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# Comparison of flexibility factors for a residential building

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**Abstract.** Buildings that are able to shift their loads without comfort restraints are important for the ongoing transformation of the power supply. This flexibility potential can be expressed in flexibility factors. The usefulness of four factors is investigated based on load control for the heat pump of a small apartment building according to electricity prices (high/low tariffs, spot market prices), CO<sub>2eq</sub> emissions share in the grid and a restricted operation period during daytime. The calculation methodology of the presented flexibility factors GSC, RIP, FF and FI is very different. RIP and FF are preferable because they have defined valid ranges which makes them easier to understand. Current electricity prices force the heat pump operation mainly into the night. The optimization of CO<sub>2eq</sub> emissions encourages operation mainly during the day. The optimization goals costs or CO<sub>2eq</sub> emissions thus lead to opposing heat pump operation times and can currently therefore not both be met simultaneously.

## 1. Introduction

Adding large photovoltaic systems to buildings and the use of heat pumps is becoming more and more popular and essential for the implementation of the EPBD and the European Green Deal. In general, such buildings are connected to the grid. Currently it is being discussed if the resulting grid interaction may not become a problem for the grid with a large increase of the number of such buildings. Therefore, it is of great interest to already be able to rate buildings in the design phase in regard to their grid interaction, i.e., energy flexibility.

It has been shown that in residential buildings the heat pump or hot water boiler are the only large consumers that can be flexibly controlled in a useful manner. In the study described here, the flexibility of the heat pump operation is investigated in connection with the following penalty signals:

- Optimization of electricity costs at high/low tariffs
- Optimization according to low spot market prices (assumption: a low spot market price means a power surplus in the grid and it is advantageous for the grid to activate consumers during these times)
- Optimization according to low CO<sub>2eq</sub> emission coefficients of the electricity mix (assumption: a low CO<sub>2eq</sub> emission coefficient of the electricity mix means a high share of renewable energy in the grid and it is advantageous for the grid to activate consumers in these times so that the renewable energy does not have to be stored or the sources regulated).
- Optimization of self-consumption (high self-consumption of own photovoltaic yield leads to lower purchase and feed-in quantities and peaks).



The energy flexibility of a building can be described with a flexibility factor. In this study, the usefulness of four different flexibility factors is compared and the impact of different penalty signals for load management is evaluated.

## 2. Methodology

### 2.1. Example building

The basis for the investigations using thermal building simulation is a well-documented and monitored small apartment dwelling with three flats. The building is well insulated (Swiss label Minergie-P) and constructed in concrete and aerated concrete (Table 1). The internal loads for people, appliances and lighting are assumed according to SIA 2024 [1]. A ventilation system with heat recovery (80 %) is taken into account. The modulating heat pump has a nominal thermal output of 9 kW (100 %, 0/35 °C) in the initial case with a base electric load of 10 W when it is “off”. The heat pump operates for heating and domestic hot water. The heating of the hot water storage takes place in two fixed block times (duration: 1 h and 2 h) per day depending on the penalty signal. Two photovoltaic system sizes are considered (3 and 20 kWp, south, slope 10°). It is assumed that the PV yield can be completely used for the heat pump when needed. A detailed building description can be found in [2].

**Table 1.** Properties of the residential building [2].

Property	Value
Heated floor area	320 m <sup>2</sup>
U-value, ext. walls/roof/floor	0.12/0.09/0.10 W/(m <sup>2</sup> K)
U-value windows, g-value	0.75 W/(m <sup>2</sup> K), 50 %
Solar control (blinds)	not applicable
Shading (surrounding buildings)	yes
Thermal capacity (with R <sub>si</sub> ) [3]	63 Wh/(m <sup>2</sup> <sub>NetFloorArea</sub> K)
Const. air exchange rate (mech. ventilation)	0.39 h <sup>-1</sup>
Climate	DRY Buchs-Aarau (CH)

### 2.2. Penalty signals and evaluation criterions

The heat pump operation is controlled according to five different penalty signals (Table 2). Each result is rated with high-low tariffs (HTLT, [4]), spot market prices (SPOT, 15 min values, Germany 2015 [11]) and CO<sub>2eq</sub> emission coefficients (CO<sub>2eq</sub>, hourly values, Swiss electricity mix 2015 [12]). The impact of the penalty signals and different ratings are analyzed for each flexibility factor. Only the electricity consumption for the heat pump is taken into account.

**Table 2.** Investigated penalty-signals for heat pump control.

Penalty-signal	Allowed operation times for heat pump (without block times for domestic hot water)	Block times for domestic hot water, 3 hours/day
DEMAND	On demand (base case)	5-6 am, 1-3 pm
LT	Low tariff only, this excludes Mo-Fr 6 am - 8 pm	4-6 am, 8-9 pm
SPOT_05	When spot market price ≤ daily mean price	2-4 am, 2-3 pm
CO2_05	When CO <sub>2eq</sub> emission coefficient ≤ daily mean coefficient	8-9 am, 6-8 pm
DAY	Block time during daytime: 7 am - 6 pm	5-6 am, 1-3 pm

### 2.3. Flexibility factors

The effectiveness of the penalty signals considered is expressed with following four flexibility factors (Table 3):

- GSC Grid Support Coefficient (corresp. to  $GSC_{abs}$  in [6]),
- RIB Relative Import Bill [7],
- FF Flexibility Factor [8] and
- FI Flexibility Index [9].

In these factors, electricity demand is offset against a variable that is representative of the electricity grid (electricity price,  $CO_{2eq}$  emission coefficient). The flexibility potential of a building is expressed by whether electricity is purchased at high or low prices or  $CO_{2eq}$  emission coefficients. Only the flexibility factor FI compares a base case with a variant.

GSC, RIB and FF are first calculated as daily values and then aggregated to an annual value. For FI the time step values are directly aggregated to an annual value.

**Table 3.** Summary of flexibility factors ( $E_{el}^i$ : electricity consumption in time step  $i$ , (kWh),  $p^i$ : cost or  $CO_{2eq}$  emission coefficient in time step  $i$ , (unit/kWh),  $n$ : number of time steps).

Flexibility factor	Value range	Grid-serving when ...	comment
$GSC = \frac{\sum_{i=1}^n (E_{el}^i \cdot p^i)}{(\sum_{i=1}^n E_{el}^i) \cdot \bar{p}}$	> 0	< 1	$\bar{p}$ : daily mean value
$RIB = \frac{\sum_{i=1}^n (E_{el}^i \cdot p^i) - \sum_{i=1}^n (E_{el}^i \cdot p_{min})}{\sum_{i=1}^n (E_{el}^i \cdot p_{max}) - \sum_{i=1}^n (E_{el}^i \cdot p_{min})}$	0 - 1	Low value	$p_{min}$ , $p_{max}$ : daily min and max value
$FF = \frac{\sum_{i=1}^n (E_{el}^i \cdot p^i)_{q1} - \sum_{i=1}^n (E_{el}^i \cdot p^i)_{>q3}}{\sum_{i=1}^n (E_{el}^i \cdot p^i)_{q1} + \sum_{i=1}^n (E_{el}^i \cdot p^i)_{>q3}}$	-1 to +1	High value	$q1$ , $q3$ : daily first and third quartile
$FI = 1 - \frac{\sum_{i=1}^n (E_{el}^i \cdot p^i)_{flex}}{\sum_{i=1}^n (E_{el}^i \cdot p^i)_{ref}}$	-1 to +1	High pos. value	flex: with penalty signal ref: without penalty signal

### 2.4. Simulation Setup

The transient building simulation program ESP-r [10] is used. The building domain contains 15 thermal zones. The heat pump and domestic hot water tank are explicitly modelled in the plant domain. The load management according to the penalty signals for the heat pump operation times corresponding to Table 2 is set up as run-time control in the plant domain using pre-defined temporal data for high-low tariff, spot-market prices and  $CO_{2eq}$  emissions coefficients. The flexibility factors are determined in the post processing based on the resulting different heat pump demand profiles.

The simulation period is one year with a pre simulation period of 30 days. The simulations are run with 12 time-steps per hour. It is verified that the operative temperatures of all zones are always above 20 °C.

### 3. Results and analysis

Fig. 1 shows the results of the flexibility factors for all penalty signals and without/with a 20 kWp PV system. Each penalty signal is evaluated with regard to its influence on the costs for high/low tariffs, spot market prices and CO<sub>2eq</sub> emissions. The following trends for GSC, RIB and FF are found without a PV system (Fig. 1, left side):

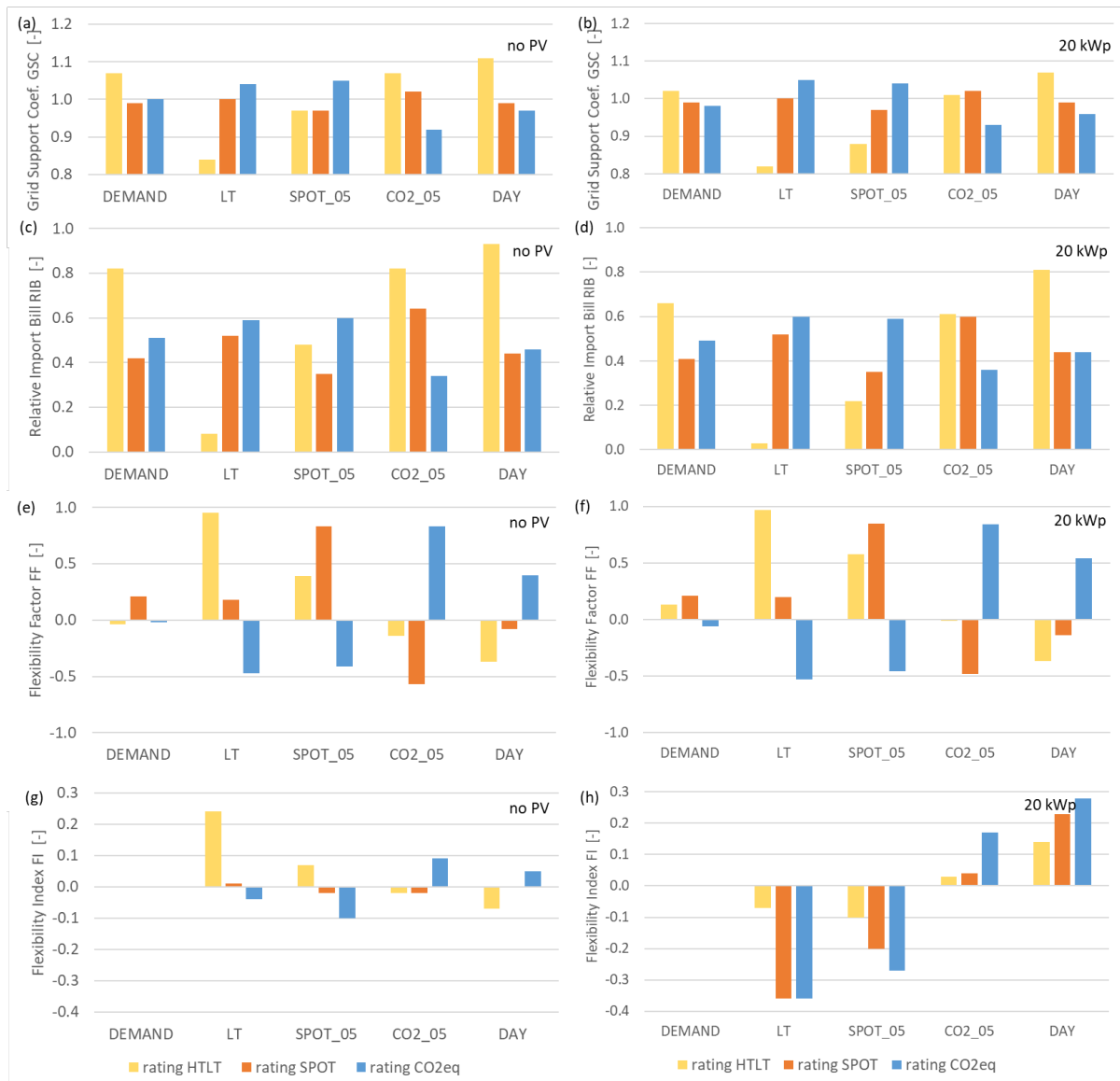
- DEMAND: GSC/RIB indicate that energy is purchased more frequently at the high tariff than at the low tariff ( $GSC > 1$ ,  $RIB > 0.5$ ), while FF shows the purchase balanced between the two tariffs ( $FF \approx 0$ ) (yellow). The evaluations according to spot market prices (red) and CO<sub>2eq</sub> emissions (blue) show that energy is purchased on average at the daily average ( $GSC \approx 1$ ,  $RIB \approx 0.5$  and  $FF \approx 0$ ).
- LT, SPOT\_05: When controlled according to costs (HTLT (yellow), spot market prices (red)), the electricity price-rated factors show correspondingly good values for procurement at low costs, but these variants perform less well with the evaluation according to CO<sub>2eq</sub> emissions (blue).
- CO2\_05, DAY: In these variants, energy is purchased at low CO<sub>2eq</sub> emissions (blue), which, however, leads to higher costs (yellow, red).

The flexibility factor FI indicates the change compared to the base case DEMAND. Thus, an evaluation according to HTLT (yellow) for the cost-based penalty signals (LT, SPOT\_05) shows that a share of the energy costs is reduced compared to the base case (pos. values). For HTLT, for example, the costs are reduced by 24 %. The negative values of the CO2\_05 and DAY variants show the share of the energy costs increases compared to the base case. The result for the evaluation of the penalty signals in respect to CO<sub>2eq</sub> emissions is exactly mirrored (blue). In the evaluation according to spot market prices (red), only the penalty signal LT shows a slight reduction in energy costs compared to the base case. The other penalty signals lead to a slight cost increase. FI shows the same tendencies as GSC, RIB and FF when comparing the penalty signals used with the base case DEMAND.

The results including a 20 kWp PV system shows Fig. 1 on the right side. During self-consumption periods the production costs are set to 20 Rp/kWh [11] and CO<sub>2eq</sub> emissions to 0.072 kg/kWh [12].

- In general, taking self-consumption into account leads to a reduction of energy costs/CO<sub>2eq</sub> because self-consumption reduces energy purchases at high tariff/CO<sub>2eq</sub> emission periods. The largest impact is seen within the rating HTLT (yellow).
- Compared to the cases without the PV system, GSC, RIB and FF give the same tendencies. By contrast, FI is strongly influenced. The cost driven penalty signals show a much higher impact on the ratings compare to the base case while the penalty signals CO2\_05 and DAY perform better. This is the consequence of the fact that the base case performs quite well, already.

The results with the 3 kWp PV system are very similar to the results without a PV system. Therefore they are not shown here. A small PV system has a very low winter yield when the heat pump's consumption is high. In summer, the heat pump operates only for domestic hot water which leads to low consumption during high PV yield periods. This results in a quite low self-consumption.



**Figure 1.** Results for flexibility factors GSC (a, b), RIB (c, d), FF (e, f), FI (g, h) depending on different penalty signals, left side without PV system, right side with 20 kWp PV system.

#### 4. Conclusion

The high heat storage capacity in combination with the good insulation standard of the building is used to operate the heat pump flexibly via load management depending on various penalty signals. Since only the load shifting of the heat pump is considered, the entire evaluation is only carried out for the heat pump.

The results are presented using four different flexibility factors. The calculation methodology of the presented flexibility factors Grid Support Coefficient (GSC), Relative Import Bill (RIB), Flexibility Factor (FF) and Flexibility Index (FI) is very different. Thus, the value range that a factor can assume and target values that indicate high flexibility are also very different. This makes direct comparison of the flexibility factors difficult. However, the flexibility factors basically show the same direction and each can be used to describe the flexibility. RIB and FF are preferable because they feature defined minimum and maximum values which makes them easier to understand.

The flexibility factors mirror that the different penalty signals lead to different heat pump operation times. However, it must be decided whether the focus should be on low electricity costs or on the reduction of CO<sub>2eq</sub> emissions. When optimizing the electricity costs (high-low tariff, spot market prices), the heat pump mainly runs at night, which leads to low costs and the use of electricity with high CO<sub>2eq</sub> emission coefficients. The optimization of CO<sub>2eq</sub> emissions leads to a heat pump operation during the day with low CO<sub>2eq</sub> emission coefficients and usually to higher electricity costs. When taking self-consumption into account, energy costs and CO<sub>2eq</sub> emissions are reduced mainly when the heat pump operation is energy cost controlled.

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