https://doi.org/10.1051/e3sconf/202236213004

Development and testing of load flexibility KPIs in the ZEN definition

Igor Sartori[1*], Synne Lien[1], Marius Bagle[1], Harald Walnum[1], Benjamin Manrique[1]
[1] SINTEF Community, Architectural Engineering, Oslo, Norway
[*] *corresponding author: igor.sartori@sintef.no*

Abstract

This paper discusses the flexibility KPIs proposed in the context of the Zero Emission Neighborhood (ZEN) definition for characterizing how a building or neighborhood exchanges energy with the surrounding energy system and presents preliminary results of testing them on single, archetype buildings. The KPIs are calculated as the deviation of a flexible load from a baseline, typical load. The results depend on the flexibility sources activated, as well as the flexibility drivers and flexibility goals deployed for the activation. It is shown how the mechanism of flexibility works and how the KPIs can be graphically represented, with emphasis on space heating. Numeric values of the KPIs are given in ranges, given their intrinsic case to case variability and the limited experience so far accumulated with testing them. This stated, it is shown that activating flexibility can bring reductions in ΔCost (in the range of 0% to 20%), in ΔEnergy Stress and ΔPeak power (in the range 20% to 50%) even if this is accompanied by a modest increase in ΔEnergy (in the range 0% to +5%) due to some energy losses.

Introduction

The Norwegian research center on "Zero Emission Neighborhoods" is developing a ZEN definition (Wiik, M.K. *et al.*, 2021), stating that "A zero emission neighborhood aims to reduce its direct and indirect greenhouse gas (GHG) emissions towards zero over the analysis period". The ZEN definition includes seven categories that focus on different aspects, using clearly defined key performance indicators (KPIs) to assess the quantitative and qualitative status and progress of ZEN pilot areas towards the emission reduction goal. One of these categories is the "Power" category (or "Load", in Norwegian: *Effekt*) that has the goal to "Manage energy flows (within and between buildings) and exchanges with the surrounding energy system in a flexible way".

The Power KPIs are described in more detail in a guideline (Wiik, M.K. *et al.*, 2022), which is currently under review. The Power KPIs are evaluated for electricity and district heating (which are the two energy carriers supplied by a grid, in Norway) and are divided into two assessment criteria: Load performance and Load flexibility. The Load performance criterion contains KPIs on the dimensioning peak load and peak export and evaluate the strain of the peak loads on the grids. The Load flexibility criterion shall reflect whether the building or neighborhood exchanges with the surrounding energy system in a flexible way, and its KPIs are still under development and are presented in this paper.

In order to define flexibility KPIs it is first necessary to define energy flexibility means. For the purpose of the ZEN definition and of this paper, and rephrasing the definition given in IEA-EBC Annex 67 (2019), Energy flexibility is defined as the ability of a building or neighborhood to manage its demand, storage and local generation to respond to external signals, while safeguarding user needs and comfort. This results in load profiles (i.e. hourly, or sub-hourly, values of net energy demand) on the grids that deviate from typical ones.

In turn, this implies the necessity to establish a reference load profile against which to measure the deviation. This is in line with the general methodology adopted for the assessment of KPIs in the ZEN definition, where a reference project is used for documenting and comparing the performance of a ZEN pilot area (Lien *et al.*, 2021). In that work, the reference project is described as the same ZEN pilot area but designed/renovated according to today's standards, so to act as a benchmark with reference values to document how much a ZEN pilot area has managed to improve its performance in the various KPI categories.

The focus of the load flexibility KPIs presented here is on the effects of energy flexibility rather than on the characteristics of flexibility itself. In this sense this work differs from most studies that try to characterize the properties of energy flexibility, well summarized in Knotzer *et al.* (2019). Rather, the flexibility KPIs presented here are similar to the Flexibility Indicators described in detail in Junker *et al.* (2018). The difference is that those indicators are based on the Flexibility Function (a property characterizing a flexibility resource), introduced in the same paper, while these ones are calculated directly on the results of two alternative projects (also named cases or scenarios), in line with the way all ZEN definition KPIs are calculated.

Methods

The methodology for calculating the load flexibility KPIs is based on the comparison of two scenarios; one flexible, where flexibility sources are activated in order to achieve a goal, in response to a driver, vs. a reference baseline that is insensitive to the driver, as shown schematically in Figure 1. The indicators are given by the difference in selected quantities, over the observation/simulation period, and expressed in percentage over the reference baseline values. The following load flexibility KPIs are thus defined:

- ΔEnergy, the difference in total energy use.
- ΔCost, the difference in operational cost due to energy use.
- ΔEnergy stress, the difference in energy use during hours that are predefined as stressful for the energy system, e.g. peak load hours for the grid, tyically occurring in early morning and late afternoon during workdays, in Norway[1].
- ΔPeak, the difference in peak load (usually referring to imported energy, but may apply also to exported energy).

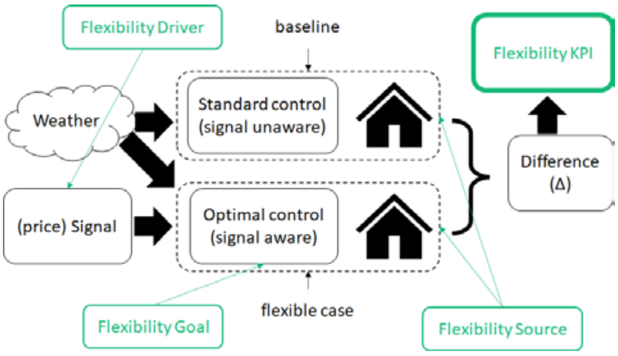

Figure 1: Schematics of the methodology for calculating the load flexibility KPIs.

As shown in Figure 1, the activation of flexibility source depends on the driver(s) as well as the goal that is pursued. Thus, flexibility KPIs can be calculated for combinations of three elements: flexibility source, flexibility driver and flexibility goal. Figure 2 provides a visual summary of such combinations.

Flexibility Source	Domestic Hot Water (DHW)	Space Heating (SH)	Electric Vehicle (EV)	All together
Flexibility Driver	Energy price	+	Grid tariff	
	Spot Price	Time of Use	Energy Pricing (EP)	Peak Power Monthly (PPM)
Flexibility Goal	(operational) Cost minimization (for the user)		Flat profile (as possible, containing losses)	

Figure 2: Visual summary of flexibility drivers and goals, in combination with different flexibility sources.

The flexibility sources considered are Domestic Hot Water tank DHW), Space Heating (SH), Electric Vehicle charging (EV), activated individually as well as together. This is because a large amount of flexibility is intrinsically available in the buildings' thermal mass and existing equipment, such as heat storage and the charging of EV, which mostly happens in connection with buildings.

The flexibility drivers considered are a combination of energy price and grid tariff, applicable to either electricity or district heating. The energy price may be a spot price or a Time of Use (ToU) price signal. The grid tariffs considered are two:

- Energy Pricing (EP), is a grid tariff that is proportional to the amount of energy used, appling either a fix cost of a ToU cost per kWh.
- Peak Power Monthly (PPM), is a grid tariff that, on top of an energy-proportional component, also has a peak power, or peak load, component. This component sets a penalty for hourly energy demand that exceed a reference (subscription) value that, in this case, is different each month.

Both tariffs contain also a fixed component and the details of how the tariffs are structured reflect the tariff applied to commercial buildings by some of the grid operators in Norway, as communicated within the "Flexbuild" project[2], and can be found in Lindberg *et al.* (2020) and Sartori *et al.* (2022). In case of the PPM tariff, in the flexible scenario the optimizer finds the most convenient level for the monthly peak power values.

The flexibility goals considered are cost minimization and flat profile. Minimization of (energy use related) cost is intended from the end-user's viewpoint. This is always combined with a driver that is the energy cost resulting from both energy price and grid tariff. The flat profile goal pursues a flattening of the load profile, as much as possible under a constraint on the associated energy loss (e.g. < 5% or 10% of the baseline energy use). Thus, the flat profile will, at the cost of some energy loss, not only smooth the high peaks – in a similar fashion as a PPM tariff – but also avoid "deep valleys" and sudden changes in the energy demand. These features might be desirable at an aggregated scale, for a smooth operation of a grid or energy supply system.

Another feature of the Flat profile that should be noted is that in this case the drivers are implicit: minimization of load variation with constraint on energy losses, resulting in a purely physical optimization that does not depend on external signals. This may seem somewhat in contradiction with the definition of Energy Flexibility given above. However, it may also be interpreted as having an implicit external signal, namely the flattening of the energy demand load profile. Nevertheless, although energy price and grid tariff do not affect the resulting load profile in a Flat optimization, the resulting cost will be

---

[1] The exact period may vary somewhat between different studies, but it is typically 2-3 hours in the morning within the time window 6-10am and 2-3 hours in the afternoon within the time window 16-20pm.

[2] https://www.sintef.no/projectweb/flexbuild/

different when assuming different combinations of energy price and grid tariff. Thus, it is possible and necessary to calculate the KPI ΔCost for the different flexibility drivers. The other (physical) KPIs, instead, are always the same, regardless of the energy price and grid tariff in place.

The optimization problem that is solved in each case can be described in the following manner:

$$\sum_t c_t \, e_t + c_{gt}$$

s.t.

$$\dot{\boldsymbol{T}} = \boldsymbol{AT} + B\boldsymbol{U}$$

$$\boldsymbol{T}(0) = \boldsymbol{T}_0$$

with c_t the energy cost, e_t the energy consumed and c_{gt} the cost of the grid tariff. The latter equation is the state-space equation governing the temperature evolution of the building envelope, which is modelled as a simplified RC-network. The initial temperature is given. For all demands $d \in D$, the demand must be covered in each timestep *t*:

$$d_t = \sum_i e_t^i$$

where subscript *i* denotes technology contributing to the demand by e_t^i. The optimization problem is transcribed using the modelling package Pyomo.

Case studies

Two case studies are presented here, with the purpose of illustrating how the flexibility KPIs are calculated.

Figure 3 shows an example of how the baseline and the flexible scenario work in an office building. It represents a simple all-electric case, for the sake of keeping the focus on understanding the mechanism by which flexibility is activated and how the results are measured in terms of the KPIs. Here, only space heating is considered as the flexibility source, the flexibility driver is given by the spot price – since the energy pricing (EP) grid tariff has a fixed charge per kWh it only adds a constant value – while the flexibility goal is cost minimization.

Figure 3a) shows the Baseline scenario. The upper graph in the figure shows the indoor temperature (*Ti*), which in this case is from a reduced order model (of the second order), like the one described in Walnum *et al.* (2020). This is a grey-box model that has been identified from measurements from an office building located in Oslo, averaging the various floors and temperature sensors into a single zone representation. The central graph shows the space heating demand, supplied by the electric boiler (SH_EB), while the bottom graph shows the total imported electricity, which is the sum of electric boiler consumption plus electric specific consumption (EL).

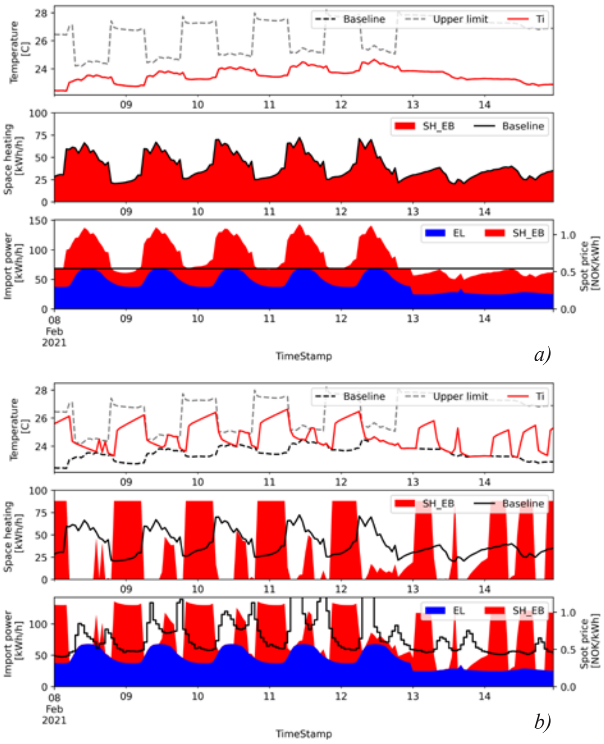

Figure 3: Office building with electric boiler, winter week. a) Baseline scenario, b) Flexible scenario, with flexibility driver: spot price + energy pricing tariff; and flexibility goal: cost minimization. Ti = proxy indoor temperature; SH = space heating; EB = electric boiler; EL = electric specific demand.

Both energy demand, space heating and electric specific, are not those of the real office building but are obtained from the PROFet tool – developed in the FME ZEN project[3] – which estimates energy demand hourly load profiles from a statistical model based on a large sample of measurements from more than 300 energy meters representing a floor area of over 2.5 million m^2, from 11 different building categories, monitored with hourly resolution over several years. The tool is described in detail in Andersen *et al.* (2021) and in Sartori *et al.* (2022) (Appendix B). The reason for using PROFet is to have a case study that is representative of an average office, thus showing results of more general validity.

The load profiles from PROFet represent the energy demand in a given climate for an average building type; in this case an office building with an efficient thermal envelope (ca. equivalent to the Norwegian TEK10 building code), in the reference Oslo climate. The *Ti* shown in the upper graph of Figure 3a) is the resulting indoor temperature when the model is given in input the EL load and forced to reproduce in output SH load from PROFet. This is why it is called a "proxy" temperature. In other words, it is the indoor temperature that allow this model to behave as a typical (efficient) office building

---

[3] https://fmezen.no/

found in the Norwegian stock, operating in a standard Oslo climate. Thus, the Baseline scenario represents an average building operated in a non-flexible way (signal unaware), as typically found in the stock.

The flexible scenario is obtained by running an optimization problem on the same model, with the same inputs, with the objective to minimize the given price signal. The results of the flexible scenario are shown in Figure 3b).

The upper graph shows the *Ti*, which is allowed to fluctuate above – but not below – the baseline level, as long as it does not exceed an upper limit that is set to +1°C during daytime and + 4°C during non-occupation time, over the baseline reference. In this way it is assumed that the user comfort is safeguarded during daytime, while the thermal envelope is allowed to be charged, mainly during non-occupation time, in order to provide for a flexible space heating load that deviates from the typical one, as shown in the central graph. A deeper discussion on what represent a feasible interval for human thermal comfort under dynamic conditions is out of the scope of this paper. For an in-depth study on the topic see Favero *et al.* (2021). The bottom graph shows the total imported electricity (left *y*-axis) and the spot price (right *y*-axis), which is the sole flexibility driver.

It can be noted how the flexible SH load (central graph) is moved as much as possible not hours with low spot price (lower graph) and how this possible thanks to the fluctuations of *Ti* (upper graph) within its given limits. The SH demand presents some flat tops (central graph) corresponding to the electric boiler (EB) operating at its maximum capacity.

Figure 4 shows the total electricity import for the same office building equipped with a heat pump (HP) system. The heat pump is dimensioned, according to engineering praxis, to cover ca. 50% of the (baseline) SH peak load, thus providing more than 90% of the annual energy demand for space heating. However, during the cold winter week shown in the figure, the HP is operating almost always at its maximum capacity, thus leaving the EB top-heater as the only available source of flexibility. In milder weeks the HP too contributes to provide flexibility.

From top to bottom, the graphs in Figure 4 show the results of the baseline scenario and three flexible scenarios. the second and third graph have in common the flexibility goal of cost minimization, while they differ in the flexibility driver: in the second graph it is an EP grid tariff while in the third graph it is a PPM grid tariff (in both cases with spot price). In the PPM scenario the flat tops do not represent the EB maximum capacity, as in the EP scenario; rather, they represent the optimal level of peak power subscription that this building should have for this month, in order to minimize its energy bill. On the contrary, it can be noted how the EP scenario shifts as much energy use as possible in hours when electricity is cheap, thus moving the peak load too in those hours but not necessarily obtaining any significant peak load reduction.

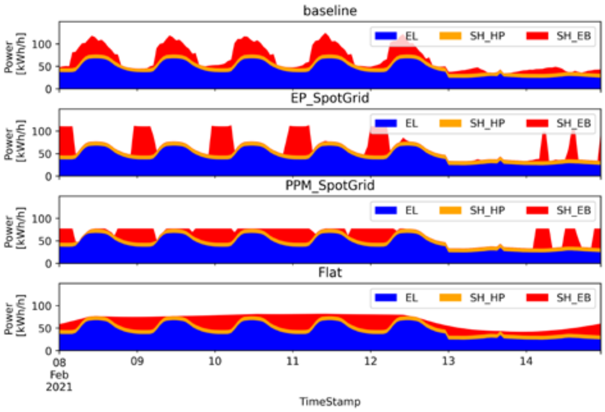

Figure 4: Office building with heat pump system, winter week. Baseline scenario (on top) and flexible scenarios with different flexibility drivers/goals. Flexibility drivers (with spot price): EP = energy pricing tariff; PPM = Peak Power Monthly tariff. Flexibility goal: cost minimization for EP/PPM; flat profile for 'Flat'. SH = space heating; HP = heat pump; EB = electric boiler; EL = electric specific demand.

In the bottom graph the flexibility goal is a flat profile (with implicit, physical drivers). Here the flexible energy demand is "smothered" over the inflexible demand to obtain minimal hour-by-hour variation in energy demand, while also limiting energy losses (multi-objective optimization).

Figure 5 shows another case study on a single building: a typical apartment block as found in the Norwegian stock, heated by electric panel ovens (direct electric heating). The reduced order model for this building is discussed in Bagle *et al.* (2021). Here all the flexibility source previously mentioned (see Figure 2) are considered and activated. The data for the EV load profiles, including the information on plug-in/plug-out time and connection capacity – needed to regulate the flexibility of this load – are taken from Sørensen *et al.* (2021). However, the focus here is not to discuss how the EV flexibility has been modelled; the focus is on how the proposed flexibility KPIs capture and describe the effects of energy flexibility. This case study represents an apartment block with 24 apartments and 10 electric vehicles. That is a penetration rate of 0.4 EV per household; a figure that may be taken as representative of a near future in Norway, considering the present trend for EV in the country.

It can be noted how in this case the Energy Pricing (EP) scenario shows peaks in energy demand that are even higher than in the Baseline scenario. In the office building this did not happen because shifting SH demand in the evening/night meant moving it away from the higher EL demand occurring in daytime. In an apartment block the EL demand is both less significant compared to SH demand (in winter) and more evenly distributed throughout the day. If anything, it presents itself higher values during the evening than during daytime. The two most significant loads are SH and EV, both of which also have a large potential for flexibility.

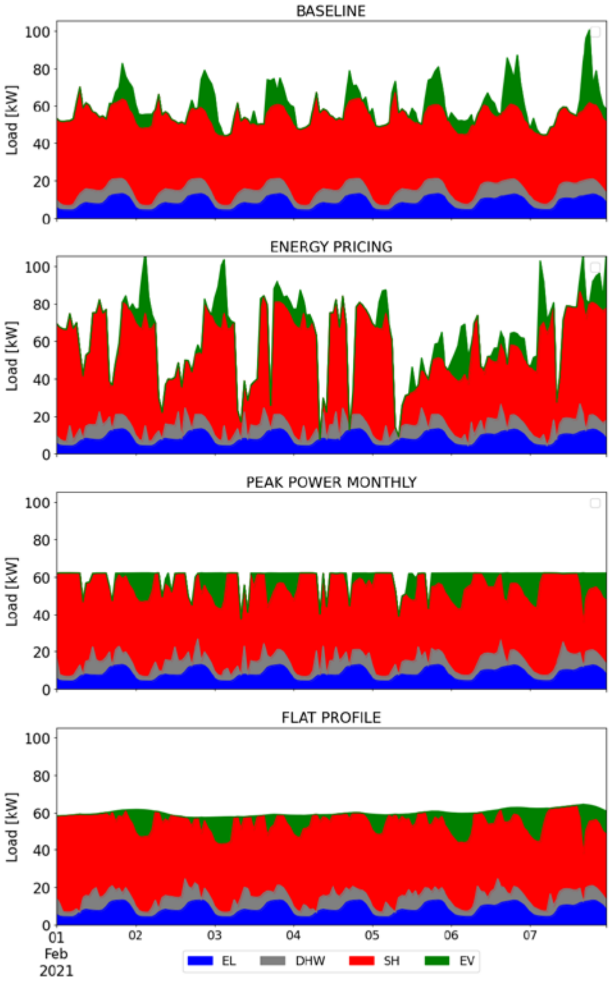

Figure 5: Apartment block with panel ovens, winter week. Baseline scenario (on top) and flexible scenarios with different flexibility drivers/goals. EL = electric specific demand; DHW = domestic hot water; SH = space heating; EV = electric vehicle. Source: Sartori et al. (2022)

Thus, moving both, for as much as possible, in the night hours of cheap electricity spot price causes higher energy demand peaks than in the baseline, and of course also a higher absolute peak load in the observed/simulated period.

Results and discussion

For the time being there are only preliminary results from ongoing work in the named FME ZEN and Flexbuild projects, where the flexibility KPIs have been calculated on single building case studies. The goal is to test the KPIs on the ZEN pilots and eventually integrate them into the set of KPIs of the ZEN definition. It should also be reminded that the main purpose so far has been to test the suitability of the proposed KPIs to quantify significant effects of energy flexibility to be included in the ZEN definition. So, in this phase, the attention should be concentrated first on the usefulness and usability of the flexibility KPIs and only in second instance on the quantitative results of the KPIs.

It is interesting to see how the flexibility KPIs capture and quantify the effect of the different elements shown in Figure 1 and Figure 2, i.e. flexibility drivers, goals and sources.

However, before coming to that, it is worth discussing that there are several other factors influencing the value of the flexibility KPIs, as already mentioned in the commentary to Figure 4 and Figure 5.

Influencing factors

The type of building is an obvious factor. For example, commercial buildings, such as offices, have a dominant occupation during daytime, thus accompanied by a substantial, inflexible load for electric specific uses. This daily pattern offer room for the flexible thermal load to be shifted, to some extent, into the non-occupation hours. The same is not true for residential buildings, where the occupation time is complementary to that of commercial buildings, the electric specific consumption is less significant in absolute terms and is concentrated mainly in the evening hours, at the same time when the EV charging – where present – tend to happen.

Other factors are the energy carrier and technology installed. The examples presented above are all-electric cases. In case of district heating as heating carrier, there is obviously a substantially different baseline scenario to begin with; the effect of different flexibility sources cannot be combined the same way (SH and DHW would affect district heating while EV would affect electricity) and the interplay with inflexible load, such as EL, is only possible for EV but not for the thermal flexibility source. The heating technology plays also a role; for example, in a heat pump system with an electric boiler top-heater, shifting and modulating the load (compared to the baseline) would also affect the systems' COP (Coefficient Of Performance). Shifting too large amounts of heating demand in cheap spot price hours may lower the system's COP (HP has a limited capacity, all the rest having to be covered by the top-heater) to a point that it offsets the potential benefit. This may limit the amount of flexibility deployed by the optimizer; in other cases, though, the flexible scenario may result in a better utilization of the HP compared to the baseline.

If a building has a solar PV system that would also influence the results, since a flexible scenario would shift the energy demand to better match with the PV production. Should there be a stationary battery as part of the PV system, that would be a flexibility source in its own; but this is not considered in this paper.

The efficiency level of the building envelope does also affect the results. More efficient buildings have lower heating loads, and lower peak loads in the first place. On the other hand, a better insulated envelope allows for shifting higher shares of the heating load for longer periods, thus eventually resulting in higher flexibility potential.

A significant difference may also be expected between single buildings and a neighborhood, where the energy demand of the various buildings combines in an aggregated level that is usually smoother due to he coincidence factor (not all users use energy at exactly the same time).

Obviously, the definition of user comfort and user needs is a highly influencing factor. How wide the allowable thermal comfort band is, and how long an EV is connected are factors that directly influence how much flexibility is available and so how much effect it may have. This definition is likely to vary in different studies and should be born in mind when comparing results across literature.

It is also worth noting that ToU pricing, in contrast to spot price, tends to increase the effect on ΔEnergy stress. This is because, while high spot prices correlate well with stressful hours (indeed there is more than a correlation, there is a cause-effect relathionship), a ToU pricing sets a consisten pattern for shifting energy use[4]. Spot price's variability, on the other hand, leads to stronger or weaker incentives, thus not yielding the same results over a longer period.

In our preliminary results we notice that a ToU pricing boosts the ΔEnergy stress KPI by an additional -5% to -15% comapred to the spot price, thus yielding results as high as ca. -50% in the best cases. This seems to be in line with the results of other studies. Knudsen *et al.* (2021) find that using economic MPC (Model Predictive Control) on space heating in a real building application – a living lab built as a single family home of passive house standard – achieves a reduction of energy use in high-price hours in the order of -80%. Walnum *et al.* (2020) investigate MPC applications on an emulator of an energy efficient office building, achieving a reduction of energy use in high-price hours of almost -50% when allowing for a +1°C comfort band in the indoor temperature during occupation hours. The figure rises to nearly -90% when allowing of a more relaxed comfort band of +4°C. Nevwertheless, these results appear numerically more significant because they are expressed as % over the space heating demand alone; while the flexibility KPIs proposed here always refer to the total use (for each energy carrier). A final remark on influencing factors is that the value of the flexibility KPIs is obviously affected also by the time frame considered. All figures shown in in the Methods section shown load profiles for a week, but the corresponding KPIs (discussed below) are calculated over the entire month, and other studies may consider yet different periods.

Graphical representation

Besides all these considerations, it is worth noting that the flexibility KPIs may be used in a broader way to compare the effect of flexibility measures, e.g. smart controls, vs. the effect of energy efficiency measures, e.g. renovation with improvement of the building's thermal envelope. This is shown in Figure 6, which is presented and discussed first, before giving a summary of the preliminary results obtained so far.

Figure 6 shows a possible way to present the flexibility KPIs in graphical form and is useful to illustrate the kind of considerations that can be withdrawn from the KPIs. The figure shows the results for the apartment block case study in two different level of efficiency. It also shows the different duration curves for the total import of electricity in the different cases.

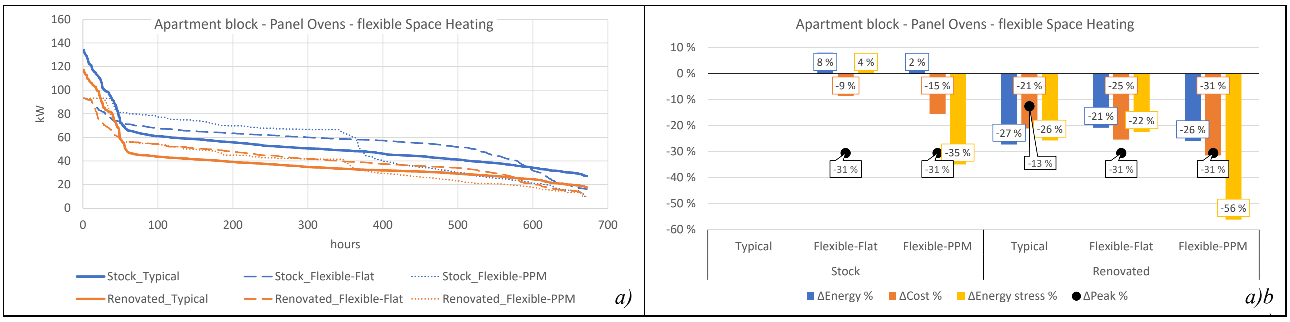

Figure 6: a) Duration curves of the different cases; b) Flexibility KPIs for different scenarios, calculated on total imported electricity over a winter month. Apartment block with panel ovens and only space heating as flexibility source. Stock = average building; Renovated = improved energy efficiency of the building envelope.

The Stock variant represents an average building in the stock while the Renovated variant represent a more energy efficient version of the same building, as it may be after a renovation. Each variant is equipped with panel ovens and space heating is the only flexibility source considered, for the sake of clarity. For each variant the

---

[4] The higher the difference between high-price hours and medium- and low-price hours, the stronger the effect.

typical load profile is considered (as given from the PROFet tool) together with two flexible scenarios obtained with different combinations of flexibility goals and drivers: a flat profile and a cost minimization with PPM grid tariff and spot price. However, in this case, all KPIs are given in reference to the Stock-Typical case as the baseline, thus also allowing the comparison between energy flexibility and energy efficiency.

Focusing on ΔEnergy, one can see how flexibility does not deliver on energy savings; at least, not the SH flexibility as defined here, which only allows upwards deviation of *Ti*, see Figure 3. On the contrary, flexible SH cause some energy loss as it obvious to expect from the underlying physics. This is visible by observing how the flexible scenario in the Stock variant, both having a positive ΔEnergy compared to the baseline. It is also visible the flexible scenarios of the Renovated variant, where the energy savings are less than in the non-flexible (typical) case.

However, turning the attention to the other KPIs, this rather limited loss in energy efficiency is counterbalanced by other gains. ΔCost is negative in all flexible scenarios. Also, when comparing the Renovated scenarios with its own Typical reference, one sees additional cost savings. This comes to no surprise when the flexibility goal is cost minimization, of course; but also the Flat profile goal delivers cost savings (to the end-user) although not explicitly pursuing them. This feature is noted consistently through the analyzed cases, not just in the one reported in Figure 6. However, the cost savings achieved by activating SH flexibility remain less significant than those achieved by implementing energy efficiency measures (perhaps better described as energy conservation measure, in this case of thermal envelope renovation).

The results change when looking at ΔEnergy stress and ΔPeak. Here, energy flexibility shows the potential to even outperform energy efficiency. This is true in particular for ΔPeak, where the Stock flexible scenarios yields ca. -30% while the Renovated typical scenario only achieves less than half of it. The Renovated flexible scenarios are again able to obtain the same performance on ΔPeak as the Stock flexible scenarios, but do not overcome it. The situation is different for ΔEnergy stress, where it is necessary to distinguish between the kind of flexibility goals (and drivers) underlying the results. The Flat profile goal (which has implicit physical drivers) appears unable to shift energy use away of stressful hours. It rather adds on it, although to a lower extent than it adds energy use in total. Another way to interpret this is that the energy losses are added mostly outside the stressful hours. At least, this is true in this case of a residential building, and it would be different in a commercial building due to the different interplay with the inflexible EL load, as discussed in the section above on influencing factors. The Flexbile-PPM scenario, on the other hand, delivers the best results on ΔEnergy stress (and ΔPeak) in both variants. Not only the Stock flexible scenario outperforms the Renovated typical one, as happens with ΔPeak too, yielding a reduction larger than -30%, but the Renovated flexible scenarios (with PPM) is able to improve further and bring the ΔEnergy stress savings beyond -50%.

Clearly, the different KPIs, and so the different results achieved with different energy flexibility (or energy efficiency/conservation) options, bear different significance for different stakeholders, such as the building owner/occupants, the energy grid or potential new actors in the energy markets, such as the aggregators. Another aspect that is worth considering is that flexibility options usually present lower upfront cost and fewer barriers than efficiency options, e.g. installing a more advanced BACS (Building Automation and Control System) vs. installing a heat pump or improving the thermal envelope. The allocation of such cost, likewise the consequent benefit, does also fall in a different way on the different stakeholders: who shall bear the cost of installing what? What business model to adopt?. It is auspicable that the flexibility KPIs may help informing the decision makers on these questions.

Conclusion

The results presented here come from a limited number of cases analyzed (and all on single buildings) and therefore present a certain variability. However, it is not unreasonable to expect that results from a wider analysis may still present a considerable variability in the results, due to the many possible combination between various factors. For this reason, the flexibility KPI results are discussed as approximate ranges rather than precise values. The preliminary results available refer to the two archetype buildings presented in the Methods section: office and apartment buildings; other unpublished work on school and nursing home buildings, and another office building, the same discussed in Bagle *et al.* (2022). Given the above premises, the preliminary results can be summarized in the following way, with respect to:

- Flexibility sources: space heating (SH) and EV charging have rather large and similar potential, especially in terms of ΔPeak and ΔEnergy stress, achieving results in the order of -20% to -50% in most cases. Domestic Hot Water tanks (DHW) achieve more modest results. Activating more flexibility source together does increase the performace, although the effects of the single sources cannot be expected to add up directly.
- Flexibility drivers: the main difference between an Energy Pricing (EP) tariff and a Peak Power Monthly (PPM) tariff is that the former cannot guarrantee a reduction in ΔPeak. On the contray, it may lead to an increase since it only has an incentive to shift loads into cheap hours, withouth restriction on the peak load other than the physically installed capacity.
- Flexiblity goals: cost minimization of the given price signal (driver) is often taken implicitly as the

fleixiblity goal, in which case the considerantios made above are exhaustive. However, here we have considered also the alternative Flat goal, which pursues a load profile that is as flat as possible while simultaneously minimizing energy losses. Compared to cost minimization, the Flat goal tends to perform worse on ΔEnergy, ΔEnergy stress and ΔCost, but is able to yield rather good results on ΔPeak: better than cost minimization with EP tariff, but not as good as with PPM tariff. This might, indeed, be an advantage of the Flat goal: that it is independent of economic drivers, thus more solid and predictable, although less performant. Another advantage may be that it guarantees a loda profiles that has no "deep valleys" together with no "high peaks".

- Flexibility KPIs: in general, it is observed that activating flexibility can bring reductions in ΔCost (in the range of 0% to 20%), in ΔEnergy Stress and ΔPeak power (in the range 20% to 50%) even if this is accompanied by a modest increase in ΔEnergy (in the range 0% to +5%) due to some energy losses.

Altogether, the proposed flexibility KPIs seems to be able provide some useful insights to different stakeholders, can be calculated with a method that is compatible with the other KPIs of the FME ZEN definition (i.e. comparing a flexible scenario to a typical baseline) and can easily be communicated both as numeric values and graphically, although their values are highly case dependent. The next step is to test them on several ZEN pilot areas.

Acknowledgement

The authors gratefully acknowledge the support from the Research Council of Norway and several partners through the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN) and the KPN project Flexbuild.

References

Andersen, K.H., Lien, S.K., Walnum, H.T., Lindberg, K.B. and Sartori, I. (2021). Further development and validation of the "PROFet" energy demand load profiles estimator. *Building Simulation 2021 Conference*. Bruges (Belgium), 1-3 Sep. 2021.

Bagle, M., Delgado, B.M., Sartori, I., Walnum, H.T. and Lindberg, K.B. (2022) Integrating Thermal-Electric Flexibility in Smart Homes using Grey-Box modelling in a MILP tool. *BuildSim Nordic*. Copenhagen (Denmark), 22-23 Aug. 2022. (In review)

Bagle, M., Walnum, H.T., Sartori, I. and Maree, P. (2021). Identifying grey-box models from archetypes of apartment block buildings. *Building Simulation 2021 Conference*. Bruges (Belgium), 1-3 Sep. 2021.

Favero, M., Sartori, I. and Carlucci, S. (2021) Human thermal comfort under dynamic conditions: an experimental study. *Building and Enviroment 204*, 108144.

IEA-EBC Annex 67 (2019) *Annex 67 Energy Flexible Buildings – Summary report*. International Energy Agency (IEA), Energy in Buildings and Communities Programme (EBC).

Junker, R.G., Azar, A.G., Lopes, R.A., Lindberg, K.B., Reynders, G., Relan, R. and Madsen, H. (2018). Characterizing the energy flexibility of buildings and districts. *Applied Energy 225*, 175-182.

Knotzer, A., Pernetti, R. and Jensen, S.Ø. (edited by) (2019). *Characterization of Energy Flexibility in Buildings*. IEA-EBC Annex 67 Energy Flexible buildings.

Knudsen, M.D., Georges, L., Skeie, K.S. and Petersen, S. (2021). Experimental test of a black-box economic model predictive control for residential space heating. *Applied Energy 298*, 117227.

Lien, S.K., Andersen, K.H., Bottolfsen, H., Lolli, N., Sartori, I., Sørensen, Å.L. and Clauss, J. (2021). Energy and Power: essential key performance indicators for Zero Emisson Neighbourhoods – An analysis of 6 pilot areas. *FME-ZEN Report no. 36*.

Lindberg, K.B, Bagle, M., Sartori, I., Seljom, P.M.S., Kvalb ein, L., Rosenberg, E., Ahang, M., Tomasgard, A. and Jaenhert, S. (2020) Flexbuild Annual Report 1 – Technical report with results analysis. *SINTEF Research 69*.

Sartori, I. *et al.* (2022) Flexbuild Annual Report 2 – Technical report with results analysis. *SINTEF Research 87*.

Sørensen, Å.L, Lindberg, K.B, Sartori, I. and Andresen, I. (2021). Residential electric vehicle charging datasets from apartment buildings, *Data in Brief 36*, 107105.

Walnum, H.T., Sartori, I. and Bagle, M. (2020). Model predictive control of District Heating substations for flexible heating of buildings. *BuildSim Nordic*. Oslo (Norway), 13-14 Oct. 2020.

Wiik, M.K. *et al.* (2021) Zero Emission Neighbourhoods in Smart Cities - Definition, Key Performance Indicators and Assessment Criteria: Version 2.0. Bilingual version. *FME ZEN Report no .32*.

Wiik, M.K., Lien, S.K., Fjellheim, K., Vandervaeren, C.M.L., Fufa, S.M., Baer, D., Sartori, I., Nordström, T., Meland, S., Cheng, C.Y. and Thomsen, J. (2022). The ZEN Definition - A Guideline for the ZEN Pilot Areas. Version 1.0. *FME ZEN Report no .40*.