled with heat pumps*

To reduce the number of individual building simulations, the initial pool of potential buildings (newly built or renovated) using heat pumps amounting to 118 million square meters net floor area (NFA) was divided into hundred equal slices, each representing 1.18 mio m²NFA of the potential building stock. Only one such section was subsequently populated by the following 2000 buildings, divided in 36 distinct types.

***Table 1. Model Building characteristics**: "Compactness" = Ratio of Building Surface to Volume, "SFH" = Single Family Homes, "MFH" = Multi-Family Homes*

Building Geometry		**Construction**		**Usage**	**Building sector Model**	
Type	Compact-ness [A/V]	**Type**	Thermally active Building mass [Wh/m²K]	**Type**	**Share**	**# of Buildings in Simulaton**
SFH	0.35	heavy	204	Residential	13%	70
SFH	0.35	mixed	135	Residential	13%	70
MFH	0.67	mixed	135	Residential	13%	461
MFH	0.67	heavy	204	Residential	13%	461

SFH	0.35	light	60	Residential	7%	375
MFH	0.67	light	60	Residential	7%	247
SFH	0.35	heavy	204	Non-Residential	6%	34
SFH	0.35	mixed	135	Non-Residential	6%	34
MFH	0.67	mixed	135	Non-Residential	6%	226
MFH	0.67	heavy	204	Non-Residential	6%	226
SFH	0.35	light	60	Non-Residential	5%	30
MFH	0.67	light	60	Non-Residential	5%	197

The thermal quality of the building is modeled in three categories MIN, MIDI and MAX resulting in 12 types, characterized by their effective thermal transmission conductance and air exchange rates, as shown in Table 2.

Table 2. *Thermal quality types of building stock: quality described by transmission conductance and thermal effective air exchange rate (ventilation and infiltration)*

Thermal Quality				
Type	Usage type	Building Geometry	Transmission conductance [W/K]	Effective thermal air exchange rate [1/h]
MIN	Residential	SFH	0.98	0.50
		MFH	0.52	0.50
	Non-Residential	SFH	1.04	1.60
		MFH	0.55	1.60
MIDI	Residential	SFH	0.56	0.50
		MFH	0.30	0.50
	Non-Residential	SFH	0.60	1.60
		MFH	0.32	1.60
MAX	Residential	SFH	0.42	0.12
		MFH	0.22	0.12
	Non-Residential	SFH	0.46	0.40
		MFH	0.24	0.40

The composition of building types in the total building stock is the same for all slices and modelled for three scenarios of varying ambition: REF, MIN and MAX. The scenarios and their corresponding distributions are as follows:

Table 3. *Scenarios for Building Sector Quality; Proportion of the Sector by Building Quality*

Building stock scenario	**Building thermal quality distribution**	**Description**
REF	MIN 33% MIDI 33% MAX 33%	**Equal** distribution across all three building qualities

MIN	MIN 50% MIDI 30% MAX 20%	Majority in the **lowest** quality category
MIX	MIN 20% MIDI 30% MAX 50%	Majority in the **highest** quality category

The thermal model for each building is a simple RC-Model, realized by a thermal capacity in the form of the thermally effective storage mass, a temperature difference-dependent heat flow (transmission and ventilation) and two external heat flows in the form of solar and internal gains. The thermally effective storage mass and the transmission conductance remain constant over the course of the year, while the ventilation, conductance and the internal gains are subject to daily and seasonal changes due to occupancy profiles and solar inputs due to the given climate data. The thermal model for each hourly timestep is schematically depicted in the following Figure 2.

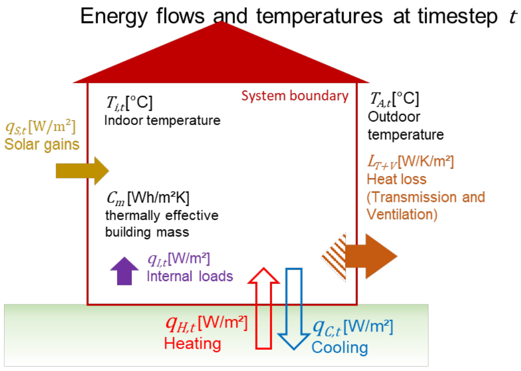

Figure 2. *Building thermal energy model for each hourly timestep t*

Formulas 1 and 2 illustrate the reference conditioning scenario. According to heat losses from transmission and ventilation as well as solar gains and internal loads, an hourly balance is determined and covered by the thermal heating or cooling load.

$$q_{H,t} = c_m(T_{set,REF} - \left(T_{i,t-1} + \frac{L_{T+V}(T_A - T_{i,t-1}) + q_{S,t} + q_{I,t}}{c_m}\right)) \tag{1}$$

$$T_{i,REF,t} = T_{i,t-1} + \frac{q_{H,t}}{c_m} \tag{2}$$

Formula 3 describes the thermal output for the case of Demand-Side-Management. In this case, the output is increased compared to the reference conditioning: This increase in output is limited by either the available output of the heat pump or the reached extended setpoint temperature.

$$q_{DSM,t} = q_{H,t} + \min(c_m(T_{set,DSM} - T_{i,REF,t}); q_{WP,max}) \tag{3}$$

The remaining maximum available output (thermal) of the heat pump is defined by formulae 4 and 5. In formula 4, the original maximum load is defined by the yearly maximum loss coefficient, the maximum temperature difference (between outdoor and set point temperatures) and the oversizing factor 1.3. The setpoint temperature-dependent control variable $f_{i,wp}$ (defined in formula 5) and the thermal output required for reference conditioning result in the remaining thermal output potential.

$$q_{WP,max,t} = f_{i;WP}((\max L_{T+V} * 30.4 * 1.3) - q_{H,t}) \quad (4)$$

$$f_{i;WP} = \min(1; \frac{dT}{2} + 0.5) \quad (5)$$

Formula 6 determines the room temperature after extended setpoint temperature control (DSM).

$$T_{i,t} = T_{i,REF,t} + \frac{q_{DSM,t}}{c_m} \quad (6)$$

The HVAC control modules consist of two parts, both resembling an ideal regulation: the first decides whether to heat or to cool based on static indoor temperature setpoints (reference control). The second part controls the demand side management on the buildings side, deciding on heating/cooling but also integrates a more realistic heat pump control. While DSM-Control the heat pump operates with a power curve depending on the temperature difference between room temperature and extended set point temperature (actual value to setpoint). Table 4 showsthe operational parameters of the HVAC System.

Table 4. *Operation parameters of HVAC System*

Parameter	Value
Minimum Indoor Temperature	22°C
Maximum Indoor Temperature	26°C
Set-Point Indoor Temperature	24°C
Heat-pump oversizing above reference heat load maximum	130%
Seasonal performance factor (SPF)	4.5
Distribution losses	10%

2.3 Flexibility Demand Signal

In line with the grid efficiency principle of "adapting demand to renewable supply", the signal used is a comparison of the generation and demand forecasts for 2030, ENTSOE time series (generation and load) for 2022 [11] linearly scaled to the Austrian government's expansion targets' equivalent 100% renewable electricity balance [12], called "*RES_Basic*". In addition to this base signal, four additional signals with different characteristics are used from research project FLUCCO+ [13] to analyse different signal durations, frequencies and seasonal distributions, which are described in Table 5. To better resolve the dynamic effects of the diverse building pool, which is only a subset of the entire building stock, the additional signals annual energy balance is scaled to match that of the investigated building pool reference energy demand.

Table 5. *Flexibility demand signals*

Signal	Method	Description	Source	Variations
RES_Basis	Hourly Renewable Surplus	Surplus Renewable 2030 with renewable energy expansion according to government targets	[11],[12]	Unscaled

<table>
<tr><td>HR50</td><td>Residual Load</td><td>Projection for 2050</td><td>[12]</td><td rowspan="3">Scaled to x% of building stock reference energy demand
<table><tr><th>Variation</th><th>x</th></tr><tr><td>Default, Flex100</td><td>100%</td></tr><tr><td>Flex50</td><td>50%</td></tr><tr><td>Flex200</td><td>200%</td></tr><tr><td>Etc.</td><td></td></tr></table></td></tr>
<tr><td>UBA</td><td>Wind Surplus</td><td>Surplus Renewable without PV based on renewable energy expansion according to Federal Environment Agency</td><td>[13]</td></tr>
<tr><td>PD18
PD20</td><td>Wind Forecast Error</td><td>Error between Wind Power Forecasts at the Intraday Market and actual Wind power, Austria 2018 - 2020</td><td>[13]</td></tr>
</table>

Figure 3 shows the variation in signal duration, frequency and seasonal distribution, which can have a significant impact on the potential utilization and flexible operation of the different building types.

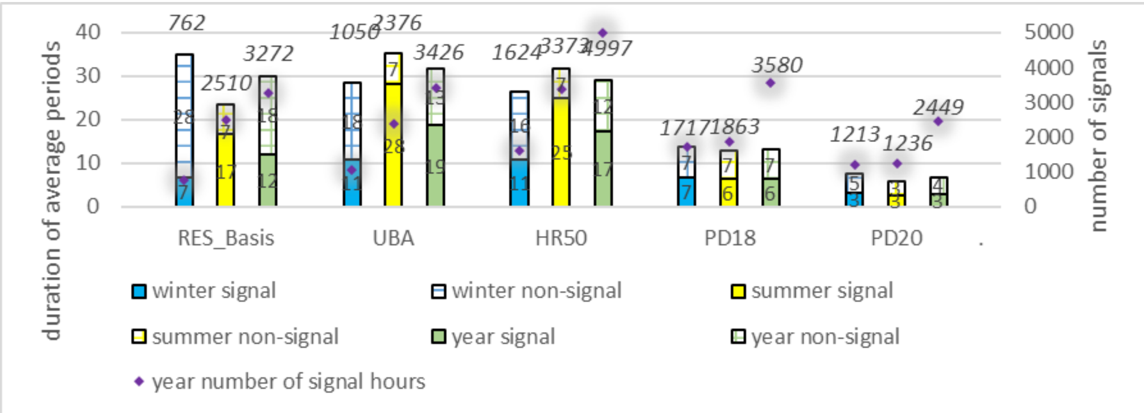

Figure 3. *signal analysis: average signal duration, non-signal duration and number of signal hours per season and year*

Figure 4 shows the annual distribution of energy surpluses from different sources that are used as signals for flexible demand increase in the building sector in this study. PD18 and PD20 magnitudes, both being wind forecast errors, correlate with times of higher wind production, whereas general RES surpluses *RES_basis* and *UBA* show higher flexibility demand in summer due to increased PV power. This trend is less visible in *HR50*, where PV is not considered in surplus calculation.

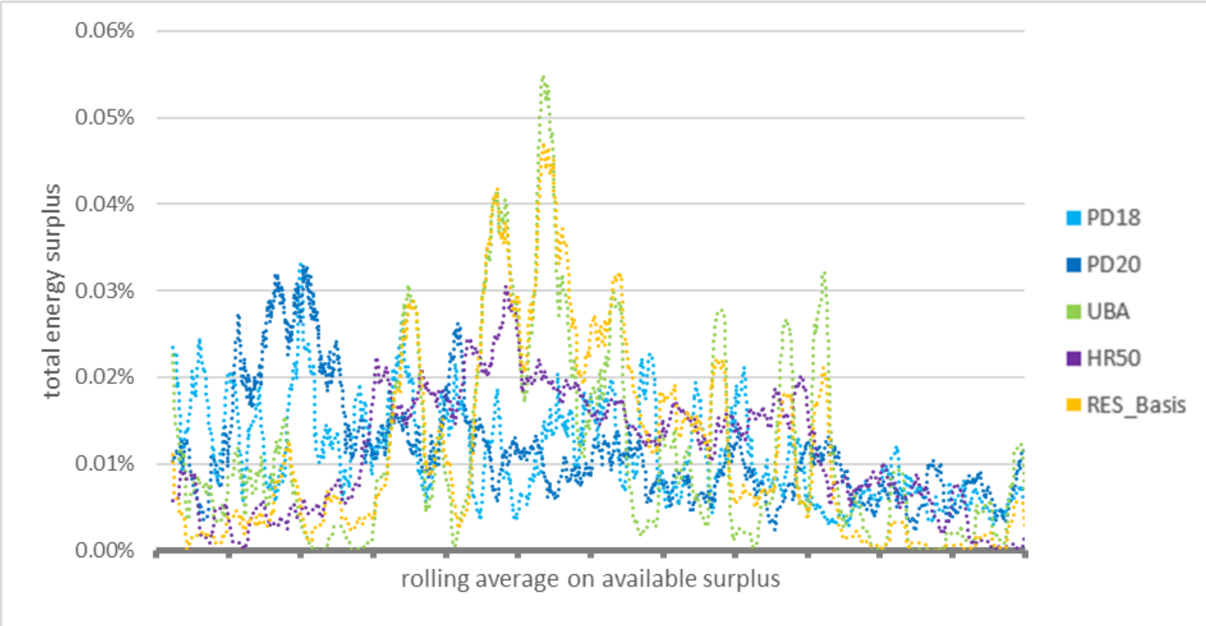

Figure 4. *Annual distribution of energy surpluses from different sources that are used as signals for flexible demand increase in the building sector*

2.3 Flexibility Dispatch

The hypothetical flexibility market developed attempts to distribute the available surplus as efficiently as possible. As such, the grid surplus is regarded as a valuable, limited resource; however, this also offers the possibility of integrating additional market participants (e-cars, etc.) for further work. Figure 5 shows the scheme of one simulated time step: after a first temperature control on reference set points, the market mechanism takes place and results in an algorithm-based distribution of the available surplus. The time step closes with the recording of consumed electricity and the newly set room temperature.

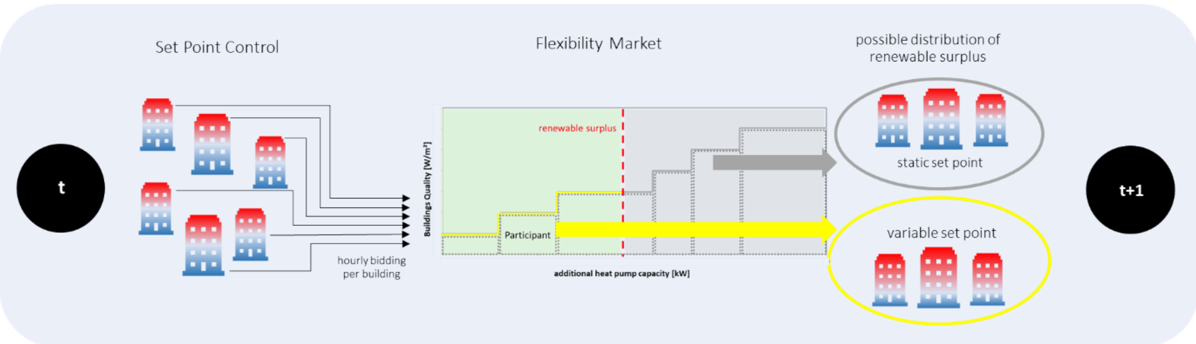

Figure 5. *schematic representation of a simulated hour: firstly the static (reference) control on minimal set points, secondly the flexibility market and last the distribution of surplus regarding an extended set point*

The flexibility mechanism comprises the submission of bids by each building, the ranking of bids, and the subsequent allocation of surplus after ranking. A bid consists of quality criteria and the offered capacity for consumption. Figure 6 depicts an exemplary market situation. The yellow bars represent bids from individual buildings. The height of the bar corresponds to the quality of the bid (y-axis), and the width of the bar represents the building's capacity offered for consumption (x-axis). The red line, measured on the x-axis, represents the amount of electricity available for distribution from the grid. Following the ranking of bids (already done here), the intersection of grid-side supply and building-side offers reveals which buildings are entirely or partially served concerning the intersection point.

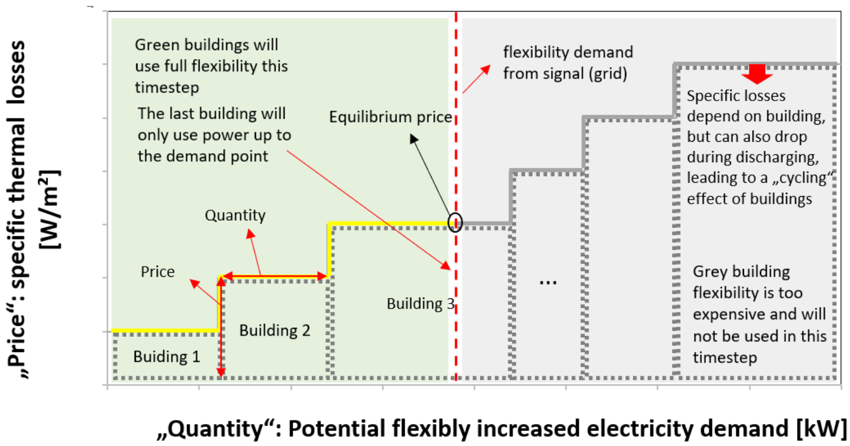

***Figure 6**. Modelled flexibility market: Flexibility supply price is based on the specific thermal losses of the building at each timestep*

In the market, flexibility capacity is offered hourly by building agents and cleared based on their estimated cost, which is defined as the expected heat loss: Better insulated buildings first.

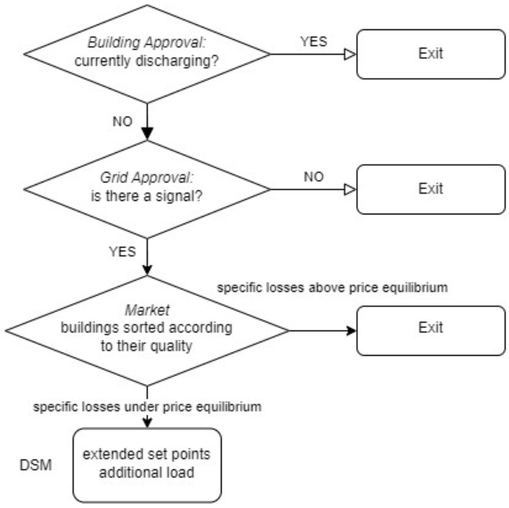

***Figure 7.** Control scheme for flexible building operation*

2.4 Flexibility assessment

The flexibility provided by the building stock is assessed by an hourly comparison of the flexible operation to the reference case: Here, the following cases can be differentiated: (1) a desired, active increase of energy demand due to TABS "charging" when a signal is present, (2) a desired, passive decrease in energy demand due to discharge in times without signal, (3) an undesired, passive decrease in energy demand due to during signals and (4) a neutral energy demand equal to the reference load. The overachievement of setpoint temperatures leads to higher thermal losses on average, which result from the difference between (1) and (2) and (3). The efficiency of this flexible TABS operation as an electrical storage (6) can be characterized by the resulting yield in "useful" energy deference (2) as a ratio of the input energy (1).

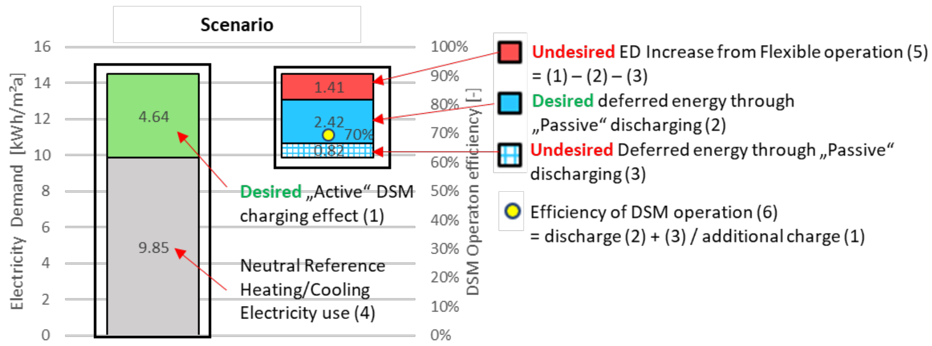

Figure 8. *Flexibility Assessment Method*

Figure 9 illustrates the hourly occurrence of the assessment criteria (KPIs) from operation during a heating period in February: Desired active charging (1) is present whenever the flexible load (green) is higher than the reference load (blue) when a signal (bottom) is present. In the absence of a signal, desired deference of energy (2) happens relative to the reference energy demand when no signal is present. In case of a present signal, deference of energy use is undesired (3). The total loss of flexible operation is determined by subtracting the desired and undesired deference of reference load (2 and 3) from the additional flexible load (1).

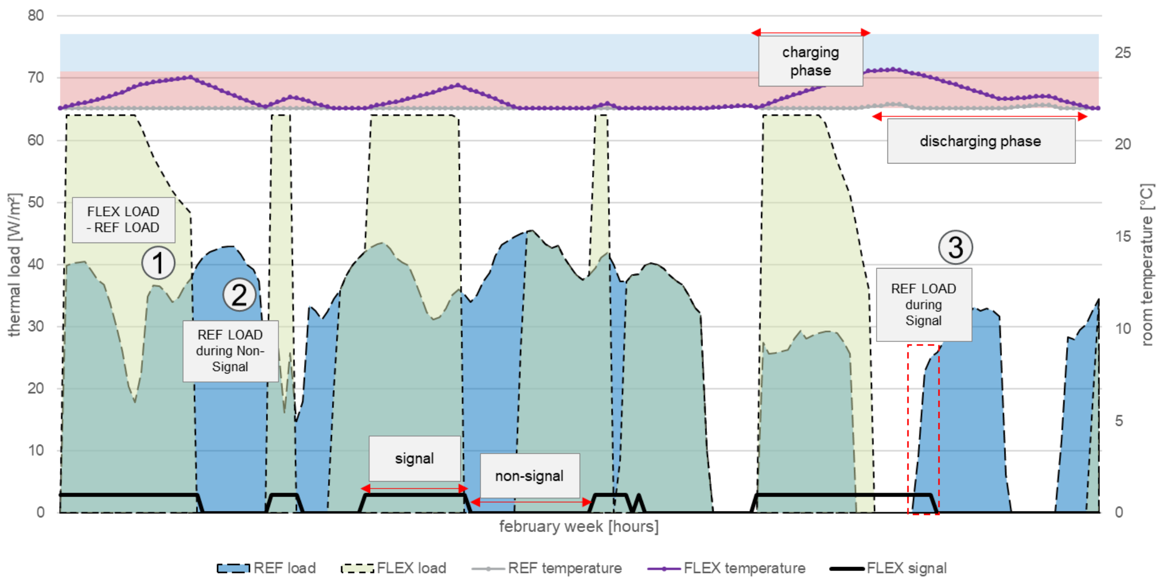

Figure 9. *load and room temperature comparison of with and without dsm DSM (ref, flex) in an exemplary February week*

3. Results

First, Figure 10 shows what can happen if buildings were not forced to discharge their built up thermal storage after they reach their maximum temperature setpoint: When the signal to charge is given to often or too frequently to allow buildings to completely discharge their thermal storage, this raises the effective average indoor temperature and incurring higher thermal losses as a consequence. Even though the times of active charging relative to all HVAC operation (green) is significantly higher than in the other investigated scenarios, so are the resulting thermal losses (red) and the storage efficiency measured as the ratio between desired deferred energy and desired increased energy demand, both relative to the reference scenario without flexibility, which drops to just around 50%.

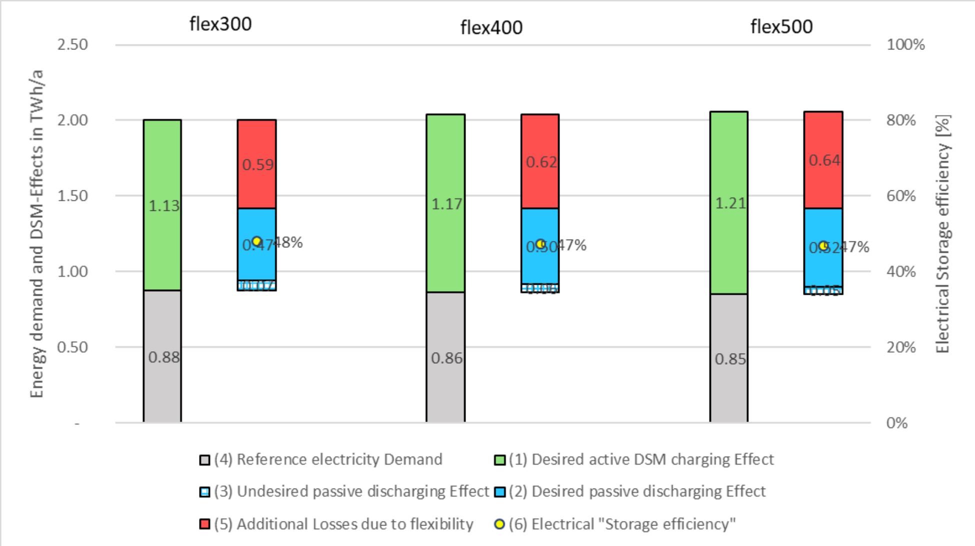

Figure 10. *PD18 assessment criteria without the interlock function*

Figure 11 shows the charging and discharging behaviour of the 36 building typologies in a winter, summer and transition month with an ideal signal being always available at possible charging times. This illustrates the importance to align signal and building characteristics, especially thermally activated building mass as the main parameter for charging and discharging speed and duration, both in heating and cooling seasons.

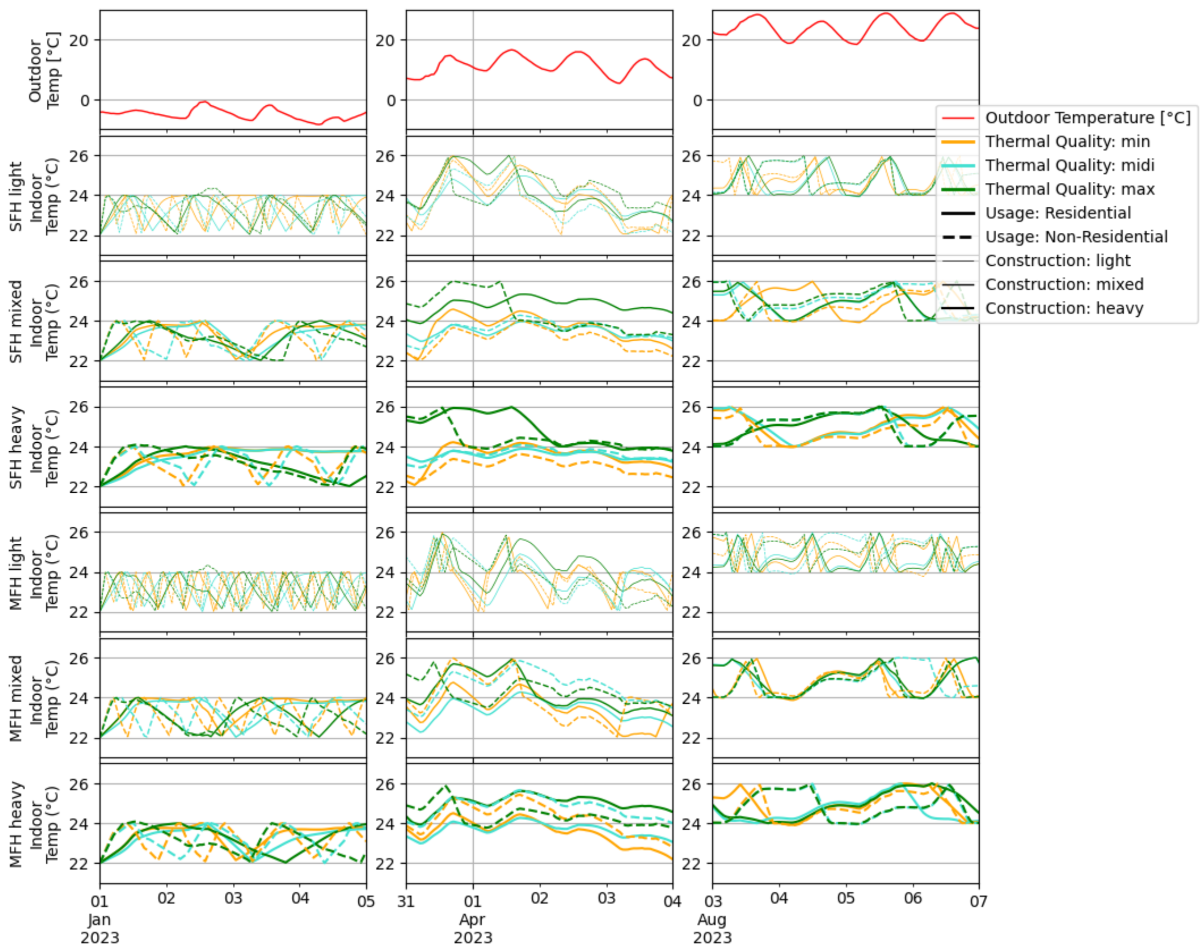

Figure 11. *Optimal indoor temperature frequencies for charging and discharging for the 36 building types in winter, spring and summer for a theoretically constant signal*

Now for the actual results: Comparing the differently ambitious scenarios of the building sector, the reference scenario can absorb 0.50 TWh (5.37 %) of surplus in the reference variant. 0.15 TWh are additionally required, 0.50 TWh can actively be shifted to times of renewable surplus and 0.26 TWh can be avoided in times of renewable shortage. The variation of the building qualities in the building sector led to deviations in the cleared surplus of -0.51 to +0.43%P. The Minimum scenario can manage the most active absorption and passive reduction but at the same time requires 28 % more energy than the Maximum scenario, also resulting in a lower efficiency.

Table 6. *Results depending on sectors quality*

	Building sector quality						
Assessment criteria	**Reference**		**Minimum**		**Maximum**		
(4) Reference electricity demand	1.42		1.60		1.25		TWh/a
(1) Desired active DSM charging Effect	0.50	35%	0.54	34%	0.45	36%	TWh/a
(2) Desired passive discharging Effect	0.26	18%	0.28	18%	0.24	19%	TWh/a
(3) Undesired Passive discharging Effect	0.09	6%	0.09	6%	0.09	7%	TWh/a
(5) Additional Losses due to flexibility	0.15	11%	0.16	10%	0.15	12%	TWh/a
(6) Electrical “Storage efficiency”	70%		70%		73%		

Figure 12 shows the monthly distribution of added or reduced emissions, including those from actively shifted energy, the theoretically prevented emissions by not resorting to emissive grid electricity, and the resulting emission reduction factors. Here, renewable electricity is assumed to emit 20 gCO2eq/kWh, while non-signal periods are applied with a monthly interpolation of the regular emission factors from the OIB RL6 [14]. Annually, this results in an emission reduction between 87 and 101 kilotons CO2eq for the whole building sector.

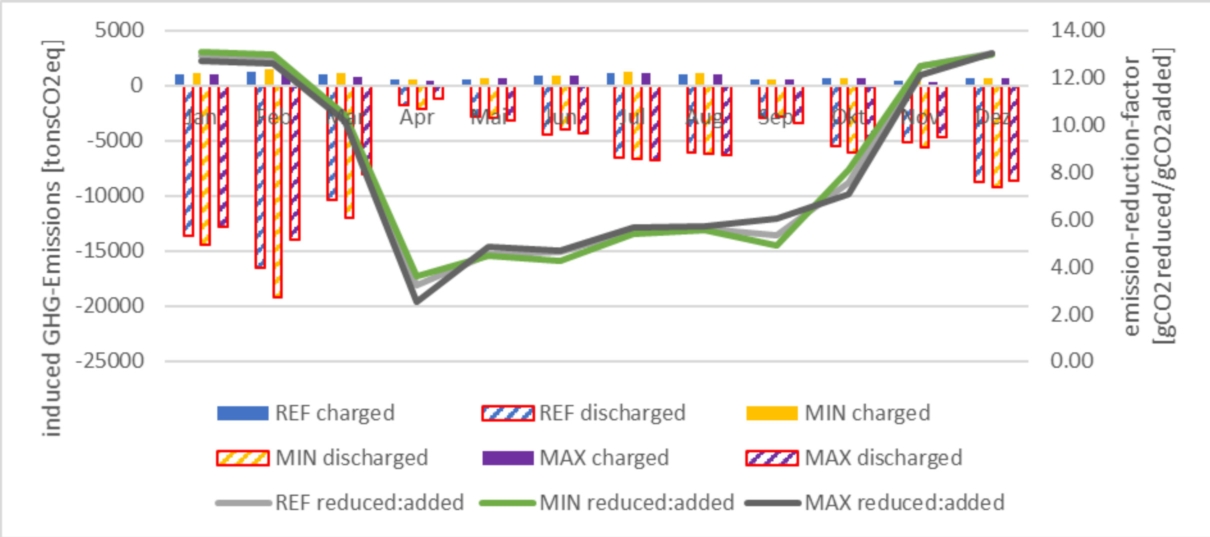

Figure 12. *Monthly emission responsibility and resulting emission reduction factor of the building sector scenarios. Ratios shown in lines are related to the secondary axis*

In Figure 13, both the coincidental grid support not induced by DSM due to reference conditioning during surplus periods (ref) and the achieved shift in electricity consumption towards grid-supportive periods are illustrated. The demand proportion during signal periods in the summer for reference scenarios ranges from 87-88%, which can be increased to 98% through load shifting, with the side effect of increasing demand by ~15%. In the winter season, the proportion of demand during signal periods can be increased from 16-17% to 41% (MIN) and up to 47% (MAX), resulting in an increase in demands of 7-9%. The MAX scenario achieves the highest reduction in demand proportion during non-signal periods.

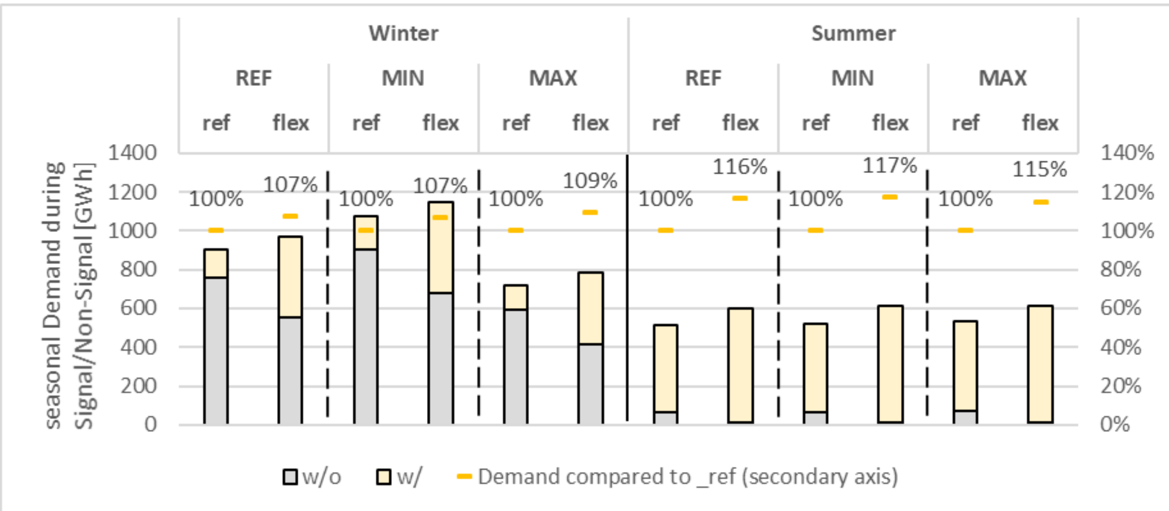

Figure 13. *Share of energy demand during Signal (w/) and Non-Signal (w/o) Hours per Season for building stock scenarios MIN, REF and MAX*

Figure 14 shows the monthly distribution of assessment criteria per building sector scenario. Active DSM charging occurs primarily in the winter and summer months and to a lesser extent in transition months April, May, September and November. Undesired discharge peaks in summer due to the predominant presence of the surplus signal, which is more than the discharge capacity of buildings. Major differences between the scenarios are not apparent.

Following this, Figure 15 shows the monthly electrical storage efficiency per building sector scenario. Highest efficiencies occur during winter and summer, with efficiencies between (0.84 – 0.90) and (0.58 to 0.70) respectively. Transition months show lower efficiencies down to 0.24 due to reduced reference demand in heating and cooling. Again, there are no significant differences between the building sector scenarios.

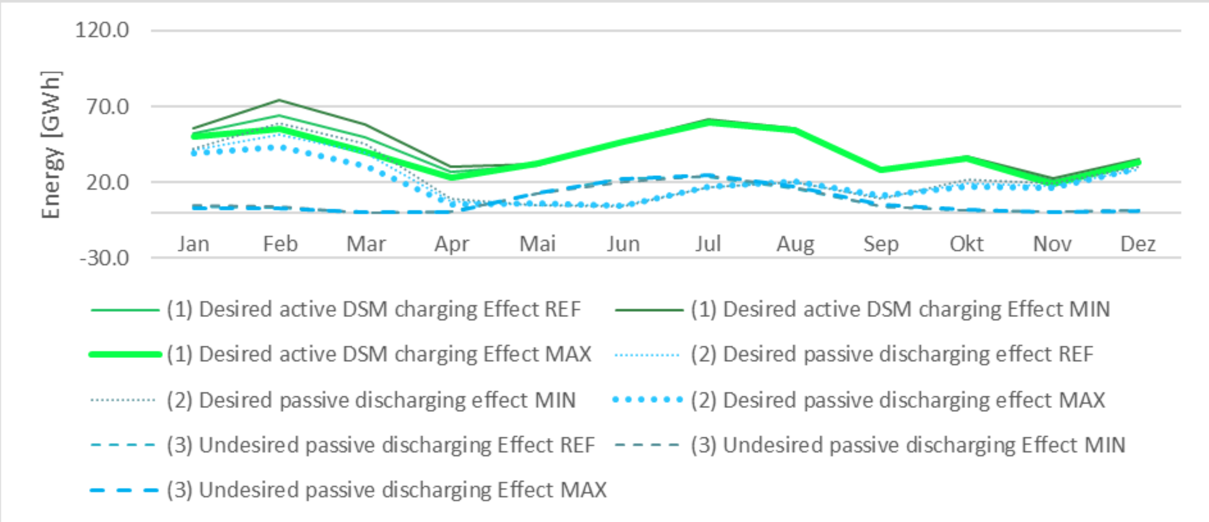

Figure 14. *monthly DSM effects for the building sector scenarios*

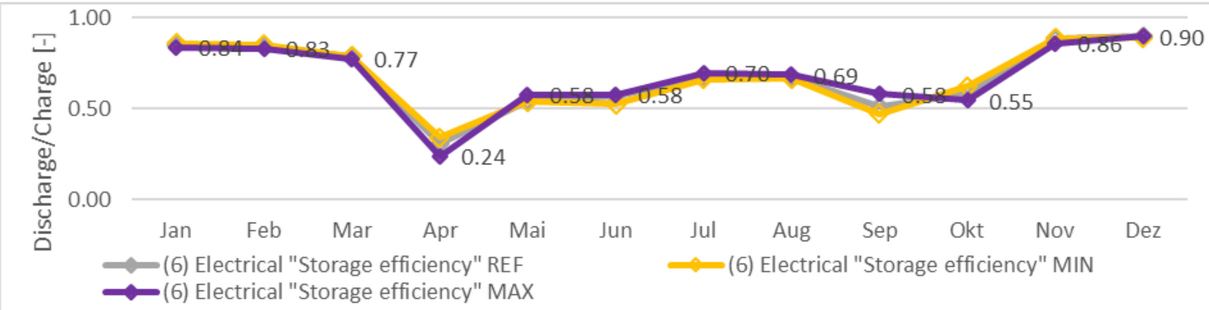

Figure 15. *monthly evaluated (6) "storage efficiency" for building sector scenarios*

In Figure 16, a comparative analysis of various scenarios reveals trends in efficiency and effectiveness of different signal characteristics on demand-side management (DSM). A visible stagnation of KPIs in every signal scenario can be seen once the annual signal surplus quantity reaches around 300% of the available flexible building energy demand. The results indicate that signals with short signal durations and seasonally evenly distributed supply achieve the highest KPIs with grid-supportive demand shifts up to 0.74 TWh (PD20_300). Signals with strong seasonality regarding signal hours and available supply all reach values of up to ~0.5 TWh in active effect with 300% surplus to flexibility. The study suggests that the optimal operation of building ensembles as flexibility participants depends on internal conditions, signal characteristics, and the availability of flexibility in the network. This underscores the importance of tailored strategies for different building ensembles based on their unique characteristics and operational constraints, inviting further investigation into optimal load management strategies for diverse building portfolios.

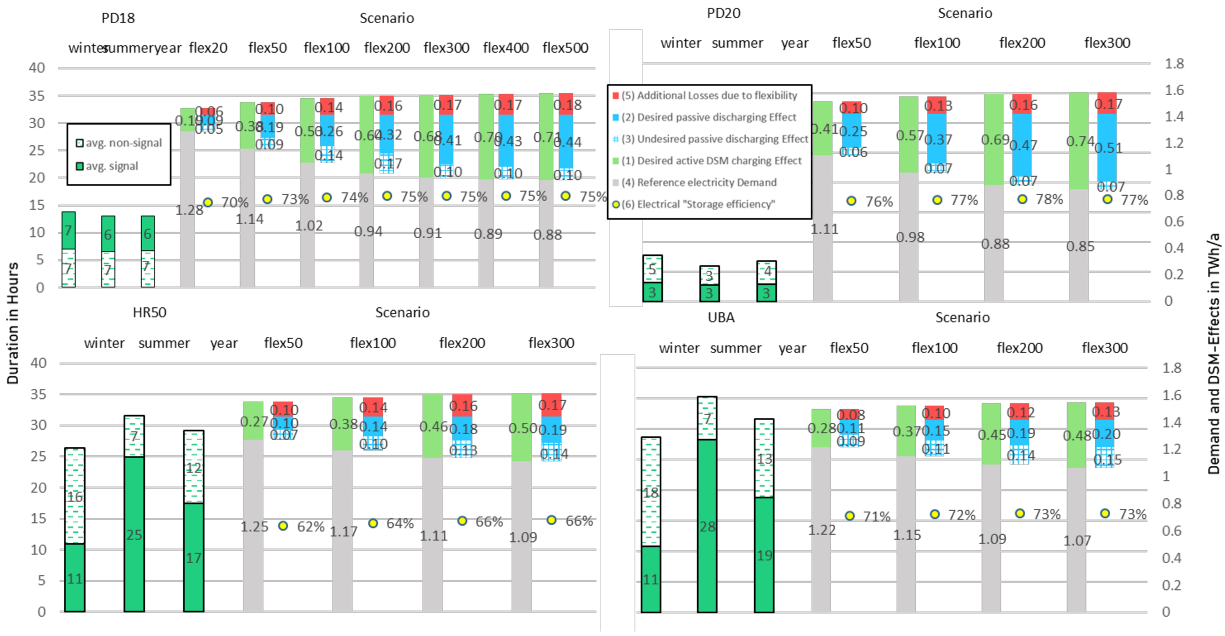

Figure 16. *Comparison of signal scenarios: assessment criteria and simplified signal analysis for signals PD18 and PD20 (Wind forecast error 2018 and 2020) on top; HR50 on the bottom left and UBA on the bottom right side*

In Figure 17 it can be observed that the two signals with seasonal characteristics (summer bias) exhibit lower efficiencies, especially during the summer months. HR50, with the longest average signal cycles and longer release periods than non-release periods, has the lowest efficiencies. Conversely, PD20, with the highest signal frequency, has the highest efficiency in most months.

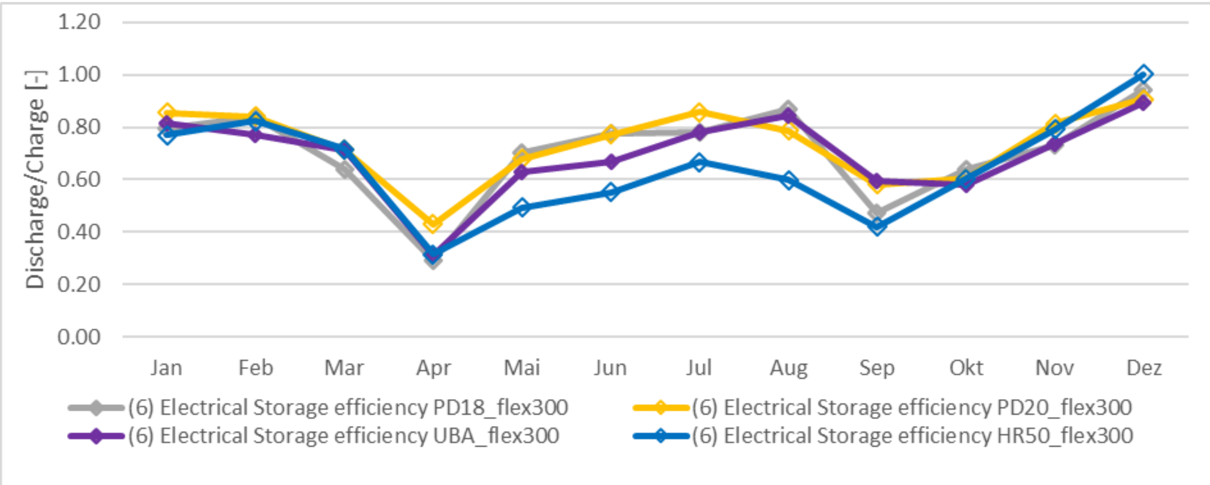

Figure 17. *monthly electrical storage efficiency for four signal scenarios*

4. Conclusion

The results show that active and passive flexibility potentials range between 0.25 TWh and 0.74 TWh annually depending on flexibility signal and response, with relatively high storage efficiencies of around 70%. This emphasises potential systemic benefits of a regulated implementation of DSM.

When comparing differently ambitious adoption scenarios in the building sector, approximately 5% (0.5 TWh) of the annual required flexible load increase and 2% (0.26 TWh) of the annual required flexible load deference can be achieved by TABS operation in the building sector. These figures could be increased by around 0.25 TWh each through shorter, more frequent, and more uniformly distributed flexibility demand signals throughout the year.

The model used and the implementation of DSM in the building sector present an opportunity to enhance energy flexibility by qualitatively distributing surpluses based on aggregated demand. Future research should focus on optimizing signals for specific building pools, integrating additional flexibility options such as electric vehicles and storage solutions, and assessing the operational and macroeconomic significance of enhanced renewable integration.

One of the major challenges lies in consumer participation and the development of business models for energy utilities. Therefore, a closer examination of the economic component is necessary. Energy policy statements should explore both the energy-economic comparison with other flexibility options and the customization of DSM regulations based on signal-to-building(pool) coupling. From the perspective of an energy provider with a pool of available buildings, building classes could be assigned a type of metric indicating which type of signal would be most effective or which buildings promise the greatest benefit. Further investigations with a small number of buildings, possibly through community energy cooperatives, would be needed to compete with other flexibility technologies and to test optimized signals. Geographic and climatic differences should also be considered to evaluate the applicability of DSM in various regions and possible benefits through simultaneity.

Data availability statement

The result data is publicly available at https://github.com/simonschaluppe/FLUCCOplus .

Underlying and related material

Publicly available and referenced datasets were analysed in this study.

Author contributions

Conceptualization, Formal Analysis, Investigation: Raphael Drexel

Methodology, Writing, Visualization: Raphael Drexel, Simon Schneider

Competing interests

The authors declare that they have no competing interests.

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