Impact of office tenants' electricity use on the cost-optimal solutions in a cold climate

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Abstract. The buildings' energy performance requirements in Estonia are based on cost-optimality analysis according to the EPBD and pre-defined building performance simulation (BPS) input data from EN 16798-1:2019. Previous studies have shown that the real electricity use of office building tenants differs from the currently used input data in BPS in Estonia – less in total energy use, but more in the shape of the profiles. The aim of this work is to investigate what is the impact of these differences on the cost-optimal solutions, which are identified based on BPS and the self-consumption of the photovoltaic panel (PV) systems. This study describes the energy performance and construction cost analysis of a new office building in Tallinn, Estonia. BPS based on the EN 16798-1 and a model derived from measurements in a real building were conducted and cost-optimal building solutions identified. The variables were building envelope insulation thickness, air handling unit size and effectiveness, electrical lighting control principles and PV system nominal power. The calculated energy use of the building with the two different sets of input data differed significantly. However, the set of cost-optimal solutions identified with EN 16798-1:2019 input data had minor differences from the set of solutions identified with the more realistic model. The decrease of net present value over 20-year period for cost-optimal solution was 11-14 €/m^2 compared to the designed building.The realistic office tenants' electricity model increased the calculated self-consumption of the PV system from 95% to 100%.

1 Introduction

Building energy calculation have to correspond to the minimum requirements [1], [2] in Estonia. New buildings have to achieve NZEB level that has energy performance certificate (EPC) rate 100 kWh/m^{2}y. Furthermore, these requirements as well European Parliament directives [3], [4] sets, that simultaneously achieving the energy efficiency in a building, there is a need to focus on cost-optimality. Energy efficiency should not be achieved if the cost-optimality suffers. Therefore, the energy efficiency should be calculated accurately, so the building solutions will be cost-optimal in practice. However, some studies [5], [6] shows that real electricity use in office buildings differs from the electricity use calculated by currently used input data in BPS.

Renewable energy produced in the building is included in EPC calculation, but for photovoltaics (PV), only the PV generation used in the building (self-consumption) will be involved. Estonian minimum requirements set the PV self-consumption for an office buildings 90%. J. Ivanov found out in his thesis, that the self-consumption (calculated with requirements input data) is 75-86% in one cost-optimal office building. The present study investigates, how much the real electricity consumption will effect the PV system self-consumption compared to regulation-based calculations.

This study investigates the impact of tenant electricity use that depends on the shape of the profiles used in BPS. BPS based on the EN 16798-1 and a model derived from measurements in the real building were conducted. Derived model has been done by Hans K. Aljas et al. study [7], where they analyzed four buildings tenant electricity use. The building used in this study has the highest electricity consumption compared to other buildings in study [7], to see the extreme case. Cost-optimal building solutions were identified and compared in between two profiles.

2 Methods and model

2.1 Building description

The reference object was one designed commercial building (bld.) what is under construction right now and planned to be ready at the beginning of 2022. This study focuses on the office area of this bld., what is from the fifth to thirteenth floor (**Table 1**). Total heat loss of the bld. envelope per heated floor area was 0.45 W/(m^2×K) and the envelope insulation was mineral wool. The building heating and cooling source was a geothermal heat pump and the thermally activated building system

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(TABS) will regulate the indoor temperature with water-based ceiling panels. The photovoltaic (PV) panels of nominal power of 5 kW (1.3 W/m^2) will be installed on the roof. The building will has passive shading (ribs) facing to the south, and in other directions windows with effective solar factor.

Table 1. Reference office building envelope and system parameters

Heated floor area, m^2	3833
External wall (EW) insulation thickness, mm	200+60
EW thermal conductivity, W/(m^2×K)	0.15
External roof (ER) insulation thickness, mm	270+30
ER thermal conductivity, W/(m^2×K)	0.1
WWR, %	61
Windows solar factor in south, -	0.54
Windows solar factor in other directions, -	0.22
Lighting control	on/off

2.2 Two energy simulation models

Two energy simulation models were composed on the basis of the reference building. The first model (**EN-profile**) was based on the usage profile from standard EN16798-1:2019 (green line in **Figure 1**), and the second model (**M-profile**) was derived from measurements in a real building with the usage profile described in Section 2.3.

The calculation models were simulated with IDA ICE 4.8. There was used an Estonian test reference year made over a period of 31 years, from 1970 to 2000. That contains typical months from a number of different years. [8]

The bld. model starts from the fifth floor and has 4 floors up. The third (7th in full bld. context) floor output has been multiplied with six as it is similar to the five following floors. The floors are divided into four zones facing to different directions and one zone is for the corridor. All parameters included in the simulation calculation have been taken from regulation [2], which are shown in **Table 2**. Only lighting usage has been taken as the project designed value of LED lamps (regulation states only 10 W/m^2 as for florescence lamps). The self-consumption of the photovoltaic panel has been calculated also by IDA ICE simulation.

2.3 Development of measurement-based model

The appliances and lighting electricity use profile has been composed based on the model from Hans K. Aljas et al. study [7]. The model used in this study was based on one existing office bld. in Tallinn, that has higher electricity use than usual as there are more IT offices. The lighting and appliances electricity use per hour has been calculated by the equations used in study [7] for every day over one year and then divided by power of the summary of default appliances and lighting power (**Table 2**) and then got the usage ratio profile (upper orange line in **Figure 1**). For the simulations in IDA-ICE, there has been used a macro to determine the usage profile. In the macro, there has been used the usage ratio profile together with the same equations and the program code calculated the final energy use by multiplying the profile with the same default appliances and lighting power from **Table 2**.

Table 2. The parameters in energy simulation models

Occupancy, W/m^2	5
Appliances, W/m^2	12
Lighting, W/m^2	6.37
Usage in workdays, h	7:00-18:00
Usage in weekends and holidays, h	0
Usage ratio, -	0.55
Heating set-point, ˚C	21
Cooling set-point, ˚C	25
Illuminance, lx	500
Air change rate, l/(s×m^2)	2
Heat system efficiency factor, -	0.99
Geothermal heat pump SCOP, -	4.4
Geothermal heat pump COP for DHW, -	2.7
Geothermal heat pump SEER, -	6.1
Drycooler SEER, -	3.5
AHU SFP kW/ (m^3/s)	1.72
AHU heat recovery efficiency η, %	78
DHW specific use, l/(m^2×y)	103

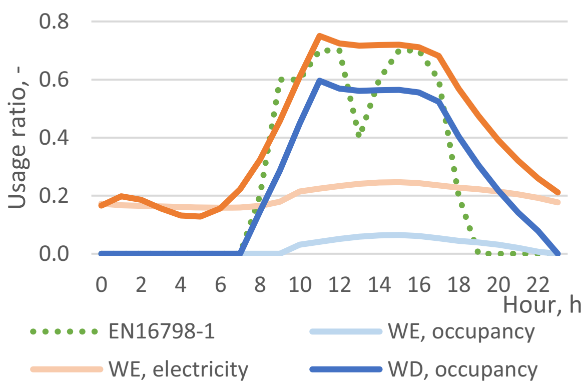


Figure 1. The usage ratio of lighting, appliances electricity use and occupancy for weekdays (WD) and weekends&holidays (WE)

The usage profile for occupancy, as the lower line in **Figure 1**, has been derived from the appliances and lighting profile. The constant background electricity use (3.4 W/m^2 as usage ratio 0.19) has been subtracted and non-working hours has been excluded.

The difference of EN- and M-profile is considerable. EN-profile is limited to working hours (7-19:00 and no work in weekends), but from M-profile in **Figure 1** one can see that occupants will work also outside so-called working hours. Appliances and lighting power is active even until 23:00 and it is assumed that occupants will be present at this time. Furthermore, there is occupancy at weekends.

2.4 The selection of cost-optimal solutions

Inside the reference models, the variables in **Table 3** have been changed to estimate the energy efficiency of measures. Altogether, 20 models have been composed for each profile to calculate the energy use with the simulation program. Furthermore, the energy performance certificate, here named as the primary energy (PE) use, has been calculated for each measure using primary side factors from **Table 2**. The added investment in relation to the previous measure has been used to estimate the cost-optimality of every measure and model.

2.5 The final combinations of cost-optimal solutions

The combinations of cost-optimal solutions shown in **Table 4** were selected among the measures in **Table 3**. For comparison, the project-designed combination has been calculated. The base model was combined with the worst measures that gave the highest PE. That was the base level for energy efficiency estimation and the zero level of investment cost. Further combinations were composed by adding cost-optimal measures to the base model considering the additional investment per 1 kWh saved primary energy (€/kWh) of the measures that was compared to the previous change. The first measure had the smallest investment per saved energy and so forth. The previous measure was retained for each next measure. Finally, the four characteristic combinations have been selected in addition to the designed and base model. Subsequently, the PE use has been estimated by arithmetical calculation as well with the simulation program. Cost-optimality of these combinations has been calculated with the net present value over 20-year, the energy price was 91.7 €/MWh, nominal interest rate was 2.7%, and inflation rate 1.7%.

Table 3. Changed variables and measures with additional investment compared to the base model

Measures	Changed variable	Variable value	Added investment, €/m²
EW100	EW insulation, mm	100	0
EW150		150	8
EW200		200	7
EW250		250	6
EW300		300	5
ER180	ER insulation, mm	180	0
ER210		210	3
ER240		240	4
ER270		270	8
ER300		300	4
Vent_1	AHU parameters, % kW/(m³/s)	ŋ = 77.3 SFP = 2.33	0 €
Vent_2		ŋ = 78.0 SFP = 1.72	1000 €
Vent_3		ŋ = 78.8 SFP = 1.52	1000 €
LED	Lighting control	on/off	0
LED_Sen		Sensors	8
LED_ Sen&dim		Sensors with dimming	6
PV 0 W/m²	PV power, kW	0	0 €
PV 1.3 W/m²		5	5 000 €
PV 3.7 W/m²		14	14 000 €
PV 6.0 W/m²		23	24 000 €

Table 4. Combinations of cost-optimal solutions for EN- and M-profile (the only difference is highlighted)

Combinations	EW/ER insulation, mm	AHU parameters	Lighting control	PV power, W/m²	PE, kWh/m²y
As designed_EN	200/270	ŋ=78,0 SFP=1,72	on/off	1.3	104.3
1K_BModel_EN	100/180	ŋ=77,3 SFP=2,33	on/off	0	116.2
2K_EN	100/180	ŋ=78,8 SFP=1,52	on/off	6.0	95.2
3K_EN	100/180	ŋ=78,8 SFP=1,52	Sensors	6.0	84.8
4K_EN	100/180	ŋ=78,8 SFP=1,52	Sensors with dimming	6.0	83.2
5k_EN	150/210	ŋ=78,8 SFP=1,52	Sensors with dimming	6.0	82.6
As designed_M	200/270	ŋ=78,0 SFP=1,72	on/off	1.3	155.8
1K_BModel_M	100/180	ŋ=77,3 SFP=2,33	on/off	0	164.2
2K_M	100/180	ŋ=78,8 SFP=1,52	Sensors	0	137.8
3K_M	100/180	ŋ=78,8 SFP=1,52	Sensors	6.0	126.6
4K_M	100/180	ŋ=78,8 SFP=1,52	Sensors with dimming	6.0	124.1
5K_M	150/210	ŋ=78,8 SFP=1,52	Sensors with dimming	6.0	123.6

3 Results

3.1 Primary energy use is significantly different

Designed building PE use with EN-profile was 104.3 kWh/m^2×y and was a little out of the boundaries that requirement set (100 kWh/m^2×y is the NZEB level for new blds.). The simulation done with M-profile resulted with PE use 152.4 kWh/m^2×y. The M-profile increased the PE use about 37-52 kWh/m^{2}y for measures, compared to EN-profile. Extended data about PE use of all measures are in **Figure 11** and **Figure 12** in Appendix 1.

The smallest influence on PE had the measure of changing the insulation thickness (**Figure 3**). The average difference of PE was only in 0.35 and 0.51 kWh/m^{2}y (respectively, for M-profile and EN-profile). **Figure 4** shows that the lighting control measure had the biggest influence on PE difference and has substantial difference in between profiles. The best PE difference and extra cost combination was for AHU size measure (**Figure 6**) as the PE difference was similar to the lighting control measure, but the extra cost was more than 25 times smaller.

Photovoltaic panel self-consumption was 100% for M-profile and about 86-98% for EN-profile with heat pump, as shown in **Figure 2**. Depending on PV system installed power, the primary energy use was reduced about 2.4-11.2 kWh/m^{2}y, and 2.4-9.6 kWh/m^{2}y respectively, for M-profile and EN-profile, as shown in **Figure 5**.

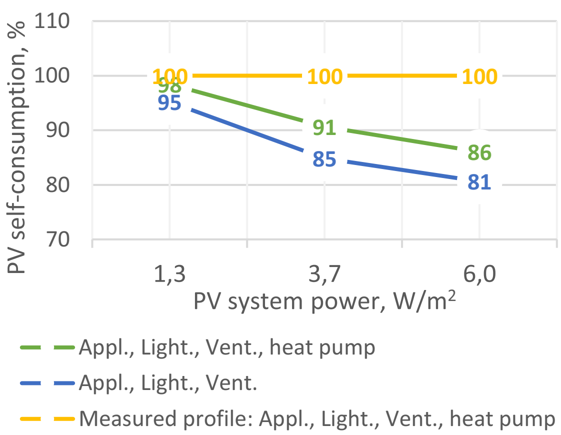


Figure 2. Photovoltaics self-consumption for M-profile and EN-profile

The net energy use of the combinations defined in **Table 4** will vary significantly in between two profiles, as shown in **Figure 7**. For the calculation with M-profile, the energy use for lighting and appliances increased 90-180% compared to EN-profile calculation. Due to higher heat gain from appliances, lighting and occupancy, the heating net energy use decreased about 30-35%, and cooling net energy use increased for 50-66% to ensure the normal temperature and comfort.

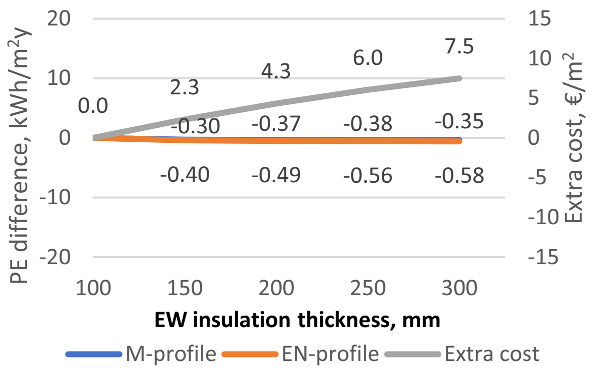


Figure 3. EW insulation measure primary energy (PE) change and extra investment cost compared to the base model

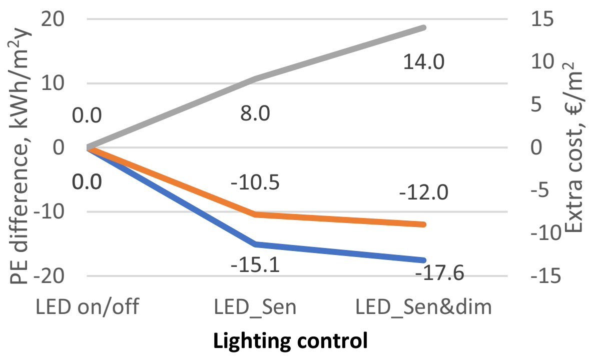


Figure 4. Lighting control measure primary energy (PE) change and extra investment cost compared to the base model

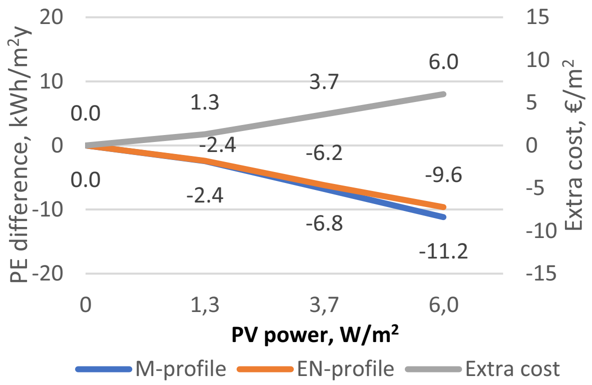


Figure 5. PV power measure primary energy (PE) change and extra investment cost compared to the base model

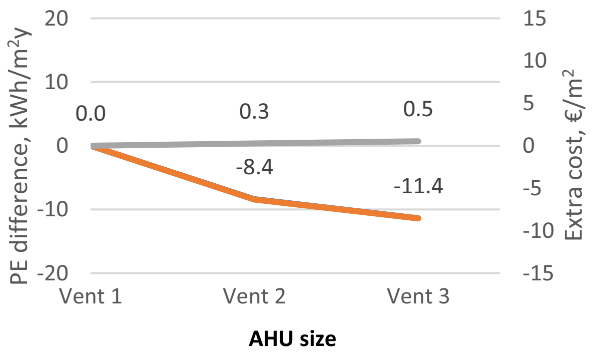


Figure 6. AHU size measure primary energy (PE) change and extra investment cost compared to the base model

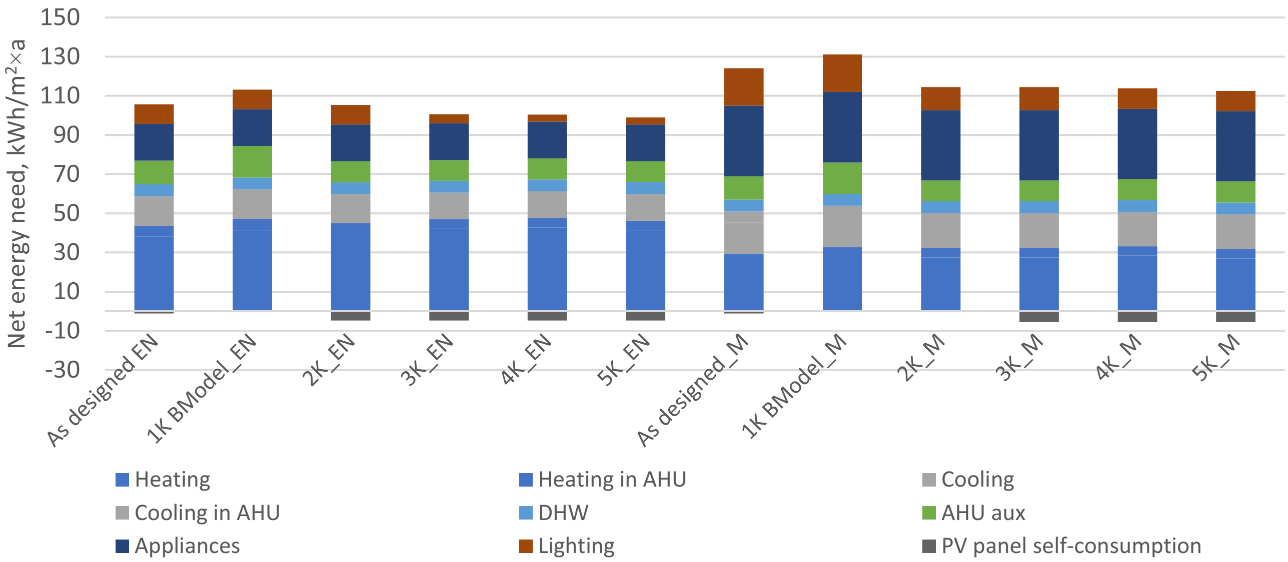


Figure 7. Net energy use of selected combinations of EN and measurement-based profile

3.2 The cost-optimal solutions

The cost-optimal solutions were combined with the best measures that had an investment cost per saved primary energy below 1 €/kWh and the insulation thickness measures were excluded. Combination as lighting control with sensors and dimming had the investment cost around 3 €/kWh, which was aslo included, but **Figure 9** shows that this was more expensive measure compared to others. Furthermore, if compare measures like lighting control with motion sensors and PV power 6 W/m², one can see in **Figure 9** that there was a big difference in investment cost per saved PE for EN-profile compared to M-profile, where the difference was almost zero.

Pareto front (**Figure 8**) shape for combinations was similar for both profiles. The only exception is the combination 2K. Turns out that the input data did not influence the cost-optimal solutions.

EN-profile reduced the PE use of cost-optimal solutions about 20 kWh/m²×y compared to the designed building and increased the investment for 6,6 €/m². NPV over 20-year period was 11 €/m² smaller than designed building. M-profile reduced PE use of cost-optimal solutions for 26 kWh/m²×y and increased the investment for 6,6 €/m². NPV over 20-year period was 15 €/m² smaller than for designed building.

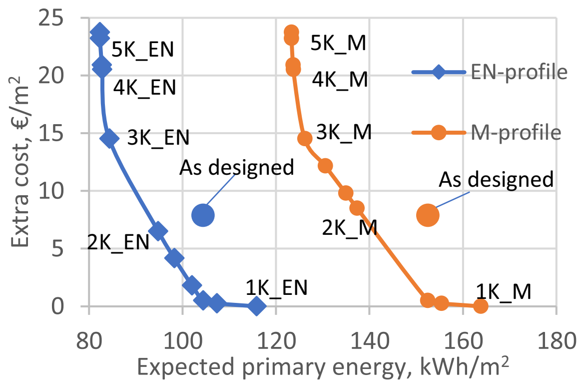
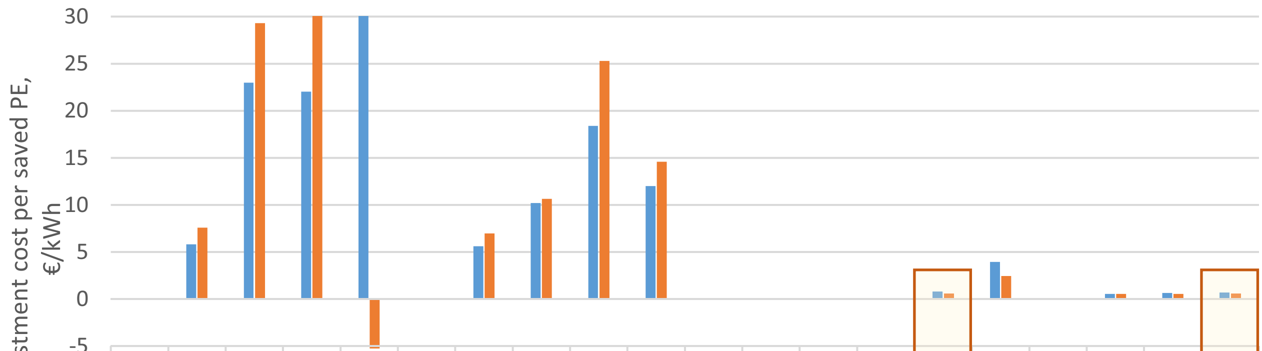


Figure 8. Pareto front for the cost-optimal solutions with EN16798-1 (EN) and measurement-based (M) profile



	EW 100	EW 150	EW 200	EW 250	EW 300	ER 180	ER 210	ER 240	ER 270	ER 300	V_1	V_2	V_3	LED on/off	LED_ Sen	LED_ Sen &d	PV 0 W/m2	PV 1,3 W/m2	PV 3,7 W/m2	PV 6,0 W/m2
EN	0	5.8	23	22	78	0	5.6	10	18	12	0	0.03	0.09	0	0.76	3.94	0	0.55	0.62	0.68
M	0	7.6	29	187	-53	0	7.0	11	25	15	0	0.03	0.09	0	0.53	2.43	0	0.54	0.54	0.54

Figure 9. The investment cost of measures per saved primary energy, €/kWh

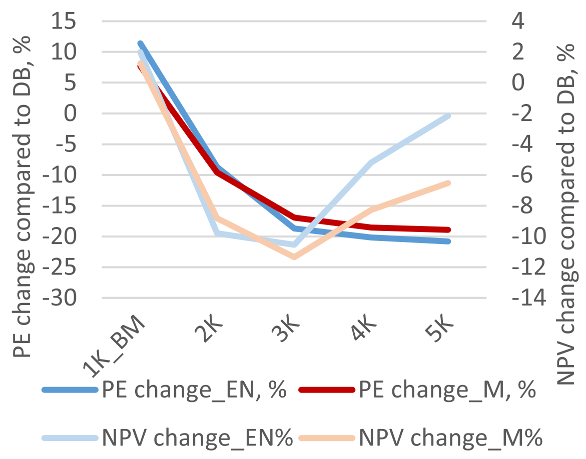


Figure 10. Primary energy and net present value change compared to the designed bld.

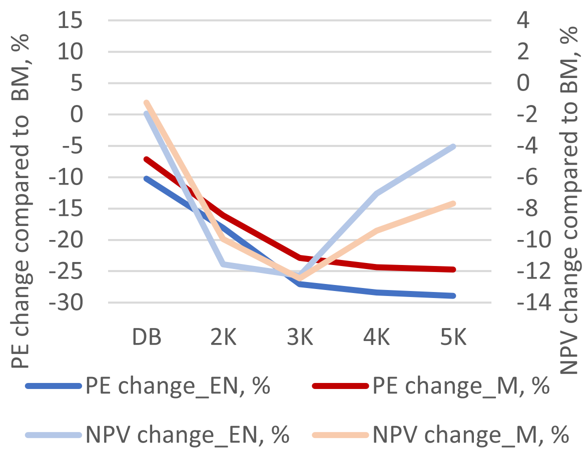


Figure 11. Primary energy and net present value change compared to the base model

From **Figure 10** and **Figure 11** one can see that M-profile behaves similarly to EN-profile. Combination 2K was different because of dissimilar measures between profiles (look **Table 4**). The M-profile relative NPV change was higher for the same measures. The higher was the investment, the bigger was the difference in between profiles. The NPV change difference between profiles was twofold for combination 5K. PE relative change was similar for profiles. However, the change was bigger for EN-profile.

The combination with the smallest NPV was 3K with bigger AHU, PV panels with power 6.0 W/m^2, and lighting with motion sensor control. The dimming will improve the energy efficiency, but the investment rises too much.

4 Conclusion

This study presents the impact of tenants' electricity use on cost-optimal solutions on the example of one office building with heated area 3822 m^2. Cost-optimal solutions were identified with EN 16798-1:2019 input data and compared with solutions identified with the model derived from measurements in the real building. The variables were building envelope insulation thickness, air handling unit size and effectiveness, electrical lighting control principles, and PV system nominal power.

The investigation shows that the primary energy use for the measures calculated with M-profile was about 37-52 kWh/m^{2}y higher than for the model with EN-profile. This was caused by increased lighting and appliances energy use. Greater difference of primary energy between profiles came from measures that reduced electricity use considerably.

The investigation over PV panel system shows that the higher was the nominal power, the higher was the exported energy (self-consumption was lower), but for the cases in this study, the self-consumption was for measurement-based profile 100% and for EN-profile 86-98%. Concerning the cost-optimal solutions, the profiles behave similarly. Still, there was one difference with the second combination, where lighting on/off control and 6.0 W/m^2 PV panel power was preferred for EN-profile. However, lighting with motion sensor and without PV panel installation was preferred for M-profile.

This study in the case of one office building shows that even if the profiles differ on energy use, still the cost-optimal solutions are the same. Therefore, in this case, it is recommended to use the standard profiles to keep the comparison with other buildings. However, this study has been done with measurement data from a building with extreme energy use that is unusual for a general office buildings. The results can not be generalized for other office buildings (at least not for administrative office buildings). Therefore, future studies should include measurement data from a reference buildings with normal energy use.

A future studies should add also the window size optimization and other primary heat sources (for example, district heat and natural gas) under investigation.

This study did not include the impact of changing the thickness of the insulation and the size of the AHU device on the value of the real estate.

Furthermore, the impact of cost-optimal solutions on heat pump power could be under investigation in future studies.

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Appendix 1

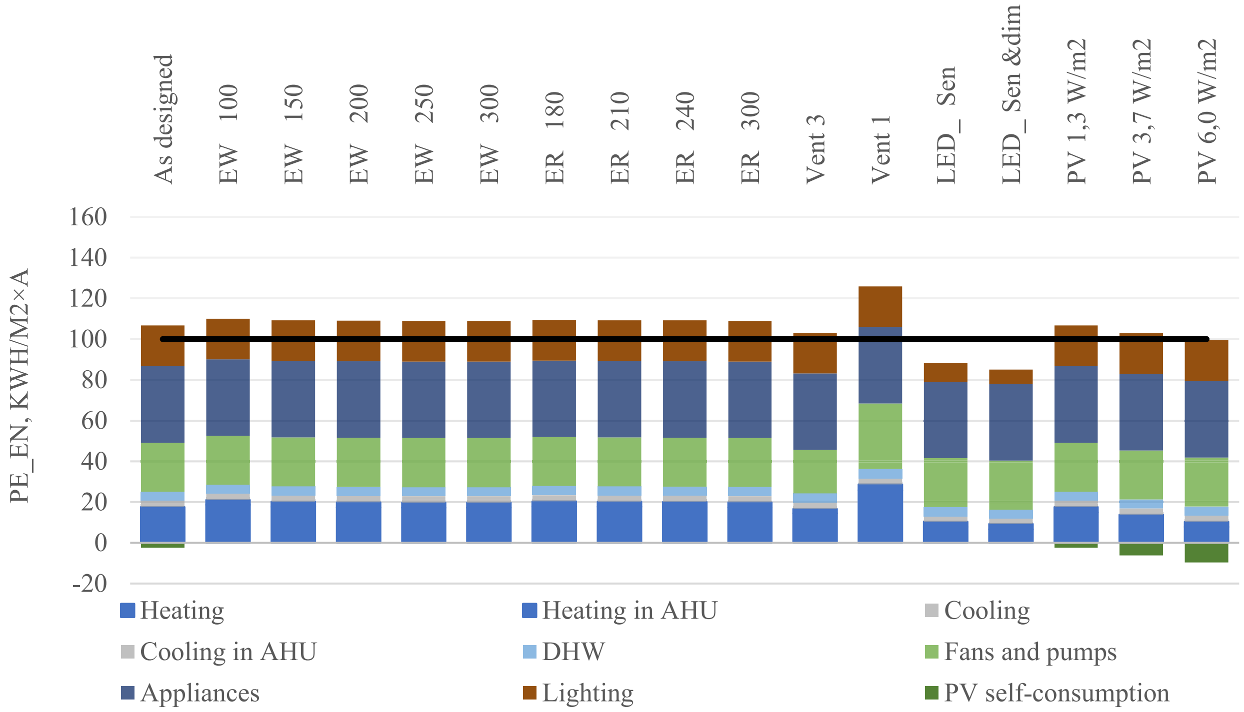

Figure 12. Primary energy (PE) use with EN16798-1 input data of all selected measures (black line is the requirement boundary)

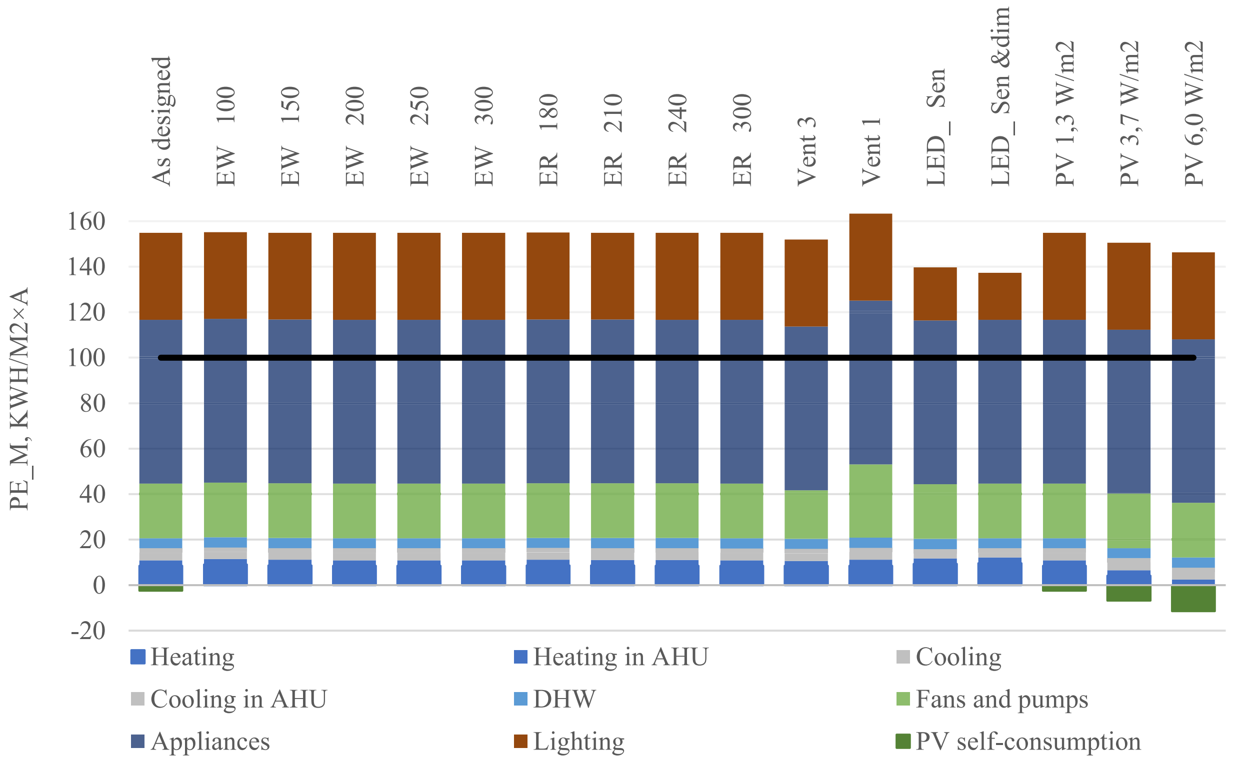

Figure 13. Primary energy (PE) use with measurement-based model input data of all selected measures (black line is the requirement boundary)