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An Evaluation of Occupants' Behavior Impact on the Energy Demand of a High-Performance Building in Norway

Case study: Verksbyen, Fredrikstad

Master's Thesis in Sustainable Architecture

Trondheim, May 2022

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Abstract

The share of energy use in the building sector is significantly higher than in the other sectors. Consequently, many measurements have been implemented to make the buildings more efficient and self-independent in recent years.

High-energy performance buildings have successfully reduced the amount of delivered energy by having better energy solutions. These solutions include reducing energy demand and production of on-site renewable energy. Zero-energy buildings in Norway use mainly passive house standard as a guideline, and consequently they have minimum energy loss. Nevertheless, some studies show higher measured energy values during operation than predicted energy for such buildings. Oversimplification of the buildings' energy modeling and the use of pre-defined and standardized inputs are among the main factors causing this gap.

The building body and systems alone have relatively static or predictable performance. On the contrary, buildings' context and surroundings characterize as more dynamic parameters. One dynamic feature that can affect the energy performance of buildings is occupants. People spend a considerable portion of their lives indoors. They would be present or absent, at the same time, they would adjust the building's systems and devices positively or negatively to fulfill their indoor, phycological, and physiological needs.

This study aims to illustrate an in-depth analysis of the possible gaps in the energy performance of a high-performance building due to occupants' roles (presence and actions). A dynamic Building Performance Simulation tool is utilized for this aim. The scenarios use stochastic modeling to show occupants' unpredictable and complicated characteristics.

The other studied areas include 1- internal load gains impact on the energy demand, 2- evaluation of the thermal comfort in the potential worst case, and 3- evaluation of possible design options to compensate for a wasteful user.

The findings show a significant gap when it comes to the negative behaviors in the overall energy performance. It also shows that internal loads have a massive impact on change of the energy needs. The low thermal comfort levels can easily reach favorable conditions by implementing the adaptive solutions in the occupant's profile, while design options cannot easily address the hostile impact of the user.

Keywords: occupant modeling, post-occupancy simulations, energy performance gap, occupant behavior, operational energy

Acknowledgement

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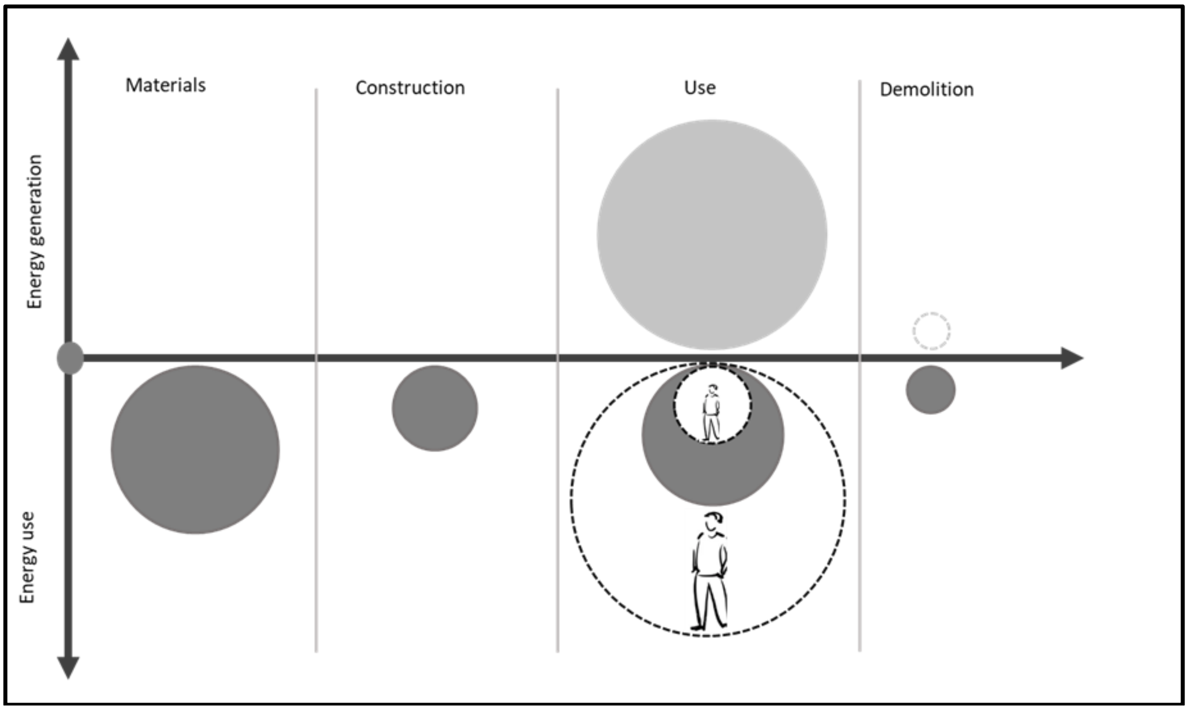

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Abbreviations

ACH	Air Changes per Hour
AHU	Air Handling Unit
BPS	Building Performance Simulation
CAV	Constant Air Volume
EPB	Energy Performance of Buildings
GSHP	Ground Source Heat Pump
HDD	Heating Degree Days
IEA-EBC	International Energy Agency – Energy in the Buildings and Communities program
IFC	Information Foundation Class
OB	Occupants' Behavior
OPA	Occupants Presence and Actions
PEB	Positive Energy Building
PPD	Percentage People Dissatisfied
SPEN	Sustainable Plus Energy Neighborhood
DHW	Domestic Hot Water
IEQ	Indoor Environment Quality
PMV	Predicted Mean Vote

1 Introduction

1.1 Background

The building sector accounts for 40% of the total energy use in Norway, of which residential and non-residential buildings are to be blamed for 22% and 18%, respectively [1]. The total energy use in a Norwegian dwelling is usually the highest for space heating and domestic hot water (DHW) [2]. These two demands contribute to approximately 70% of residential buildings' total energy demand [2]. Thus, implementation of energy-saving measurements in buildings and predicting their actual performance is vital in achieving sustainable energy goals.

According to Energy Agency – Energy in the Buildings and Communities program (IEA-EBC) Annex 53, six major parameters affect the energy use in buildings, including: (1) building envelop (2) climate, (3) building energy and service system (4) indoor design criteria (5) building operation and maintenance and (6) occupant behavior [3]. Among all, occupants' behavior studies have been more recent and complicated.

Occupants' presence and interactions with building devices and systems has caused a significant difference between predicted and measured energy [4]. Some studies indicate that user behavior has more influence on the energy performance than envelop [4]. Users' behavior has been found to be responsible for exceeding of over 50 % of the total electricity use. Ventilation and temperature rates are also among parameters that show different values from actual and prediction [5] [6] [7]. Other studies show significantly higher DHW consumption than calculated values [8]. An interview in [8] shows that most people think it is positive to save energy, but they mostly do not tend to decrease their comfort levels to save energy.

Considering the occupant's role is even more crucial for high-performance buildings with an active connection to the grid for exporting and importing electricity. The main reason is to ensure that such buildings remain within the predicted energy balance. Otherwise, even a high-performance or positive energy building may perform as an ordinary building.

So, this study will analyze the impact of occupants on the building's operation in a zero-energy residential building under the Norwegian climate condition. The input data and scenarios are based on the valid literature as explained in the relative section. The occupant modeling includes the following interactions: lighting, DHW, appliances, temperature setpoints, ventilation rates, and window opening patterns. Also, a more detailed analysis was done on the IEQ of a case with the most undesirable PMV ranges caused by energy-saving behaviors. On the contrary, some additional energy-saving design options were investigated for the case with the most wasted energy.

1.2 Objectives

This thesis aims to evaluate the energy performance of a zero-energy building by use of post-occupancy simulations. The results aim to illustrate three main energy demand gaps between: 1- Minimum occupant model and standard model, 2- Maximum occupant model and standard model, and 3- Minimum and Maximum occupant model. Then, an evaluation of PMV conditions was done for the minimum energy user, while for the maximum energy user, an evaluation of possible design improvements was considered [*Figure 1-1*].

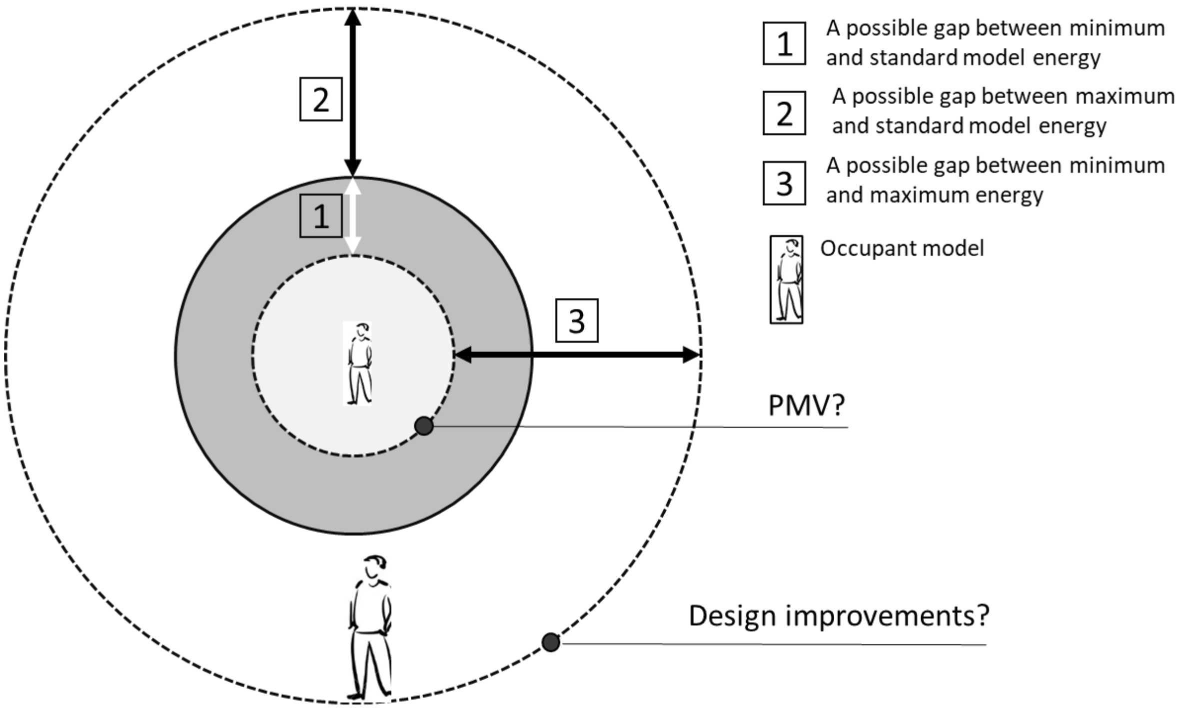


Figure 1-1 The main research goal

The process was then divided into particular questions for a better understanding of different behavioral impacts on energy use. Also, to have integrated and more reliable results. Each of these questions was discussed in detail at the end of their relative sections. In the end, all the findings were combined and included in a more comprehensive discussion part.

The research addresses four primary questions, as shown in [

Figure 1-2]. This figure also shows how the occupant modeling process was performed:

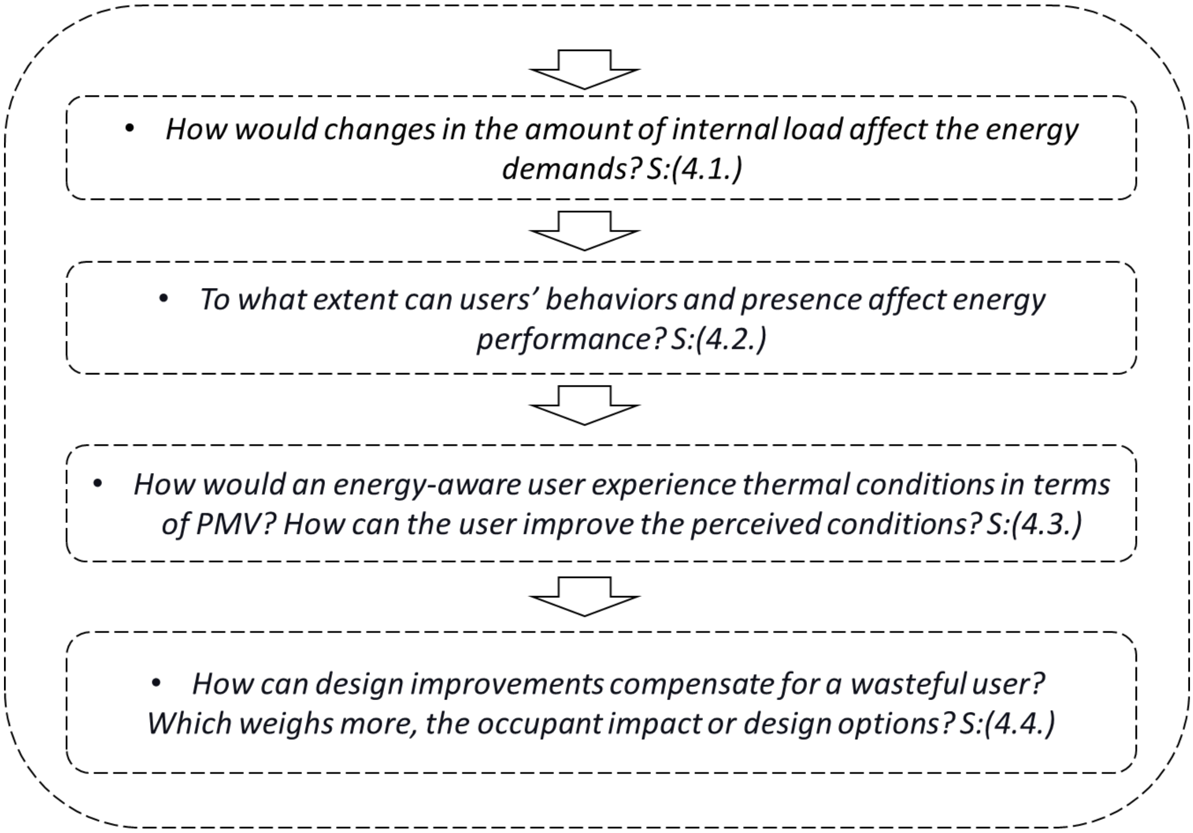


Figure 1-2 The research questions and the process

1.3 Scope and limitations

Occupant models can include variety of parameters and inputs that are not all addressed in this thesis. Figure 1-3 summarizes the items included and not included in this work:

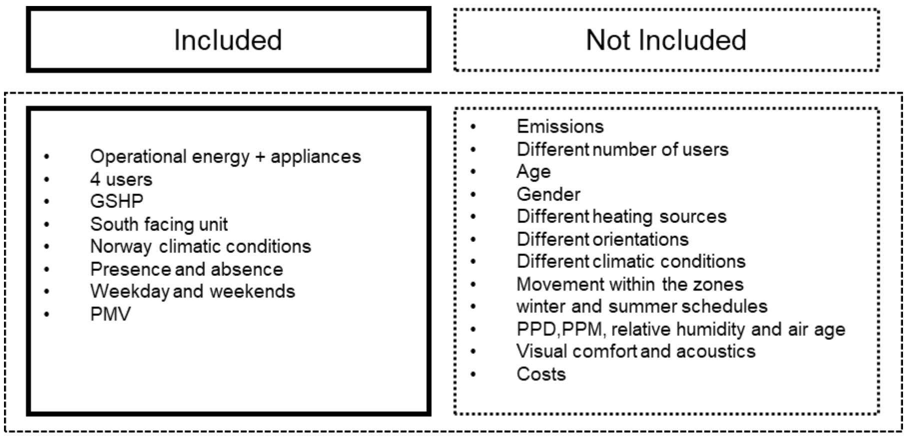


Figure 1-3 The scope and limitations

1.4 Thesis outline

This thesis includes 6 chapters in addition to the introduction that are described below:

Chapter 2 – explains the major reasons behind choice of this study. In addition, it describes the terms, methods and concepts used throughout the process and in the following chapters.

Chapter 3 – provides detailed information about the methodology and framework. The first sub-chapter gives information about the case study, software tools, occupant modeling approach and national codes and frameworks. The second sub-chapter describes the Base case including: systems, internal gains, input values, energy performance and energy balance

Chapter 4 – includes 4 sub-chapters. The first sub-chapter shows the changes in the energy demand by impact of behaviors on the internal loads. The second sub-chapter adds the complementary interactions including heating, cooling and ventilation in the behaviors. Third part evaluates the thermal comfort in terms of PMV, and the last chapter evaluates the possible design improvement. Each sub-chapter includes a detailed discussion section to evaluate the results. The focus on the first and second parts in here is explaining the problems, while section third and fourth describes possible solutions.

Chapter 5 – includes a summarized discussion after combining all the evaluation phases.

Chapter 6 – provides a conclusion of the whole study

Chapter 7 – suggests possible areas for future study

2 Literature review

2.1 Energy use in buildings

In western countries, buildings are blamed for more than one-third of the total energy use [9] [10]. Thus, it is more environmentally friendly and cost-effective to have more efficient buildings rather than higher capacity in the energy systems [11] [12].

In Norway, buildings account for 1/3 of total energy demand, of which electricity has the largest share [13] [14]. The use of solar energy and biomass has helped a lot to reduce the heating demand in Norway [12]. However, other means of energy demand, such as appliances, lighting, fans, and pumps, and DHW still need further attention. The key solution for such indicators is shifting to more efficient equipment and clean energy supply systems [12]. As [12] describes the energy balance in zero-energy (or zero-emission) buildings is achieved by: 1- reducing the net energy demands by using highly efficient building envelope and energy systems. 2- the production of on-site renewable electricity and thermal energy [*Figure 2-1*].

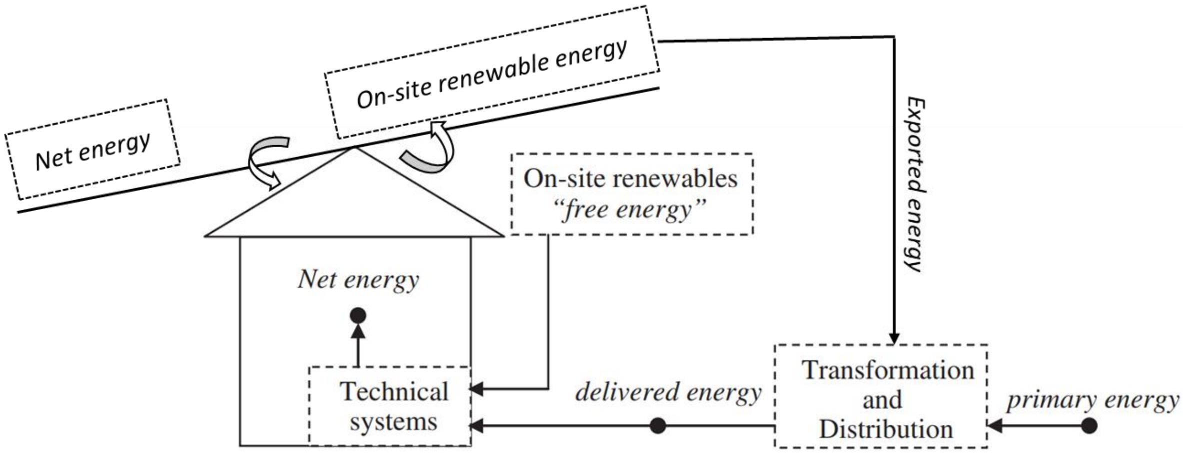


Figure 2-1 energy chain and energy balance in a high-performance building

(Modification on a sketch in [15])

2.2 Energy performance gap

The performance gap refers to the difference between building's predicted and actual performance [16]. In addition to the energy consumption, the performance gap can address the difference in calculated and measured Indoor Environment Quality [17].

Many studies have investigated the energy performance gap in residential buildings. For example, [18] has compared building's measured and calculated energy in Cyprus with a relatively warm climate. This comparison includes 10 dwellings, and the results show an average ratio of around 2.5 between the measured and calculated energy use. A similar study in Norway [19] evaluated seven passive houses and two TEK10 homes with comparable outdoor climates. For the passive houses, the average annual energy need was 90 kWh/m2, while TEK 10 homes had around 135 kWh/m2 of total energy needs. The same project shows a measured heating demand of 51 kWh/m2 compared to the predicted value of 18 kWh/m2 [19]. Furthermore, a study done by [20] found around 22 times higher heating energy demand than predicted. A study in Belgium on 2 residential buildings by [21] illustrates a performance gap of 1.79 times for 8 buildings and a variation of 2.03 times for 12 buildings.

Several issues may lead to a performance gap, which can be different from one building to another. Here some of the possible reasons is mentioned:

miscommunication in the design phase among the design team or between the design team and the clients [22] [23]. Another problem is that the design team cannot fully predict the future use of the building. Then, the change in the operation, equipment and requirements would cause enormous difference in the predicted energy [23] [24].

In the "green" or "high-performance" buildings, the energy systems might not perform as good as predicted. This can be due to manufacturer faults or overestimating the performance of the products by the design team [25] [23]. It is also possible that lack of attention in the construction phase cause later underperformance of the systems [26].

Incorrect modeling and simulation can also cause performance gap. This can be caused by using wrong method, tool or model [22] [24] [27]. At the same time, low level of competence and knowledge from the analyst may increase this uncertainty in the results [28].

Also, occupants usually behave different than predicted in the design stage which leads to performance gap. Many studies identify the occupants as the main reason for the performance gap [24] [27] [29].

2.3 Occupants and building energy

Occupant presence, activities and interaction with building has been a huge influential factor affecting the building energy use [30] [31] .Since high-performance buildings follow passive house criteria and use highly efficient systems, the impact of occupants is expected to have a substantial impact on such building's energy consumption [32]. A study illustrates a saving potential of over 35.5 % by occupants [33]. On the other hand, [34] shows higher energy consumption during non-working hours as a result of wasteful occupant behavior. For example, by leaving lights or equipment on when there was no active occupation in the zone [34].

The probability of occupancy and occupants' interaction makes it difficult to predict the final energy performance of the buildings. The real building performance is highly dependent on the state of occupancy [35]. Occupant presence can directly affect the building performance due to heat production, CO2 emission and moisture production from the people. Also, presence of occupants is basis of any other interaction with building parts [35].

[36] divides occupancy and occupants' profile by two main indicators: 1- occupancy that refers to the number of hours that users are present or absent within the dwelling and the activity performed by them. 2- Occupant profiles that shows the number of occupants. [37] separates the behavior of occupants in 2 categories of :1- short term: the phycological, physiological, and economic conditions, and 2- long term parameters: culture, sex, comfort, income, and age.

2.4 Data collection methods

Considering occupants in a study requires a thorough set of data to generate reliable models. There are different methods for data collection such as, in-situ studies, laboratory studies and surveys [37]. In-situ studies utilize sensors to observe occupants' behavior in a daily basis. Use of sensors helps with long term data collection and less environmental distractions. On the other hand, sensors position, size and accuracy can affect the results from the study group. Also, cost of sensors is another factor to consider [37].

The other data collection method is laboratory studies. In this case experts would observe the users in an equipped environment. As the occupants are unfamiliar of the space and they are aware of being observed, it may affect their behaviors. Also, this method is more costly than in-situ studies. However, laboratory observation provides the possibility of having better observation of the behaviors and control of indoor environment conditions [37].

The survey collection refers to self-reporting approach for personal behaviors. Using the surveys can provide a large amount of data with the lowest cost [38].

2.5 Occupant's modeling methods

There are several ways to model user's presence and action in a simulation-based analysis. The modeling process can be separated to 1- static or dynamic simulations, and 2- deterministic or probabilistic approach [39]. Dynamic models makes it possible to couple the impact of building and the occupants on each other. On the other hand, the static models are not capable of identifying the two-way influence of building and users [39]. Both static or dynamic simulations can have either deterministic or stochastic modeling approaches [39]. The results from the deterministic models would remain the same in various simulations, while the results would differ every time by use of probabilistic models [39]. The difference in the result is due to random selection of the inputs. Thus, deterministic models cannot show the range of energy performance or comfort conditions of building [39].

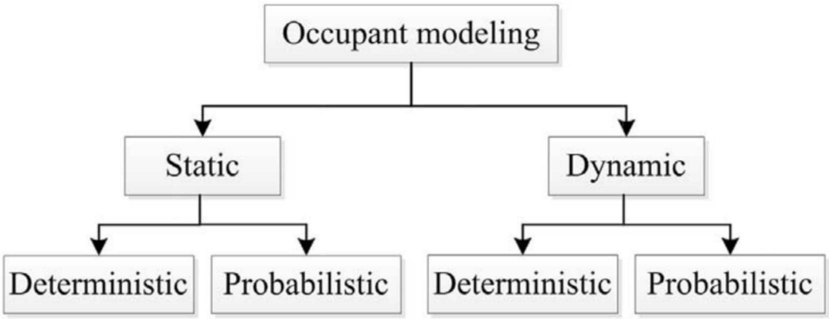


Figure 2-2 occupant modeling approaches defined by [39]

There are two terms acquainted with the occupants modeling: 1- occupancy and 2- occupant energy use behavior. occupancy shows the possibility of presence or absence of the occupants, while occupant energy use refers to the interaction of occupants with artificial lighting, appliances, heating setpoints and etc. [40] [41].

Also, [42] divides the modeling methodologies of occupancy in buildings in 4 categories of deterministic (rule-based), data-driven, stochastic (probabilistic), agent-based.

Deterministic models use fixed schedules such as ASHRAE or NECB with more simplicity [43]. The deterministic schedules provides hourly inputs for different building typologies to form a daily profile [44]. Some studies introduce deterministic models as rule-based models.

Data- driven models are based on the different occupancy profiles that are defined using smart energy monitoring devices and survey data [43].

Agent-based models are based on individuals' interaction with the building and models users' movement pattern in the building, their energy behavioral impact, and their thermal comfort adaptability [43] [45].

Stochastic models which are used for simulations in this study calculate the probable behaviors by users. As mentioned in [46], the simulated values are more reliable if one uses stochastic occupancy profiles. The stochastic models follow the Markov Chain process which can include occasional periods of prolonged absence [47].

2.6 Occupants in BPS tools

BPS tools help with designing buildings that address both the resource consumption and occupants needs by providing quantitative results [48] [49] [50]. As [51] describes BPS tools should have the following characteristics: 1- should illustrate a clear representation of dynamic, connected and non-linear physical process in the building performance. 2- should show the interaction between different building devices in their operation. 3- should follow up design processes by interactive adjustments in design hypothesizes. Regardless of the physical process in the buildings, users can change the predicted building performance to a great extent [51].

Occupants' presence and interaction is rather underestimated in the simulation phase of buildings [52]which can be due to 3 main reasons: 1- not enough data about the impact of occupants in the existing buildings. 2- not having supporting standards with detailed representation of occupant's role in the buildings. 3- limited performance of simulation tools for proper occupants modeling as well as lack of expertise in use of such simulations [52] [50].

One can specify the number of occupants and the active occupation by giving hourly presence schedules. In addition, both schedules and design peak powers can be defined for lighting, plug loads, and DHW. BPS tools also provide the opportunity to describe use of windows, shading devices and thermostat setpoints and setback periods. However, the level of details that one can get from a BPS tool may differ from one tool to another [53].

3 Methodology

3.1 Case study

3.1.1 Location and neighborhood

The case study is located in a residential SPEN called Verksbyen in Fredrikstad (59.2205° N, 10.9347° E), Norway. This neighborhood consist of six different building typologies: 1- Verkshaugen, 2- Verksbakken, 3- Løkkeberghagen, 4- Verket Panorama, 5- Verket Atrium, and 6- Capjøn Park. Furthermore, it includes detached houses, semi-detached houses, terraced houses, and apartments [Figure 3-1].

Figure 3-1 Verksbyen neighborhood, building typologies and selected apartment building. [https://www.arcanova.no/]

The energy model of this study is done on a single-family apartment unit from Verket Panorama [Figure 3-2]. All the information, drawings and details was provided by Arca Nova, the developer.

Figure 3-2 The selected apartment building- Typology: Verket Panorama

Verket Panorama includes 3 apartment buildings and 66 units in total. Each apartment unit has different size that can vary from 52 to 125 m^2. Also, the building is currently under construction and will be ready for people to move in from June 2023.

Following the available information about the apartment unit and the scenarios made, a south-facing apartment was chosen for further analysis. This unit consists of 3 bedrooms and has a total useful area of 105 m2. It is also assumed to accommodate a family of 4 members [

Figure 3-3].

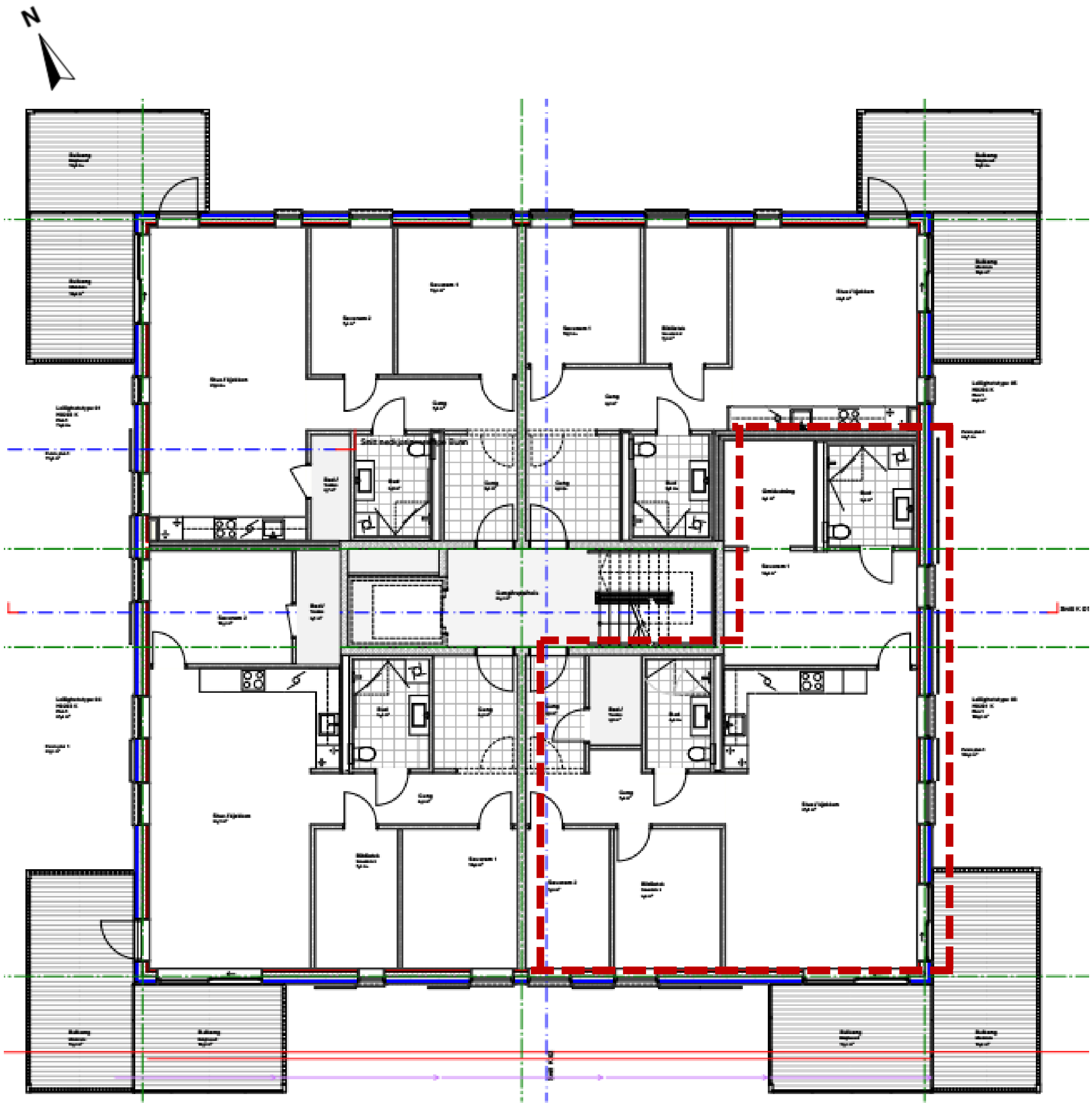


Figure 3-3 The selected south-facing apartment unit in Verket Panorama

3.1.2 Climate

The climatic conditions characterizes under the sub-arctic category with long, usually freezing winters and short, cool summers.

The annual temperature is mainly below the comfort zone, with an average of +6 ◦C. The temperature is minimum during January with approximately -15◦C, and it is maximum during June at around 25◦C [Figure 3-4].

Overall, the HDD (Heating degree days) is 4787 hours. Thus, heating seems to be the main challenge in this climate. Also, the image below shows the low levels of available solar radiation throughout the year for this location.

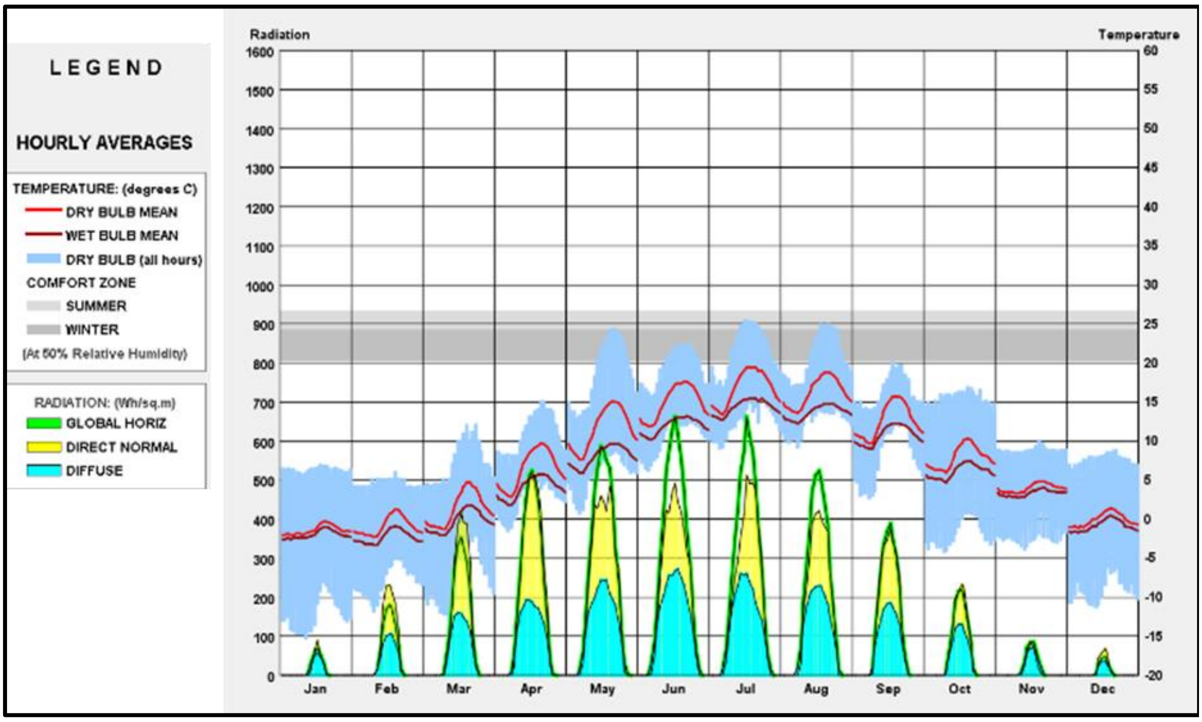


Figure 3-4 The temperature and radiation ranges for the case study in Fredrikstad climate consultant 6.0

3.2 Software tools

The base of all the calculations is use of dynamic modeling. For this aim, the building was firstly modeled in Revit. Then, the IFC (Information Foundation Class) file was directly imported into IDA-ICE 4.8 for energy calculations.

IDA-ICE Stands for Indoor Climate and Energy and is a dynamic tool for simulating multiple zones. The results from IDA-ICE would describe a detailed indoor climate of each zone and provides the energy consumption of the entire building [54].

For the energy model the adjacent rooms were also modeled. So, the software can distinguish interior walls and spaces from exterior ones. [Figure 3-5]shows the model in IDA-ICE. Moreover, Pvsyst was used for PV calculations.

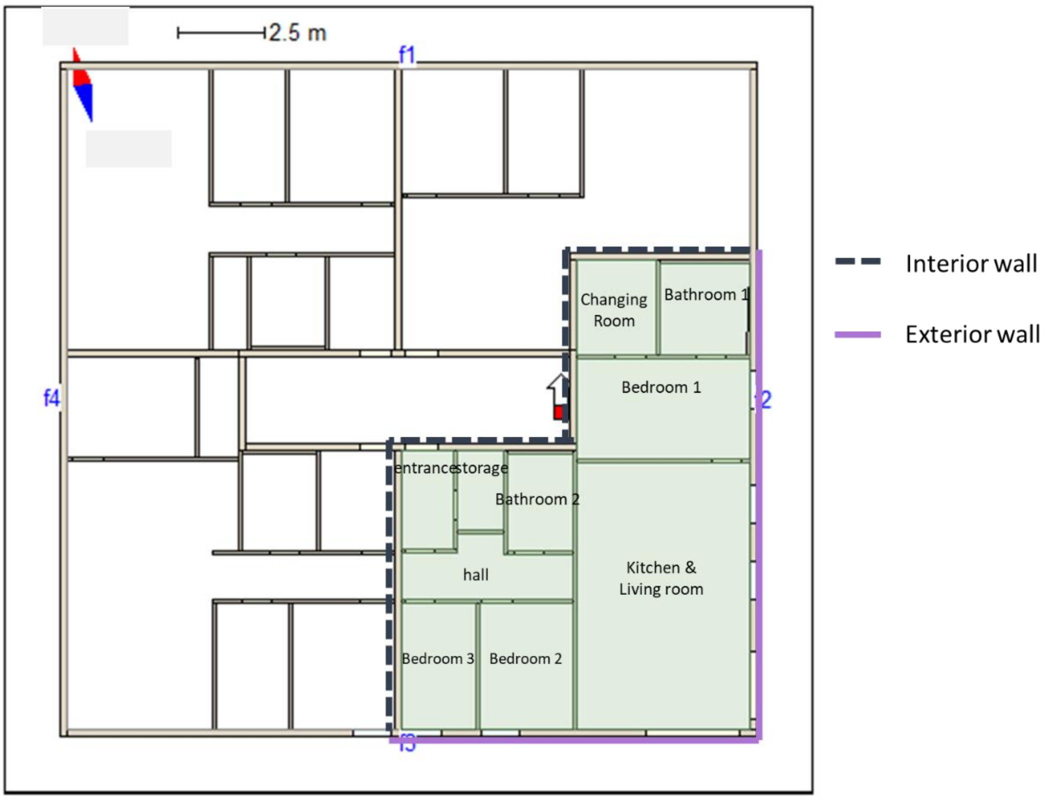


Figure 3-5 The energy model in IDA-ICE 4.8

3.3 Occupant modeling

The occupant modeling approach for the scenarios is under the stochastic modeling category explained in chapter 2. The stochastic inputs were inspired and compared with relatable studies that is discussed further in this study.

On the contrary, the base case follows the deterministic schedules and inputs from SN-NSPEK 3031:2021 and NS 3700 [55] [56]. SN-NSPEK 3031:2021 provides patterns for occupants' presence, lighting, DHW, and equipment use on an hourly basis, which forms a daily profile.

[Figure 3-6] shows a summarized flow chart of the overall methodology:

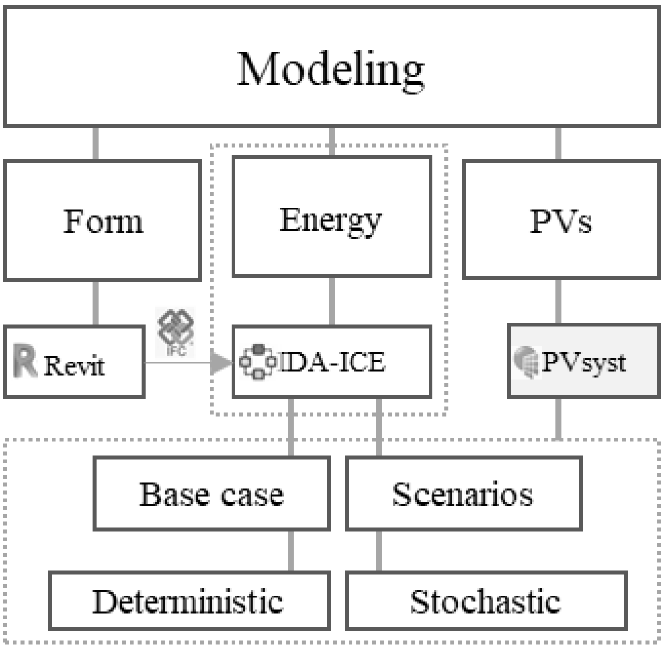


Figure 3-6 A summary of software tools and occupant modeling approach used

3.4 National code and regulatory framework

All the buildings in Verksbyen neighborhood follow passive house standard for the quality of construction. The building body in Verket Panorama has wooden frame walls and the floor slabs are made of Hollow core concrete slab. The developer, Arca Nova, provided all the details for this study that can be found in the appendix.

The base case uses the national code and regulatory framework described on the table below as the main source for inputs:

Table 3-1 national codes and inputs used for the energy model

Source	Criteria	Value
Tek17 14-4 Energy supply	Total energy need	≤ 95 kWh/(m2/y)
	Energy supply solution	No use of fossil fuels for covering the heating demand Buildings with a heated gross internal area of more than 1000 m2 shall have multi source heating systems and be adapted for use of low-temperature heating solutions. Low temperature heating (TSUPPLY< 60°C) must cover ≥ 60% of the heating demand
	U-value outer roof	≤ 0.18 W/(m2K)
	Outer wall	≤ 0.22 W/(m2K)
	Slab on ground and toward exterior	≤ 0.18 W/(m2K)
	Windows and doors	≤ 1.2 W/(m2K)
	Air tightness (at 50 Pa pressure difference)	≤ 1.5 ACH
NS 3700: 2013 criteria for passive houses / residential buildings	Specific space cooling demand	No mechanical cooling allowed
	Air tightness (at 50 Pa pressure difference)	≤ 0.6 W/(m2K)
	Normalized thermal bridge value	≤ 0.03 W/(m2K)
	Specific fan power (SFP) for ventilation fans	≤ 1.5 W(m3s)
	Ventilation heat recovery efficiency	≥ 80%
	Specific space heating demand	≤ 15 kWh/(m2y) considering an annual average temperature at site over 6.3 °C
	U value roof	0.08-0.09 W/(m2K)
	U -value outer wall	0.10-0.12 W/(m2K)
	U-value foundation	0.08 W/(m2K)
	U-value windows and doors	≤ 0.8 W/(m2K)

3.5 Base case

3.5.1 Systems

Each apartment unit in this block has its own Air Handling Unit (AHU) and the ventilation system is CAV (Constant Air Volume). The minimum supply air volume of 1.2 m3/h.m2 was defined based on SN-NSPEK 3031:2021 for bedrooms. In the kitchen, however, this value is set to 1.5 m3/h.m2 to maintain higher IEQ since cooking takes place in this zone. The air velocity is set to 0.1 m/s in all the zones for the mechanical ventilation. Also, exhaust air is collected from both the kitchen and bathrooms.

Ground Source Heat Pump (GSHP) is the primary heating source in this apartment. The heat is then distributed to the zones by ventilative and water-based floor heating. Additionally, AHU preheats the air to 19 °C before it supplies to the zones. If more heating is required, the water-based floor heating system would provide it. The heating load for the floor heating is optimized as an ideal heating unit to meet the setpoint requirements. Also, it has a PI controller that works in accordance with the indoor air temperature level.

There is no mechanical cooling unit in this building and all the cooling load is treated by natural ventilation. Thus, the windows will open if the indoor temperature goes higher than 25°C.

3.5.2 Internal gains

The power loads and schedules for lighting, appliances, DHW, and people are extracted from SN-NSPEK 3031:2021. Also, the percentage of internal heat gains from different interior heat sources is set as below [56]:

Table 3-2 The share of heat gains from different internal heat sources

	DHW	People	Lighting	Appliances
Apartment buildings	0	100%	100%	60%

In IDA-ICE, the occupancy can be defined by MET and Clo rates. One occupant in IDA-ICE with 1 MET and between 0.25 and 0.85 clo produces heat of around 106 W. The figure on the next page shows an example of defining occupants in IDA-ICE.

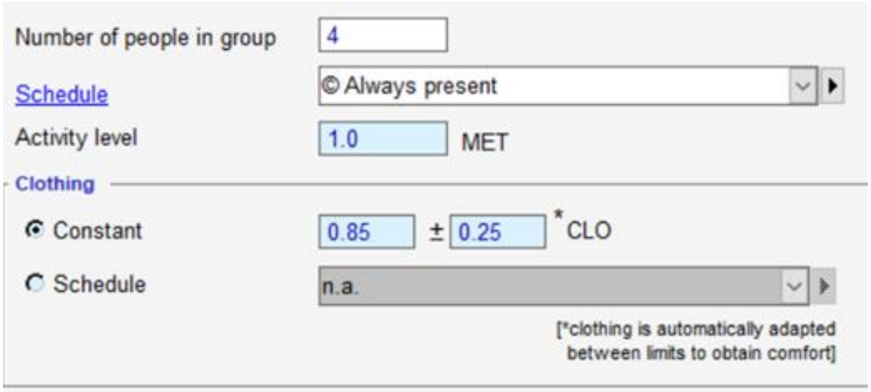


Figure 3-7 Defining occupants in IDA-ICE by number, schedule, activity level and clothing

3.5.3 Input values

The rest of the input values for the base case follows as below:

Table 3-3 The properties and inputs used for the Base case

Base case	**Properties**		**Unit**
	Usable floor area	105	m^2
Envelop	Exterior walls U-value	0.1	W/ (m^2 K)
	Floor slabs U-value	0.83	W/ (m^2 K)
	Windows U-value	0.8	W/ (m^2 K)
	Normalized thermal bridges	0.03	W/ (m^2 K)
	Glass to wall ratio	40	%
	Infiltration rate (n50)	0.6	ACH
Ventilation	Exchange rate	Min: 1.2/ 1.5	M^3/ h.m^2
	Heat recovery efficiency	80	%
	Specific fan power	1.3	W/ (m^3s)
Internal gains	Occupancy (constant)	1.5	W/m^2
	Lighting (schedule)	Average: 1.3	W/m^2
	Appliances (schedule)	Average: 2	W/m^2
Operation time	schedules	Source: SN-NSPEK 3031	
Heating set point	20	Constant	◦C
Cooling set point	n/a		
Heating system	GSHP	COP: 4.4	
Heating distribution system	Water floor heating		
Cooling system	n/a		

3.5.4 Energy performance

Ambition level: Operational phase of a zero-energy building, including appliances and plug loads energy. The calculation of the emissions is not included.

Table 3-4 Energy performance of the base case, kWh/m2.year

	Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Energy produced on-site [kWh/m2]	**45.77**	0.33	0.84	2.92	5.32	7.7	8.38	8.41	5.85	3.70	1.69	0.48	0.16
Total energy demand [kWh/m2]	**67.28**	7.39	5.73	6.21	5.39	5.14	4.83	4.92	4.94	4.92	5.44	5.84	6.53
Total electricity demand [kWh/m2]	**42.89**	4.08	3.47	3.77	3.49	3.47	3.34	3.43	3.43	3.36	3.57	3.62	3.86
Exported electricity	**18.84**	0	0	0	1.83	4.23	5.04	4.98	2.42	0.34	0	0	0

This study includes the energy demand for plug loads and appliances as one of the primary factors for evaluation of the net energy demand and/or energy balance. Technical appliances are not calculated in many projects. By adding them in here, the on-site renewable energy remains slightly above the total electricity demand which makes this building closer to a zero-energy building. On the other hand, if the appliances and plug load's energy is not to be considered as a primary need, this building would be more of an PEB. For more clarification, another energy balance chart is made and put in the appendix 15.

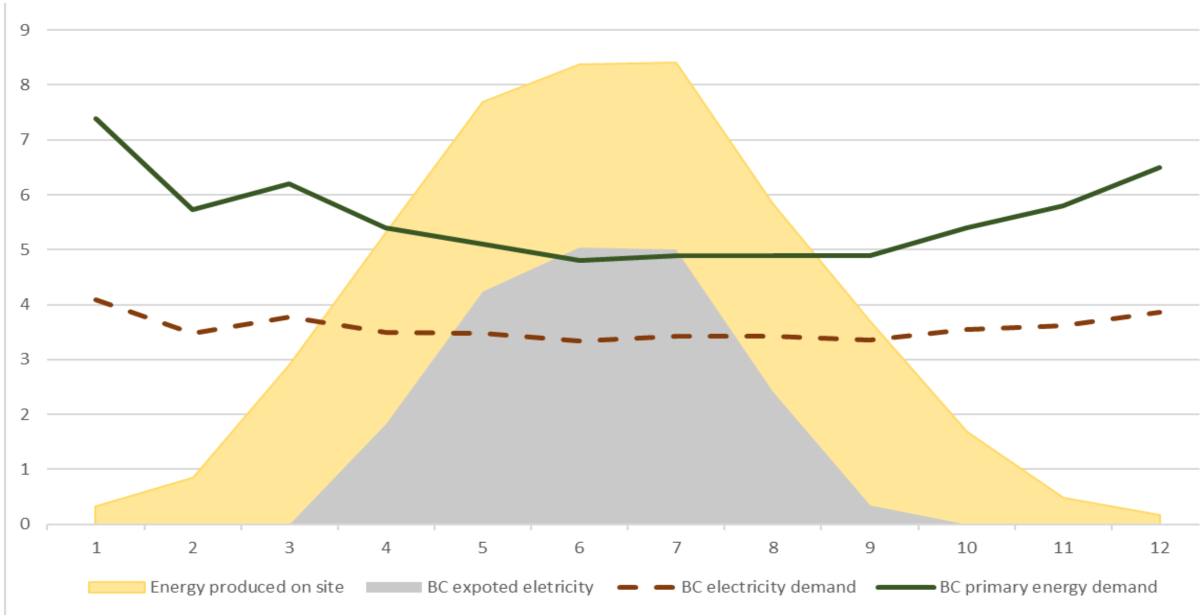


Figure 3-8 Base case energy balance, kWh/m2. year

4 Occupant modeling

The occupants' energy simulations were done in 2 main parts: 1- occupants and internal loads and 2- occupants and heating, cooling and ventilation.

The first part includes patterns of behavior in relation to lighting, appliances and DHW. In addition, stochastic patterns of user's presence and absence is defined in this part. Except for DHW, the rest of the parameters have impact on the amount of internal heat gains. On the contrary, except for occupancy schedules, all the other indicators directly impact the electricity demand (lighting, appliances and DHW). More detailed information about the approach is mentioned in the respective sections.

The second part of simulations concerns the interactions with heating, cooling and ventilation systems. The cooling does not consider interactions with mechanical cooling systems, but rather natural cooling (window opening patterns). In some extreme cases, cooling demand was evaluated for better understanding of the overheating situations. The second part is a completion to the results from part 1 (internal loads), which gives a comprehensive understanding of the possible energy performance gaps [Figure 4-1].

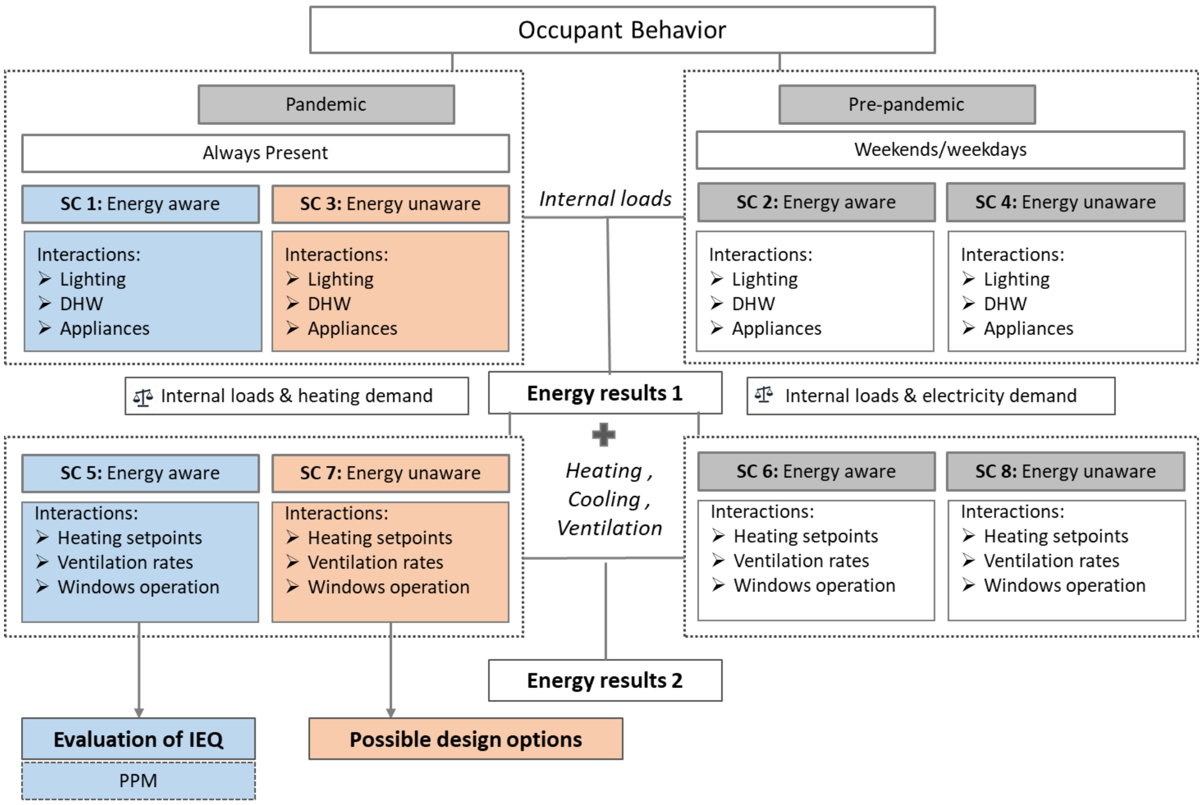


Figure 4-1 Scenario planning and evaluation process.

All the cases in part one and two consider 2 user profiles: 1- energy-aware (energy saving) user, and 2- energy-unaware (energy wasting) user. An energy-aware user is someone that accepts some levels of discomfort as energy is highly important for him. On the contrast, an energy-unaware cares mostly about his comfort conditions rather than energy. Energy wasteful user, therefore, would have higher energy needs compared with an energy aware user and this research will show the difference.

This study is further followed by possible solutions for extreme conditions caused by each user profiles. This, in the case of an energy-aware user, includes an evaluation of PMV values. Whereas, in the case of an energy-unaware user includes possible design options to reduce the negative impact of the user on the energy demand.

After evaluation of PMV values, this research will show how the energy saver occupant can experience the thermal comfort conditions. Also, it illustrates how the solutions impact the net energy and heating demand.

The last part weighs/ compares the impact of a wasteful user with possible design options regarding the total net energy demand. The proposed design options in this part consider only the possible ways to reduce the energy demand and not options for more on-site renewable energy production [Figure 4-1].

4.1 Occupants and internal loads

4.1.1 Occupancy

Occupancy refers to presence and absence of users in the building and it directly affects the amount of internal gain from people. Additionally, people's active occupancy (presence) in each zone increases the chance for more interactions with building devices and systems. Examples of the interactions are with lighting, appliances, windows, heating setpoints and etc.

In IDA-ICE occupants can be defined by 1-the number of users, 2- Clo and MET values, 3- schedules, 4- their position in the zone [Figure 3-7]. The total number of users in this study is assumed to be four. The MET and Clo values for all the energy cases, except for IEQ part (4.3.), is set to:

MET= 1 and CLO = 0.25 to 0.85 that are default values in IDA-ICE.

Further information about the definition of each activity levels and clothing levels is provided in the appendix 16.

In addition, the occupancy schedules follow stochastic approach and is divided in 2 primary scenarios: 1-Pandemic and 2- Pre-pandemic. The main concept for this division is to compare an extreme presence pattern with normal working days schedule. Both schedules concern energy-aware and energy-unaware profiles.

The pandemic scenario has 24 hours of occupancy (100% occupancy rate) per day. On the flip side, the pre-pandemic schedules includes the absence periods for working, school, or leisure throughout the day. [Figure 4-2] summarizes the occupancy scenarios.

It needs to be mentioned that occupant's movement is not within the scope of this study.

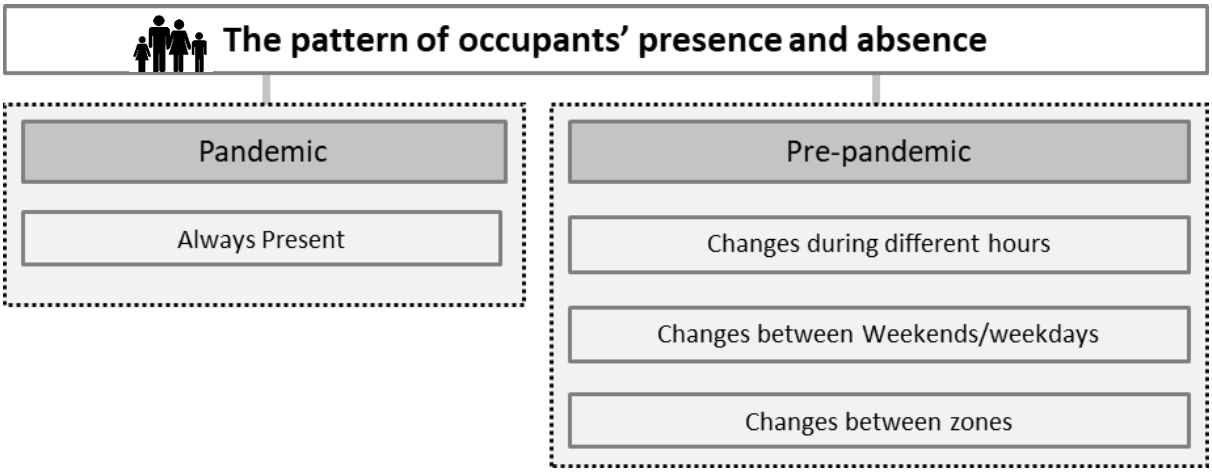


Figure 4-2 Description of each occupancy schedule scenario

The given probable schedules for the pre-pandemic scenarios were inspired by [57]and is shown below. There is no difference in the defined schedules as for energyaware and unaware user:

Pandemic

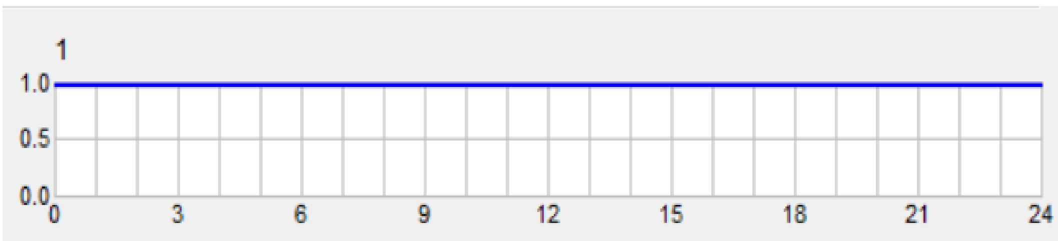
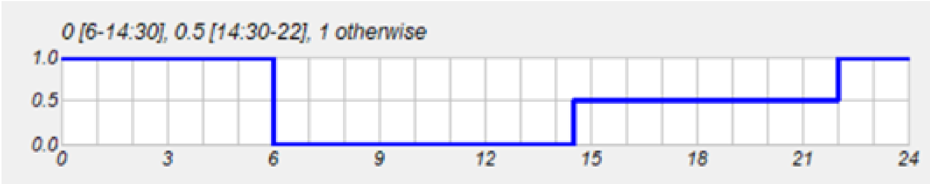
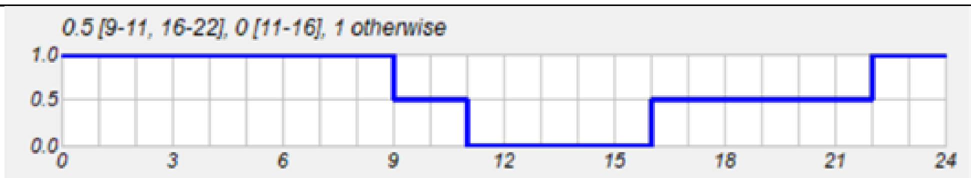
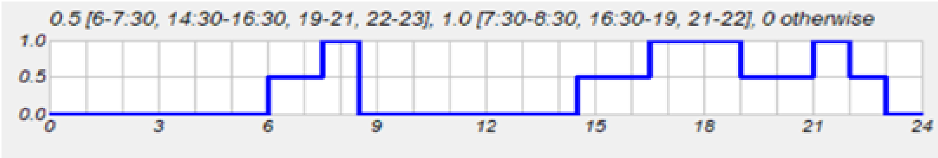
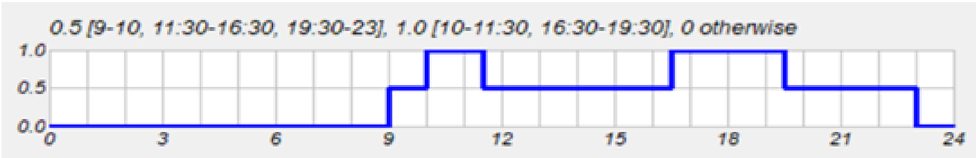


Figure 4-3 Occupancy schedule for the pandemic scenario during both weekdays and weekends and living room/ kitchen and bedrooms.

Pre- pandemic	Bedrooms	Weekdays	 *Figure 4-4 Occupancy schedule for pre-pandemic scenario in bedrooms during weekdays*
		Weekends	 *Figure 4-5 Occupancy schedule for pre-pandemic scenario in the bedrooms during weekends*
	Kitchen/living room	Weekdays	 *Figure 4-6 Occupancy schedule for the pre-pandemic scenario in the kitchen/living room during weekdays*
		Weekends	 *Figure 4-7 Occupancy schedule for the pre-pandemic scenario in the kitchen/living room during weekends*

The major difference between weekdays and weekends is in the morning when users wake up. Also, bedrooms have full occupancy rate 23:00 to at least 6:00 (sleeping time), while during same time the occupancy in the kitchen is = 0.

4.1.2 Lighting

The recommended total electrical demand in SN-NSPEK 3031:2021 is 33.7 kWh/m2 (lighting 11.4 kWh/m2, appliances 17.5 kWh/m2, fans and pumps 4.8 kWh/m2).

On the other hand, [19] has evaluated four types of passive house buildings and the measured results show an average of 18% higher electricity demand than predicted values. However, this research does not provide separate information about lighting and appliances loads.

Another study compares the amount of electricity used based on the number of users in a dwelling. In case of 4 users, the lighting shares 13% of the total electricity demand, while it changes to higher share of 18% if there is only one user in the dwelling [58] [59]. Same study divides the electrical energy demand into three categories 1- low, 2- medium, and 3- high consumption. In a family of 4 people, the lowest and highest consumptions are 4350 kWh/ year and 8100 kWh/ year, respectively [58]. The table below summarizes the findings from this research:

Table 4-1 The relation between the number of users and electricity and lighting demands

Number of users	Level of energy consumption	Total electricity demand kWh/ year	Total electricity demand kWh/ m2. year	Share of lighting	Lighting demand kWh/m2
1	Low	2350	22.57	18%	4.0
	High	5600	53.79	18%	9.7
4	Low	4350	41.79	13%	5.4
	High	8100	77.80	13%	10.1

The table illustrates that having 4 people with low electricity consumption gives around 50% higher total electricity demand than having 1 person. As the lighting shares 13% in case of 4 people and 18% in case of 1 user, there is only a minor difference between the lighting demands of both cases. Also, the results show that high consumers have around twice of both lighting and total electricity demand than low energy consumers.

For this thesis, the lighting scenarios has the presence and absence schedules mentioned in section 4.1.1. and the level of user's energy awareness as the main influential factors. This approach is inspired by lighting modeling in [60] [61].

Table 4-2]Shows the scenarios used for the simulations:

Table 4-2 Lighting scenarios

User profile	Scenario description
Energy aware	▪ Uses artificial lighting with <u>higher efficiency</u>: lm/w = 84 ▪ Adjust the lighting <u>based on the daylight levels</u> to 100- 150 Lux in bedrooms, and 200-250 Lux in the living room/ kitchen. ▪ <u>Turns off</u> artificial lighting during <u>sleeping time</u>, or when <u>occupancy = 0</u>.
Energy unaware	▪ Uses artificial lighting with <u>lower efficiency</u>: lm/w= 40 ▪ Turns the lights on <u>regardless of the daylight level</u>, and when the <u>occupancy >0 in a zone</u>. ▪ <u>Preferred lux levels</u>: bedrooms: 200- 220 Lux, kitchen/living room: 300-350 Lux. ▪ Has <u>some levels of artificial lightings on during sleeping hours</u>, and when occupancy = 0.

Some examples of defined lighting schedules according to user profiles and occupancy schedules follows as below. Also, the rest of the schedules for bedrooms is included in the appendix.

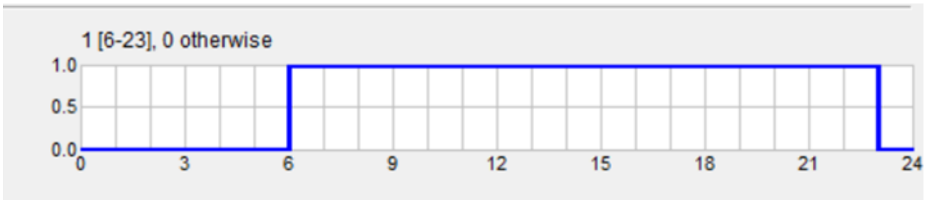
<table>
<tr><td rowspan="2">Energy aware</td><td rowspan="2">Schedule based control: based on daylight level and active occupancy</td><td>Pandemic</td><td>


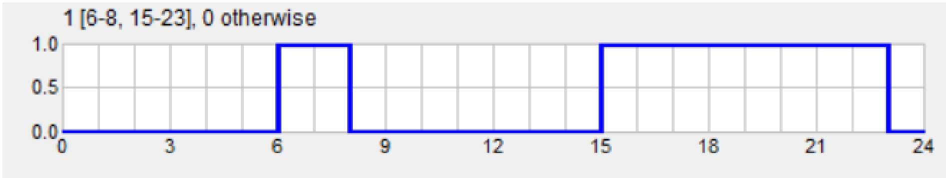
Figure 4-8 lighting schedule for energy-aware in kitchen/living room and in pandemic scenario</td></tr>
<tr><td>Pre-pandemic</td><td>


Figure 4-9 lighting schedule for energy-aware in kitchen/living room and in pre-pandemic scenario</td></tr>
</table>

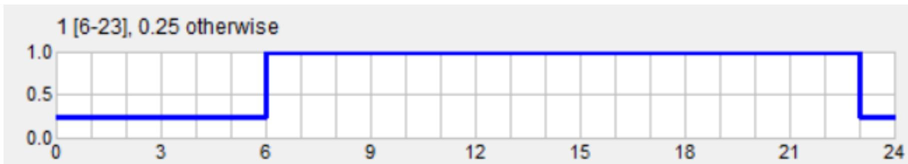
<table>
<tr><td rowspan="2">Energy unaware</td><td rowspan="2">Scheduled based control: Active occupancy. Also, some lights on when occupancy =0</td><td>Pandemic</td><td>


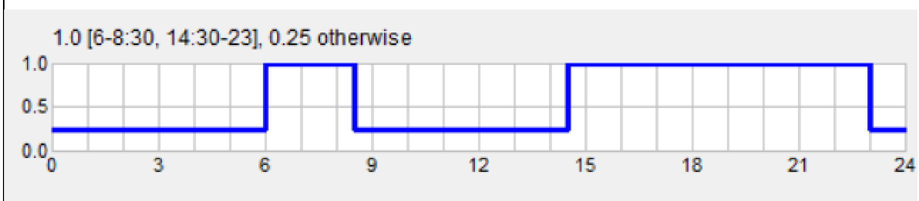
Figure 4-10 lighting schedule for energy-unaware in kitchen/living room and in pandemic scenario</td></tr>
<tr><td>Pre-pandemic</td><td>


Figure 4-11lighting schedule for energy-unaware in kitchen/living room and in pre-pandemic scenario</td></tr>
</table>

The major difference between the pandemic and pre-pandemic is non-occupancy hours from around 8:30 to 15:00. Moreover, comparison between the schedules for each energy awareness profile illustrates that some levels of artificial lighting is on during night and during non-occupancy hours for an energy-unaware user. Whereas the energy aware-user has the lights off during the same hours to save more energy.

4.1.3 Domestic Hot Water

NS 3700 offers the value of 29.8 kWh/m2 for the net DHW energy demand. On the other hand, SN-NSPEK 3031: 2021 uses 25 kWh/m2 as an average amount which is used for the base case of this study.

Also, a comprehensive DHW study in [62] agrees that 25kWh/m2 can be used as an average in apartment buildings. In the same study, a project called "prosjektet varmtvann2030" measures the DHW demand of four apartment buildings including 294 household units in total in Oslo. The measurement period was 6 weeks per apartment, and it was done during the years 2018 and 2019. The result from this project shows a variation from 30 kWh/m2.year to 49 kWh/m2. year of this energy demand. Also, this study provides a graph with average hourly power loads for DHW of these 4 apartments. The DHW schedule in this thesis is inspired by these schedules [62].

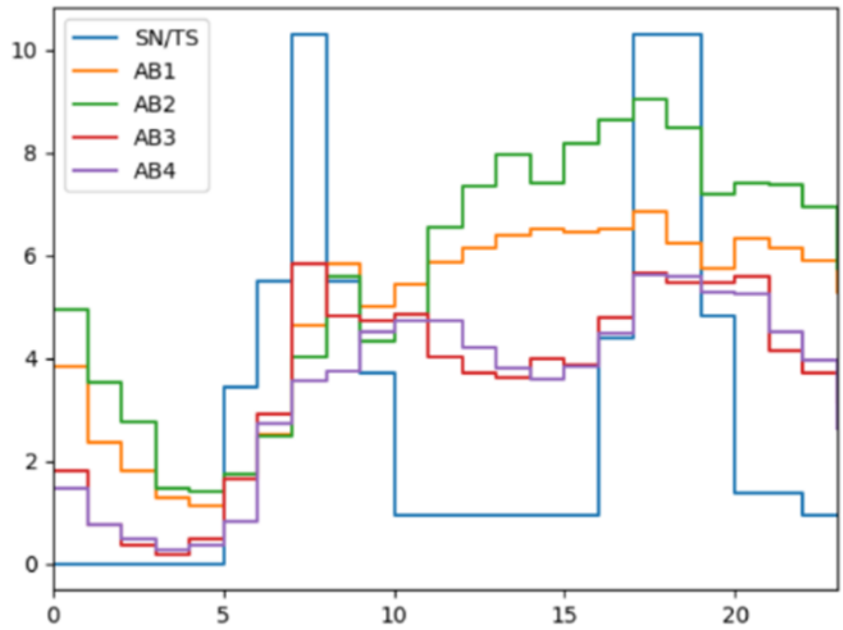


Figure 4-12 A comparison of different DHW use patterns in 4 apartment buildings. From prosjektet varmtvann2030 in [62]

A factor that highly affects DHW use is the number of users in a dwelling. The mentioned study and mentioned standards does not give information about the number of users. On the other hand, [19] shows a variety of DHW demands in kWh/ person throughout a year. This data are measured from passive house cases and shows around 500 kWh/person. year as the lowest and 1600 kWh/person. year as highest values. It also illustrates that the energy demand for the DHW can vary from 5 kWh/m2 to 55 kWh/m2 per year. Thus, the DHW calculations in here considers the schedules from [62] and energy demand ranges from [19].

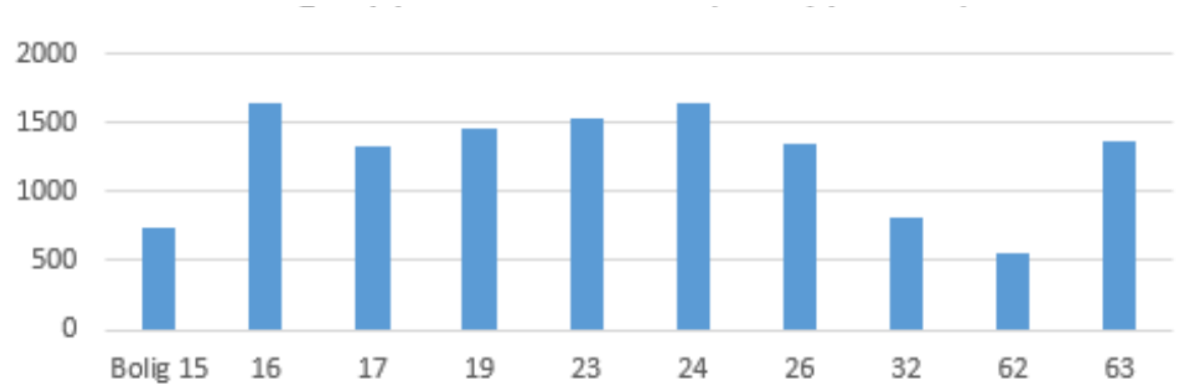


Figure 4-13 Yearly DHW use in kWh/ person per year from [19]

Table 4-3 Calculation of yearly DHW demand for 4 users (low consumer and high consumer) as a conclusion of the results in [19] and [Figure 4-13]

Occupant's profile	Yearly demand Number of users: 	Yearly demand Number of users: 	Yearly demand/ m2 for 4 users
Low consumer	500 kWh/person. year	2000	19.2 kWh/m2
High consumer	1600 kWh/person. year	6400	61.5 kWh/m2

After applying the number of 4 occupants, the lowest DHW demand goes to 19.2 kWh/m2 while the highest demand reaches 61.5 kWh/m2 [Table 4-3].

4.1.4 Appliances use

A study in [63] presents different electricity profiles for households in Sweden. As it explains, the electricity profiles with maximum power demand in the evenings make up to 75% cases. Profiles 12- 22 are more common than the others and include 65% of the users. Profile 22 has 2 peaks during the day of which the largest is during the evening and it represents 40% of the users. Profile 33 also has the largest use in the evening and the 3 profile types 12,22, and 33 together make up to 75% of the users. On the other hand, the profile types 11,21, and 31 with largest household electricity in the morning make up 7-8% of the users [63].

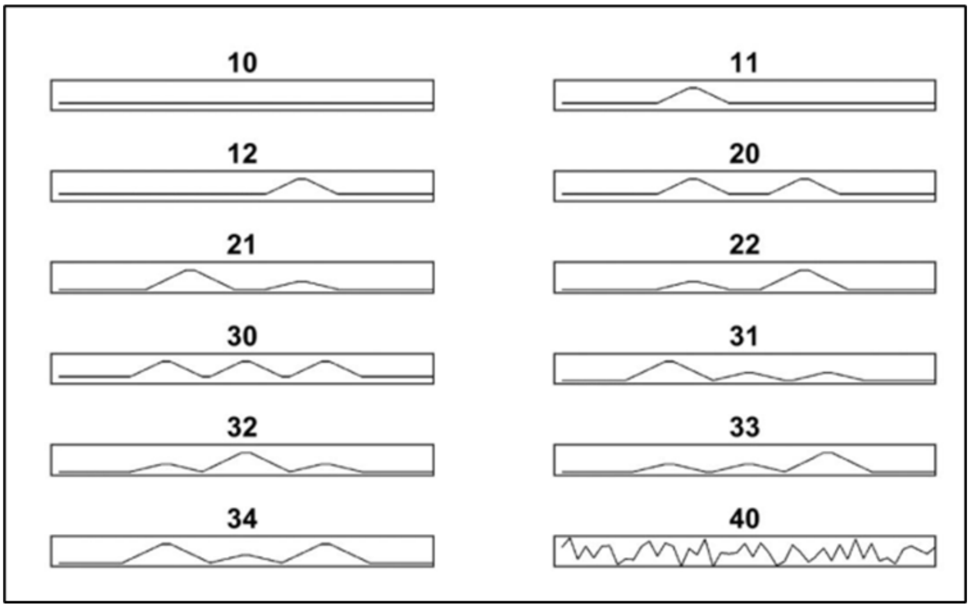


Figure 4-14 Daily electricity profiles in Swedish households [63]

The chosen daily electricity profiles for this thesis is describes in the table below:

Table 4-4 Chosen electricity profiles for each occupancy pattern based on [Figure 4-14] and [63]

Occupancy profile	Electricity profile
Pandemic	33
Pre-pandemic	22

Also, [64] has studied 7 properties in terms of annual use of household electricity. The result of that study shows annual average of 35 kWh/m2 (4 W/m2). The highest energy demand is 47 kWh/m2 (5.4 W/m2) and the lowest is 22 kWh/m2 (2.5 W/m2). Another study by [65] shows annual electricity demand of 30 kWh/m2 for a highly efficient house in Sweden. The stochastic model of [57] also presents annual energy demand of around 22.90 kWh/m2 for annual energy demand for appliances in zero energy building called “Multikomfort” in Norway. This number almost agrees with the measured electricity demand in [19] which is around 18% higher than the passive house standard.

The installed power depends on the type of appliances used. The type of appliances were chosen based on a survey about the most common appliances in passive houses in Norway [57] . [Table 4-5] shows more illustration about the distribution of appliances in different zones of the energy model in this study.

Table 4-5 Chosen appliances and their distribution in different zones

Rooms	**Appliances**
Bedrooms	Personal computer
	TV (only bedroom 1)
Living room	42 Inch LED TV
	Vacuum cleaner
Kitchen	Small appliances [1]
	Refrigerator
	Dish washer
	Electric stove + oven
Bathroom	Cloth dryer
	Washing machine

4.1.5 Energy results and discussion

Question 1.

How would changes in the amount of internal loads affect the energy demand?

Table 4-6 Summary of energy results after changes in the internal loads

KPIs Unit: (kWh/m^{2}y)		**Energy aware**		**Energy un-aware**	
	BC	**Pandemic**	**Pre-pandemic**	**Pandemic**	**Pre-pandemic**
Heating demand	9.3	7.1	11.6	6.3	8.9
Cooling demand	-	-	-	-	-
DHW demand	25	22.1	19.2	53.8	46.1
COP GSHP	4.4	4.4	4.4	4.4	4.4
Lighting	11.4	3.5	3.1	18.5	14.5
Appliances	17.5	14.5	13.3	21.1	19.2
Fans+ pumps	4.1	4.1	4.1	4.1	4.1
Total energy demand	67.3	51.2	51.3	103.8	92.8
Electricity for GSHP	9.9	8.5	9.0	17.1	15.7
Total electricity demand	42.9	30.6	29.5	60.8	53.5
PV production	45.8	45.8	45.8	45.8	45.8

The four cases show relatively lower heating demand in case of pandemic than pre-pandemic after implementing the changes in internal loads. This is primarily due to more heat gains from people and more appliances and lighting use during occupancy periods [Table 4-6]. This stage does not consider any change in the heating setpoints, and it is assumed to have constant heating of +20 °C as the base case. Thus, these heating results cannot be considered final values, and more simulations are presented in section 4.2.

In pre-pandemic, the difference between the heating demand for an energy-aware becomes 4.54 kWh/m2 higher than in the pandemic. The reason is that the energy-aware tends to turn off most appliances and lighting units when the occupancy is zero, whereas the heating system would still heat the apartment to 20 °C [Table 4-6].

On the other hand, for an energy-unaware profile, the heating varies around 2.26 kWh/m2 between full occupancy and working schedules. This shows around a 50% less difference compared to 4.54 kWh/m2 in the case of energy- aware. The reason is that the occupant has more levels of electrical devices on (lighting, appliances, and plug loads) even when the occupancy is zero [Table 4-6].

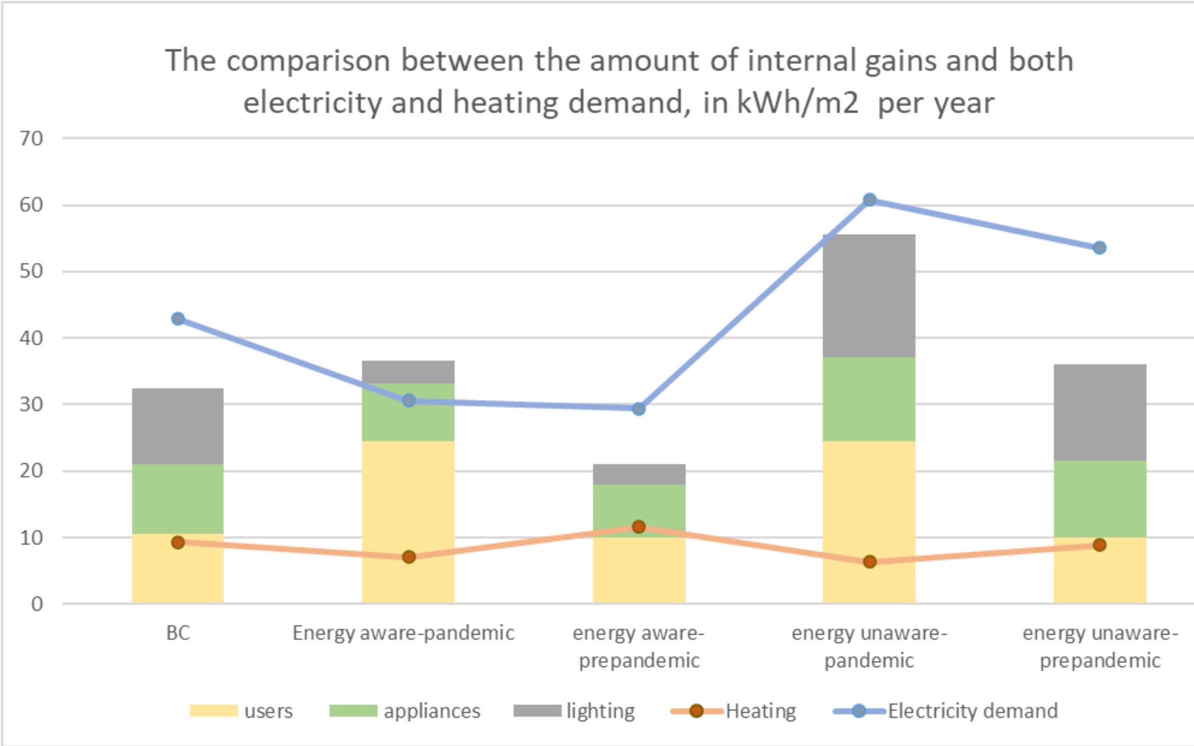


Figure 4-15 Different internal gains impact on the heating and electricity energy demand

Even though in the case of an energy-unaware pandemic, the heating demand is the lowest, the electricity demand is the highest [

Figure 4-15]. Considering electricity demand for only lighting and appliances: there is a difference of 5.9 kWh/m2. year between the two energy-unaware schedules, while in the case of energy-aware, this difference is only 1.6 kWh/m2. y. This shows that the less an energy-unaware user is present, the more electrical energy can be saved.

On the contrary, neither lighting nor appliances energy demand would significantly change if an energy-aware is fully present or not [

Figure 4-15]. An example of this is the use of artificial lighting by energy- aware. As the lighting schedules [Figure 4-9] show, non-occupancy hours are mainly during the day when the daylight level is the highest. An energy-aware user will tend to maximize the use of daylight rather than artificial light. So, if the existing daylight answers his demand, he will have the artificial lights off during the pandemic [Table 4-2]. Consequently, this keeps the demands in both energy saver cases closer compared with energy-unaware cases.

Another lesson learned from [

Figure 4-15] is that even though cases of energy aware-pandemic and energy unaware pre-pandemic have almost similar internal gains, the electricity demand for energy-aware is lower. The reason is that a large portion of internal gains, in the case of an energy-aware pandemic, comes from the occupants. While in the case of an energy-unaware pre pandemic comes from the electrical devices.

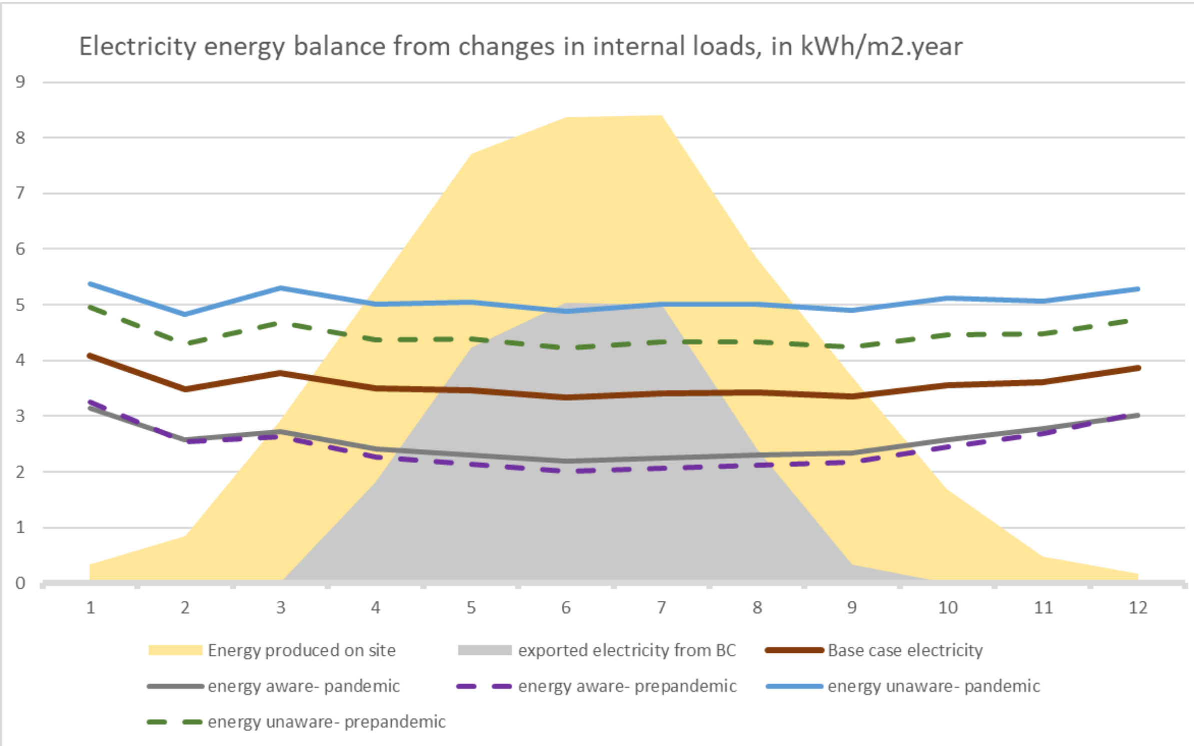


Figure 4-16 The impact of the internal loads on the electrical energy balance

The total electricity demand in both cases of an energy-aware would reduce by around 30% than the base case. On the flip side, it would increase by 42% for an energy-unaware user in the pandemic situation. Also, the energy-unaware pre-pandemic scenario has around 20% higher electricity than the base case which is half of the full-occupancy [

Figure 4-16].

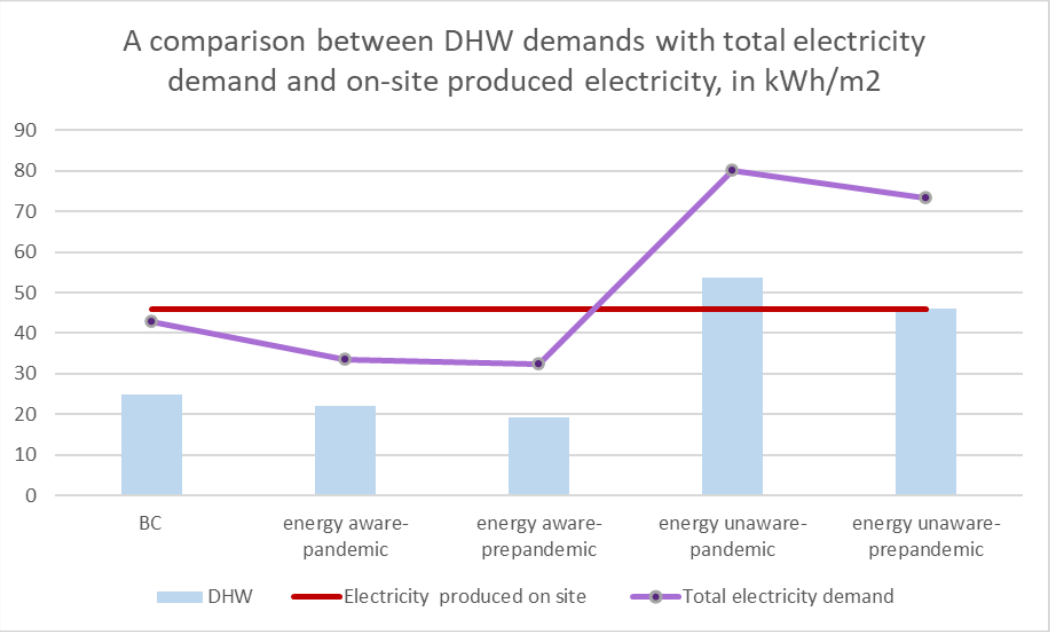


Figure 4-17Share of DHW in the total electricity need and in use of on-site renewable electricity

DHW results show the most significant gap between the standard energy and the occupant model. A high energy consumer may use over twice DHW than the predicted value (53.8 kWh/m2 compared to 25 kWh/m2). This rise has also changed the electricity demand for GSHP to twice the base case value. On the contrary, the case of an energy-aware has relatively closer DHW values to the base case. For an energy-aware, the overall electricity demand for GSHP is almost similar to the base case as well [Table 4-6] [Figure 4-17]. Moreover, DHW contributes to almost 50% of the total energy demand of all 5 cases.

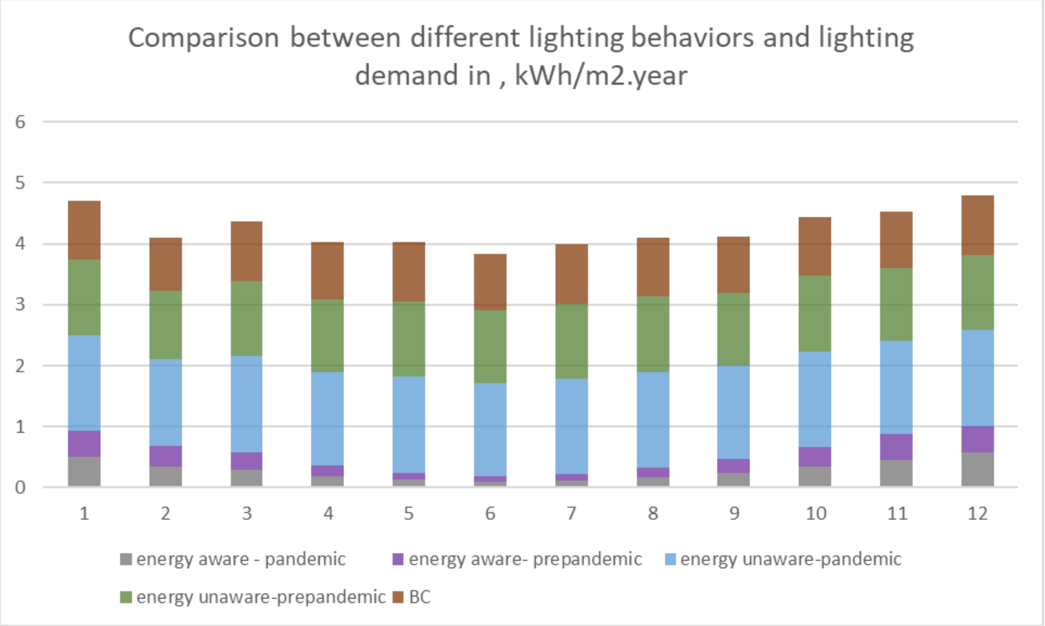


Figure 4-18 The impact of different behaviors in share of lighting demand during a year

[Figure 4-18] was chosen to illustrate the difference in occupants' lighting control behavior according to daylight levels. In this figure, lighting demand is lower during summer than winter for energy-aware users due to more available lux levels. Not considering the daylight levels for energy-unaware cases and standard model cause evenly distributed lighting demand throughout a year.

Table 4-7 Co-relation between the internal heat gains and electricity demands

Electricity & heating Unit: (kWh/m2y)	**Energy aware**		**Energy unaware**	
	Pandemic	**Pre-Pandemic**	**Pandemic**	**Pre-Pandemic**
Electricity demand after	30.6	29.4	60.9	53.5
Electricity demand before, Base case	42.9	42.9	42.9	42.9
Reduction	-12.3	-13.5	18.0	10.6
Heat gain after	36.6	21.0	55.6	36.0
Heat gain before, Base case	35	35	35	35
reduction	1.6	-14.0	20.6	1.0
Yearly utilization factor[1]	0.2	0.5	0.1	0.3

Lastly, [Table 4-7] illustrates the co-relation between heat gains and electricity demand. The energy-unaware pandemic has the highest internal heat gain that is more than 1.5 times higher than the base case. Having such huge portion of internal heat is a result of about 40 % higher electricity demand in the same case.

The heat gains in both "energy-unaware pre-pandemic" and "energy-aware pandemic" are the same. But the energy-aware user has around 12 kWh/m2 less electricity demand than the base case. On the contrast, the energy un-aware has 10 kWh/m2 more electricity demand than predicted. The main reason is the higher heat gain from people in pandemic energy-aware and higher heat gain from electrical devices in pre pandemic energy-unaware case.

[1] Yearly utilization factor = Δ Heating consumption/ Δ Heat gains

4.2 Occupants and heating, cooling and ventilation

4.2.1 Heating

Measured heating demands in [66] show a minimum value of 31 kWh/m2 and a Max value of 189 kWh/m2 in Sweden. The measured apartment buildings were part of the “Stockholm program for environmentally adapted buildings” and thus considered high-performance buildings. Another study in Sweden [67] on low-energy terrace houses found that decreasing the indoor temperature setpoint from 21◦C to 18◦C reduces the heating demand by 28%.

According to the Finnish housing health code [68], an indoor temperature of 18 °C is the minimum indoor tolerable temperature. Also, 21°C is the most adequate and favorable indoor temperature, while this temperature should not be higher than 23-24 °C during winter. Higher temperatures than 26°C are only accepted due to extreme outdoor conditions [68].

In addition, an interview in [19] shows desired indoor temperature ranges by occupants. Most of the user’s desire to have high temperature of around 23,24 °C in the main zones and Underfloor heating in the bathroom at 26 degrees, even in summer. Also, users prefer to have a high temperature in the bathroom and living room while preferring a lower temperature in the bedroom.

[19] also shows the measured annual heating consumption of 58.4 kWh / m2 from passive house dwellings in Oslo. Estimated heating demand with measured local outdoor climate and setpoint temperatures for heating from NS 3031 (21 ° C during the operating period and 19 ° C outside operating time) is 14 kWh / m2. From this it can be concluded that the residents' desire to have high indoor temperatures leads to an increase in the calculated heating need.

According to the mentioned studies the following scenarios were made for the heating setpoints:

Table 4-8 Heating set point scenarios

Occupant profile	Occupancy profile	Zones	Heating set points
Energy aware	Pandemic	Kitchen/living room	20 °C when occupancy in the zone: > 0 19 °C when occupancy in the zone: = 0
	Pre-pandemic	Bedrooms	19°C when occupancy in the zone: > 0 18 °C when occupancy in the zone: = 0
Energy unaware	Pandemic	Kitchen / living room	23 °C constant in bedrooms 24 °C constant in the living room
	Pre-pandemic	Bedrooms	

4.2.2 Mechanical ventilation

Mechanical ventilation rates have been assumed based on the values provided in NS-EN 16798-1:2019 [69]. The [Table 4-9] and [appendix 20] were used as the main references for mechanical ventilation input rates. As the standard mentions, the total ventilation rate should never be lower than 4 l/s per person due to health issues. Even the case of 4 l/s considers neither building nor activities emissions, and it is given based on only emissions from people [69] . Thus, none of the scenarios are using 4 l/s per person as minimum, but rather a value within category "II" and "III".

Table 4-9 Mechanical supply ventilation air flow rates categories [69] : total ventilation and ventilation per person

Category	Total ventilation including air infiltration (1)		Supply air flow per. person (2)	Supply air flow based on perceived IAQ for adapted persons (3)	
	l/s,m2	ach	l/s (per person) [a]	q_p l/s (per person)	q_B l/s,m2
I	0,49	0,7	10	3,5	0,25
II	0,42	0,6	7	2,5	0,15
III	0,35	0,5	4	1,5	0,1
IV	0,23	0,4			

[a] Supply air flow for Method 3 is based on Formula (1) from 6.3.2.2.

[Table 4-10] shows the values used for this research. The supply air volumes were given in l/s per person, but exhaust air rates were defined in l/s. Furthermore, the exhaust air is considered to be collected from the kitchen and bathrooms and the rates are based on [appendix 20]. The exhaust ranges are rather similar in both cases of energy aware and energy unaware and supply air shows the primary difference.

Table 4-10 Chosen mechanical supply and exhaust air flow rates for each zone for the model

	Energy aware		Energy unaware	
Rooms	Supply air per person, l/s(person)	Exhaust air, L/s	Supply air per person, l/s(person)	Exhaust air, L/s
Kitchen & living room	5.5	20 (kitchen)	8	20 (kitchen)
Bedrooms (nr: 3)	5.5	-	8.5	-
Bathrooms (nr: 2)	-	13	-	15

The values are set per occupant and based on each energy awareness profile. The pandemic and pre-pandemic scenarios make no difference in this study as they only refer to the schedules and not really presenting a disease situation. Also, no set back period is defined for the ventilation system.

Table 4-11 total mechanical air flow rates in the model

Apartment		Energy aware	Energy unaware
Total for zones (l/s. m2)	Supply air	0.42	0.58
	Exhaust air	0.34	0.35

4.2.3 Natural ventilation

[70] identified CO2 concentration levels as the main influential factor for opening the windows. On the contrast, it introduces the outdoor temperature as the main reason for closing the windows. Also, the study of [71] agrees to this by showing higher frequency in window opening during the non-heating days to lower the indoor CO2 concentration.

Thus, in this thesis, for the behavioral window pattern of an energy-unaware the window opening hours was chosen to be among/after the hours with higher occupancy rate. In the bedrooms, for example, users would tend to open the windows in the morning and in the afternoon to get some fresh air. When in the kitchen the windows would be mainly open when the cooking takes place. More information about the scenarios is shown in [Table 4-12]:

Table 4-12 The window opening scenarios

Occupant profile	Occupancy profile	Blind and window operation
Energy aware	Pandemic	Optimal us of windows based on indoor temperature. Occupancy >0
	Pre-pandemic	Optimal us of windows based on indoor temperature. Occupancy>0
Energy unaware	Pandemic	Window opening 2 hours in bedrooms (1 hour in the morning, 1 hour in the evening), and 2 hours in the kitchen (1 hour lunch time and 1hour dinner time)
	Pre-pandemic	Window opening 2 hours in bedrooms (1 hour in the morning, 1 hour in the evening), and 1 hours in the kitchen (1hour dinner time)

4.2.4 Energy results and discussion

Question 2.

To what extent can users' presence and behaviors affect the energy performance?

All the results in this section is combined with the results from occupants and internal loads in section 4.1.

Table 4-13 A summary of the final energy results

KPIs Unit: (kWh/m²)		**Energy aware**		**Energy un-aware**	
	BC	**Pandemic**	**Pre-pandemic**	**Pandemic**	**Pre-pandemic**
Heating demand (kWh/m²)	9.3	8.0	12.1	55.9	60.8
Cooling demand(kWh/m²)	-	-	-	15.7	9.7
DHW demand(kWh/m²)	25	22.1	19.2	53.8	46.1
COP GSHP	4.4	4.4	4.4	4.4	4.4
Lighting (kWh/m²)	11.4	3.5	3.1	18.5	14.5
Appliances (kWh/m²)	17.5	14.5	13.3	21.1	19.2
Fans+ pumps	4.1	6.8	6.8	9.4	9.4
Total energy demand	67.3	54.8	54.5	158.7	150.0
Electricity for GSHP	9.90	8.7	9.1	31.0	30.3
Total electricity demand	42.9	33.5	32.3	80.0	73.4
PV production	45.8	45.8	45.8	45.8	45.8

The calculated energy for an energy-unaware user would significantly increase after adding interactions with heating, cooling, and ventilation systems to the results from section 4.1. (Internal loads). For example, the total energy demand rises by more than 50% in here compared to the results from internal loads. On the contrary, the case of an energy-aware user has almost the same energy values as calculated in 4.1. (Internal loads). So, this shows the importance of merging all possible behaviors to reach more reliable results in evaluating occupants' impact on building energy.

The main influential KPIs on the performance gap can be identified as heating, DHW, and lighting demand. The energy for fans and pumps has changed to two times higher value as well.

The vast proportion of the difference from previous energy results is due to higher air flow rates through ventilation systems. When applying the number of occupants and the required supply-air per occupant, the energy need for fans increases by 50% for energy-aware and more than 100% for an energy-unaware. Furthermore, both increase in the ventilation rate and constant performance of the ventilation system results in higher heating demand than before. However, there is only a minimal change on the heating demand of an energy-aware user.

Even though in section 4.1. (Internal loads) the heating demands of energy-unaware profiles reached similar and even lower values than the energy-aware user; this section shows an increase by around 10 times higher values. The heating demand of the wasteful user can be approximately 10 times higher than both the base case and energy-aware user. Higher zone heating demand also increase the electricity demand for GSHP from 17 kWh/m2 to 31 kWh/m2 (twice more). At the same time, the enormous difference between the primary energy need and GSHP electricity demand shows the effectiveness of using this system for saving more energy.

The heating demand of the base case is a value between the heating demand of pandemic and pre-pandemic cases of an energy aware. Surprisingly, the pre-pandemic scenario (energy-aware) shows higher heating demand than the pandemic scenario, even though this scenario takes advantage of more temperature setback periods. The main reason for this result is low internal heat gains in non-occupancy periods. At the same time, the heating system should keep the temperature to around 18 ◦C to 19◦C. Also, higher ventilation air flow rates with no setback periods increases the need for heating, especially during non-occupancy times. Thus, further study is required for concluding the difference between 2 energy saver profiles.

Lower energy demand for DHW and appliances in case of pre-pandemic energy aware compensates for the higher heating demand. Hence, the net primary energy demand illustrates similar results for both energy-aware cases. Besides, the total electricity demand of the pre-pandemic case (energy-aware) shows a lower value than the pandemic.

The energy-unaware user has also higher heating demand in the pre-pandemic. This is also due to constant work of the heating system to 24 °C and 23 °C in non-occupancy hours. Another factor is the impact of constant and higher ventilation rates on the heating system to reach the setpoints.

Cooling demand was simulated for the energy-unaware cases to show the risk of overheating (no cooling unit is installed), which may be caused by having more internal heat. Based on the results, the cooling demand can rise to around 10 kWh/m2 to 16 kWh/m2, which is comparable to the heating demand of both the base case and energy-aware cases. Another contributor factor to high cooling load is not optimized use of natural cooling.

The discussion about DHW, lighting, and appliances energy demand is covered in section 4.1.

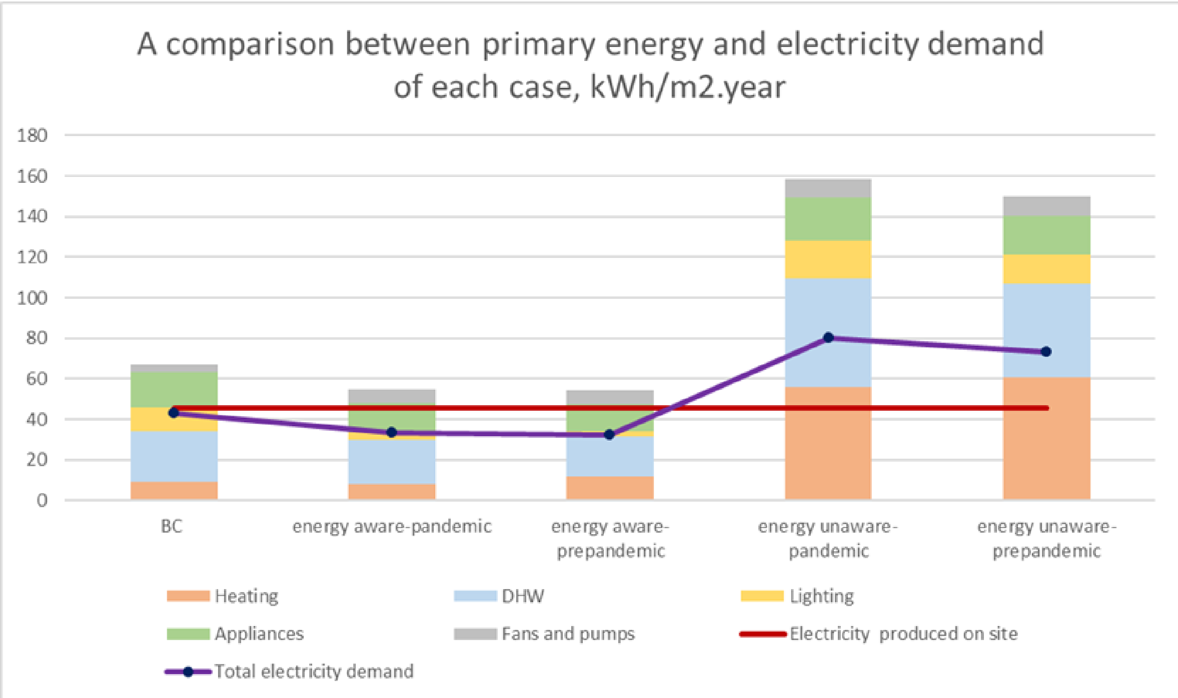


Figure 4-19 A comparison between different energy demands, on-site produced electricity, and electricity demand in different cases

[Figure 4-19] shows that the available on-site renewable electricity can only cover between 40-50% electricity demand of an energy-wasteful user. It also shows close and slightly lower electricity demand for the energy-aware cases than the base case. On the contrary, energy-unaware users can cause around 100% higher electricity demand than the predicted value.

The DHW demand is between 2-3 times higher than zone heating demand in the base case and energy-aware cases. Whereas in the case of energy-unaware, the heating and DHW demands have almost similar share [Figure 4-19]. Same graph shows that the total electricity demand is around half of the total primary energy demand in all 5 cases, which is mostly due to effectiveness of GSHP as heating source. This chart also shows twice larger gap for energy-unaware than energy aware between the total electricity demand and on-site electricity.

The pre-pandemic scenario for the energy-unaware shows 7 kWh/m2 lower primary energy demand than pandemic. Thus, energy wise it is beneficial if an energy wasteful user spends less time in the dwelling. While for an energy aware user, the energy performance would not differ much with higher occupancy rate.

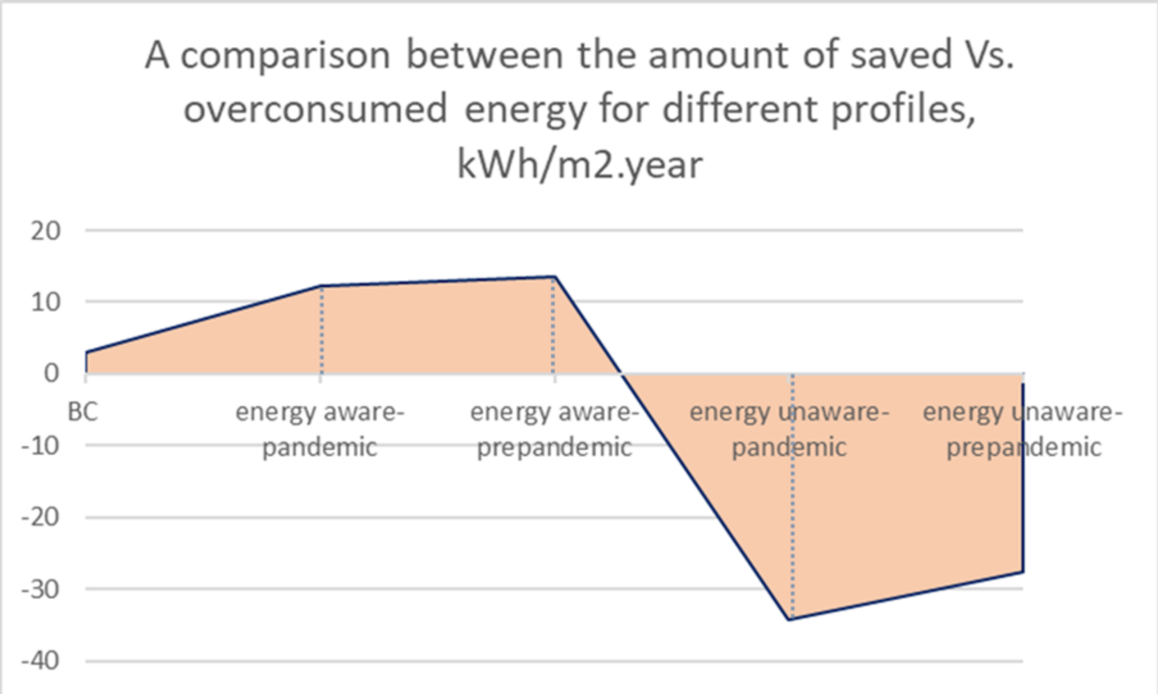


Figure 4-20 A comparison between the amount of saved and wasted energy in different scenarios

[Figure 4-20] compares all four profiles in terms of saved or over-consumed energy. According to this graph, the negative impact of an energy-unaware is significantly higher than positive impact of an energy-aware user. Also, it shows that the energy saved by energy-aware users cannot compensate for wasted energy by energy-unaware user if there is a combination of both profiles. An energy-aware user can save more than 3 times electricity than the base case. While an energy unaware can cause more than 10 times over-consumed electricity.

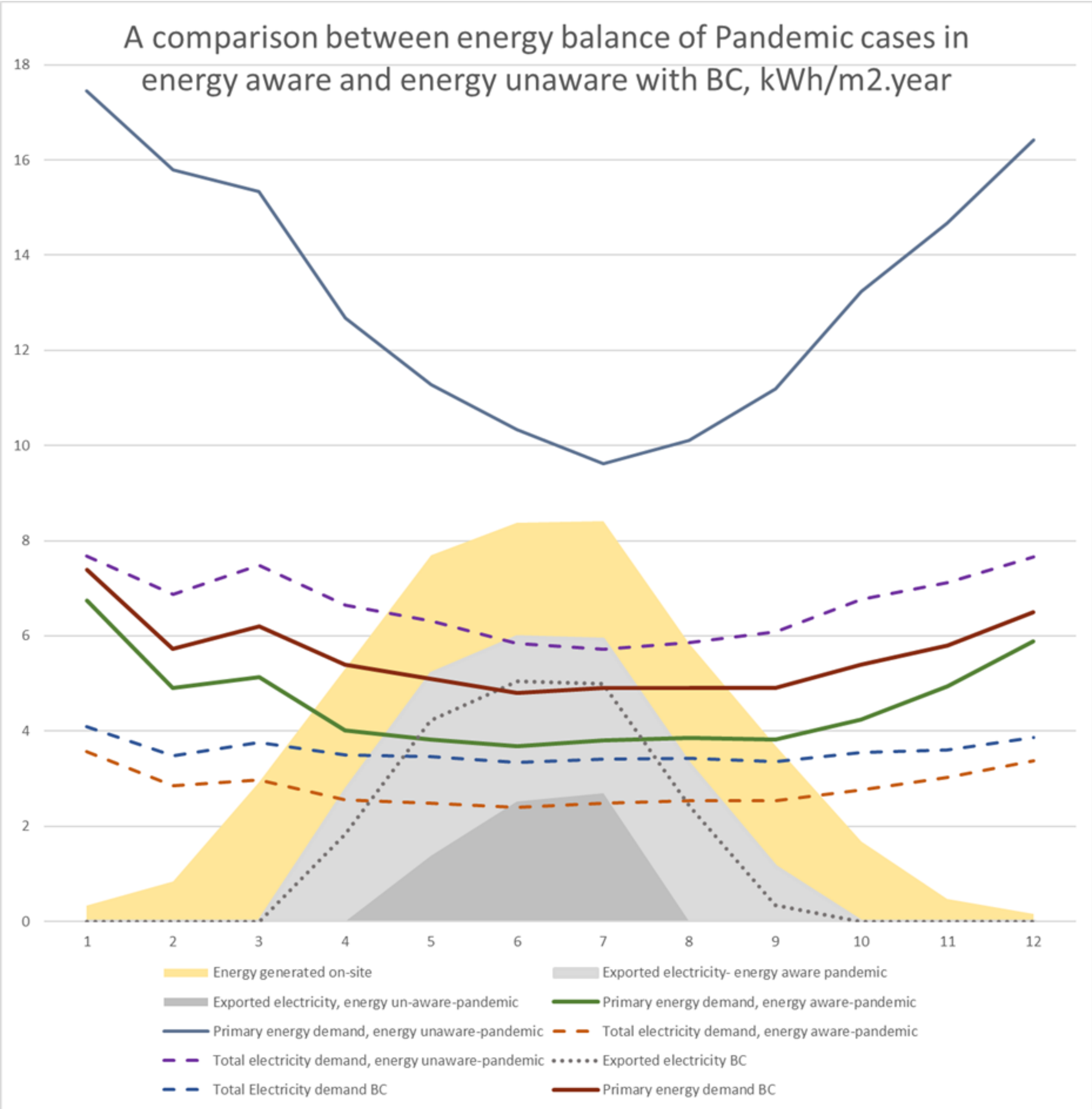


Figure 4-21 A comparison between energy balance of energy saver and energy wasteful users with base case

The results from [Figure 4-21] show that an energy-aware has closer primary energy demand to the predicted energy. Additionally, energy in this case would be around 20% lower than the base case. The distribution of the energy demand throughout a year is almost similar between the base case and energy-aware case. In comparison, primary energy in the case of an energy un-aware is more than two times bigger than the base case. It is also three times larger than an energy saver user. Also, the case of an energy wasteful user has a larger difference between summer and winter months. The energy demand for this profile is 1.8 times higher during the winter times than summertime (around 18 kWh/m2 in winter, around 10 kWh/m2 in summer).

4.3 Indoor Environment Quality (Thermal comfort)

4.3.1 Evaluation framework

Two indexes called PMV and PPD can quantify the body’s thermal condition. PMV means Predicted Mean Vote and PPD stands for Predicted Percentage of Dissatisfied. PMV shows how a person experiences the thermal situation [72].

This study uses PMV as the only indicator for evaluation of the IEQ and thermal comfort. Also, this part focuses on only the energy-aware profile as the temperature ranges are lower for this user profile. while an energy-unaware would provide the thermal comfort conditions regardless of the building’s energy consumption.

As for an energy-aware, the values have been evaluated and compared in the pandemic scenario due to higher occupancy rate in this case. The PMV values are exported in a monthly basis (coldest and warmest months). Minimum, maximum, and average levels during each month has been used for the evaluations. Also, the evaluation is done on 2 zones :1- kitchen/living room and 2- bedroom nr.2. One bedroom was chosen as the defined interactions and conditions are similar in of them. In addition, bedroom 2 and 3 has the same orientation and almost same size.

The PMV values were evaluated based on the table below [69] [73] :

Table 4-14 Different categories of PMV and PPD

Category	Level of expectations	Predicted Mean Vote (PMV)	Predicted Percentage of Dissatisfied (PPD) (%)
IEQ_1	High	-0.2 < PMV < +0.2	<6
IEQ_2	Medium	-0.5 < PMV < +0.5	<10
IEQ_3	Moderate	-0.7 < PMV < +0.7	<15
IEQ_4	Low	-1.0 < PMV < +1.0	<25

4.3.2 Results

The initial results is for the existing condition for the energy model in 4.2. Thus, it has MET =1 and Clo = 0.25 – 0.85 as inputs.

As the graphs below show the PMV values fluctuates between -0.6 to -0.9 in the kitchen and living room, and from -0.6 to -1.2 in bedroom 2 in the coldest month. The worst perceived thermal condition is during January than July. In July, only 2 days have inconvenient levels of PMV.

Table 4-15PMV Values during the coldest and warmest months for primary rooms

Clo: 0.25 -0.85				
Date	Room	Min PMV	Max PMV	Mean PMV
July	Kitchen	+ 0.2	+0.7	+ 0.3
	Bedroom 2	+0.1	+0.6	+ 0.2
January	Kitchen	-0.9	-0.1	-0.8
	Bedroom 2	-1.2	-0.2	-0.9

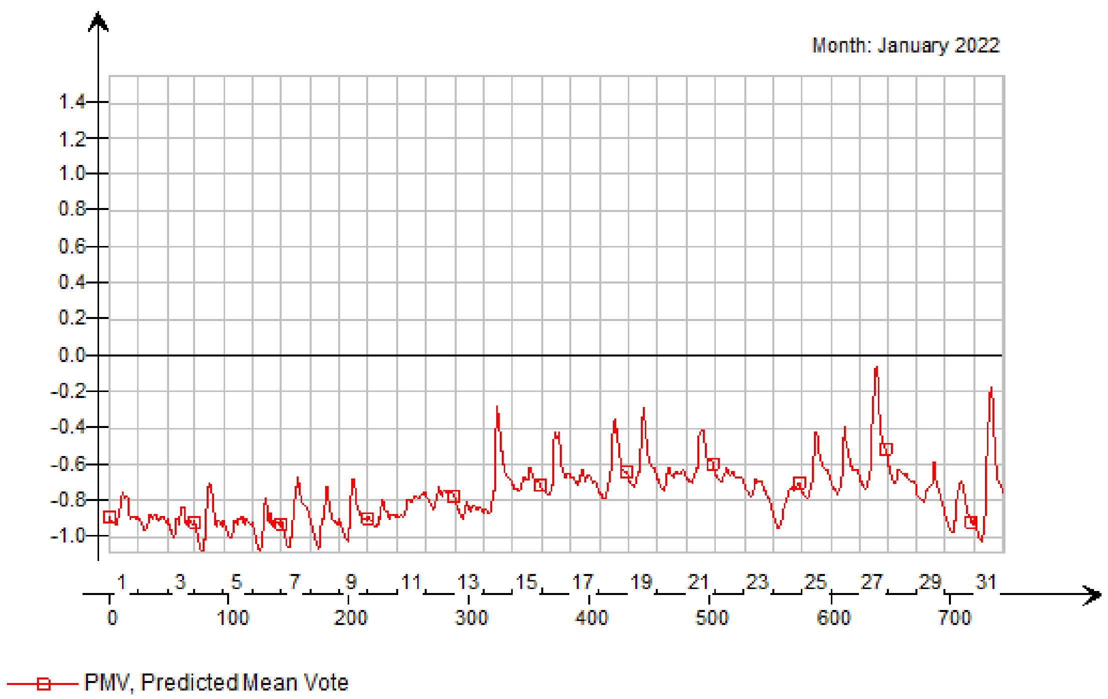


Figure 4-22 PMV ranges in the kitchen/ living room during January

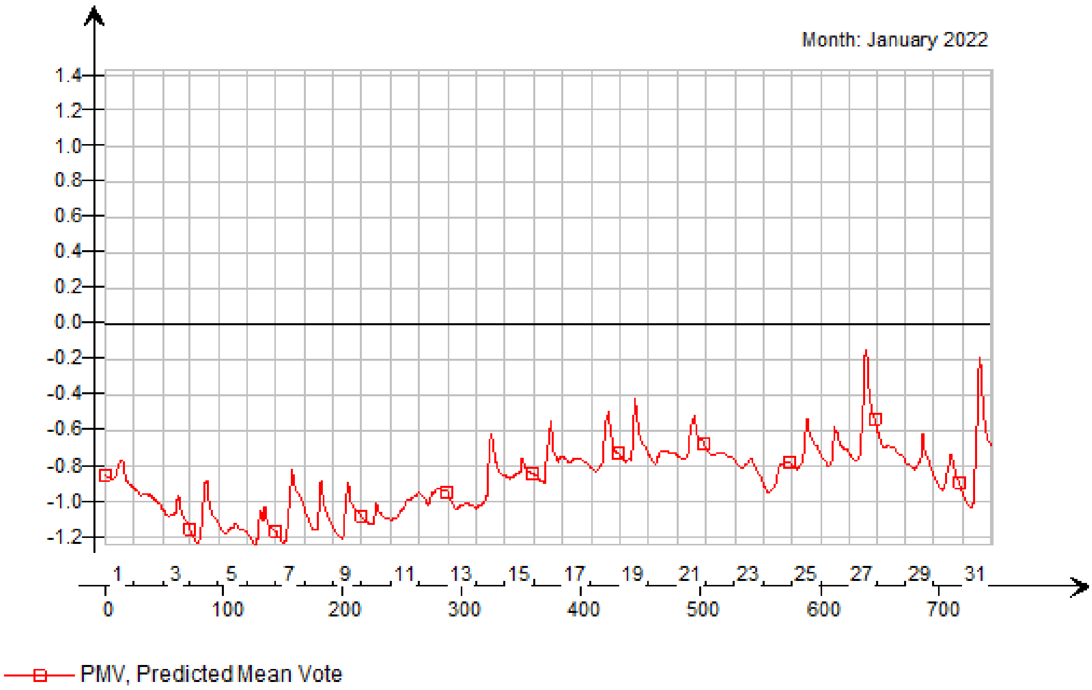


Figure 4-23 PMV ranges in bedroom nr. 2 during January

4.3.3 Solutions

Stage 1: The first solution considers adaptive reaction of the user by changing the levels of clothing. So, based on this assumption the maximum Clo value has been change from 0.85 to 1.0 to see how the perceived situation would correspond.

Table 4-16 Results after changing the max Clo to 1.0

Clo: 0.25- 1.0				
Date	Room	Min PMV	Max PMV	Mean PMV
January	Kitchen	-0.7	-0.3	-0.6
	Bedroom 2	-0.9	-0.4	-0.7

The results after having higher Clo value shows improvement in thermal conditions, but it does not provide fully comfortable conditions for the user.

Stage 2: In the next step, the heating setpoints have been increased by +1 °C in both the living room/ kitchen and all 3 bedrooms. In this case, the set point temperature is 21 °C in the living room when there is an active occupation in the zone. Also, the setback temperature is 19°C in non-active occupancy periods. For the bedrooms also the setpoint has changed from 19°C to 20°C.

Table 4-17 The PMV results after increase of temperature setpoints by 1°C

+1 °C increase in temperature setpoints				
Date	Room	Min PMV	Max PMV	Mean PMV
January	Kitchen	-0.6	-0.3	-0.4
	Bedroom 2	-0.7	-0.4	-0.6
Heating demand (kWh/m2)	Before: 8.0		After: 8.5	
Total energy demand (kWh/m2)	Before: 54.8		After: 55.3	

The rise in the temperature setpoint has reduced the mean PMV rate in the kitchen from -0.6 to -0.4, which shows a favorable value. Furthermore, the mean PMV in the bedroom has improved by + 0.1. This evaluation also includes the heating demand and net energy demand to compare the impact of +1 °C change in temperature with the energy performance of the building. **stage 3:** Due to having low minimum value of -0.7 in the bedroom, a change in the metabolic rate was made from 1 MET to 1.2 MET. 1 MET shows the activity level when user sits and 1.2 changes the activity to standing. More details about the activity levels and Clothing levels are included in the appendix.

- It needs to be mentioned that the solutions has a sequence and shows additional changes to the previous results (solutions) in this part.

Table 4-18 PMV values after changing the MET:1 to MET: 1.2

Change the MET value from 1 (relaxed – sitting) to 1.2 (relaxed- standing)				
Date	Room	Min PMV	Max PMV	Mean PMV
January	Kitchen	-0.2	+0.08	-0.1
	Bedroom 2	-0.3	-0.0	-0.2
Heating demand (kWh/m2)	Before: 8.5 (last evaluated case)		After: 6.9	
Total energy demand (kWh/m2)	Before: 55.3 (last evaluated case)		After: 53.7	

The table below also compares the internal gains from people with MET= 1 and MET= 1.2.

Table 4-19 Impact of MET rates on the internal heat gains from users

Change the MET value from 1 (relaxed – sitting) to 1.2 (relaxed- standing)		
	Before	After
Internal gains from occupants (kWh/m2)	24.30	28.04

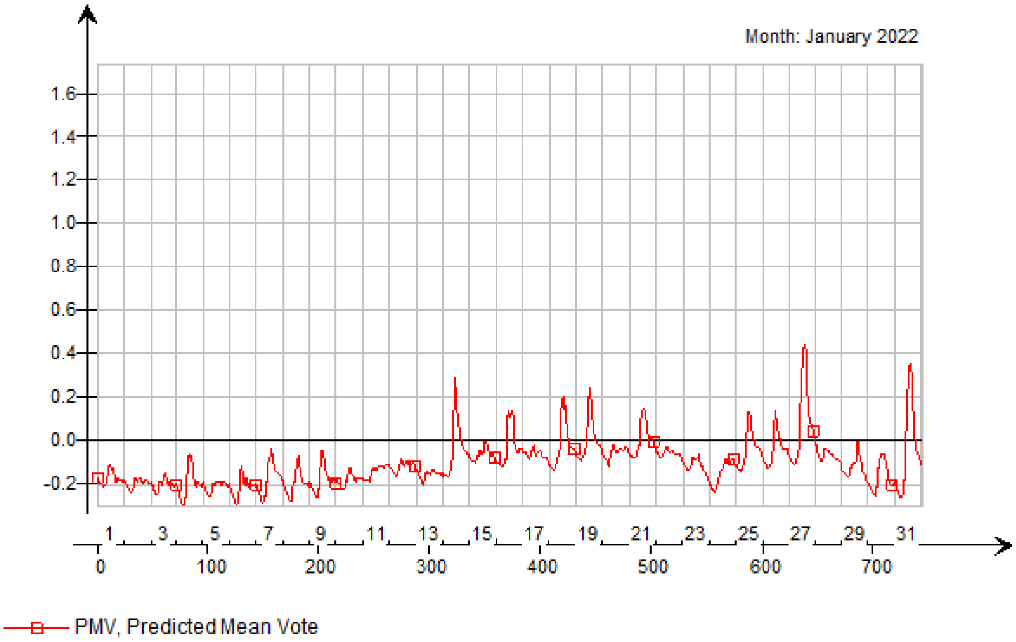


Figure 4-24 Changes in the PMV ranges in kitchen/ living room from the last solution in [Table 4-18]

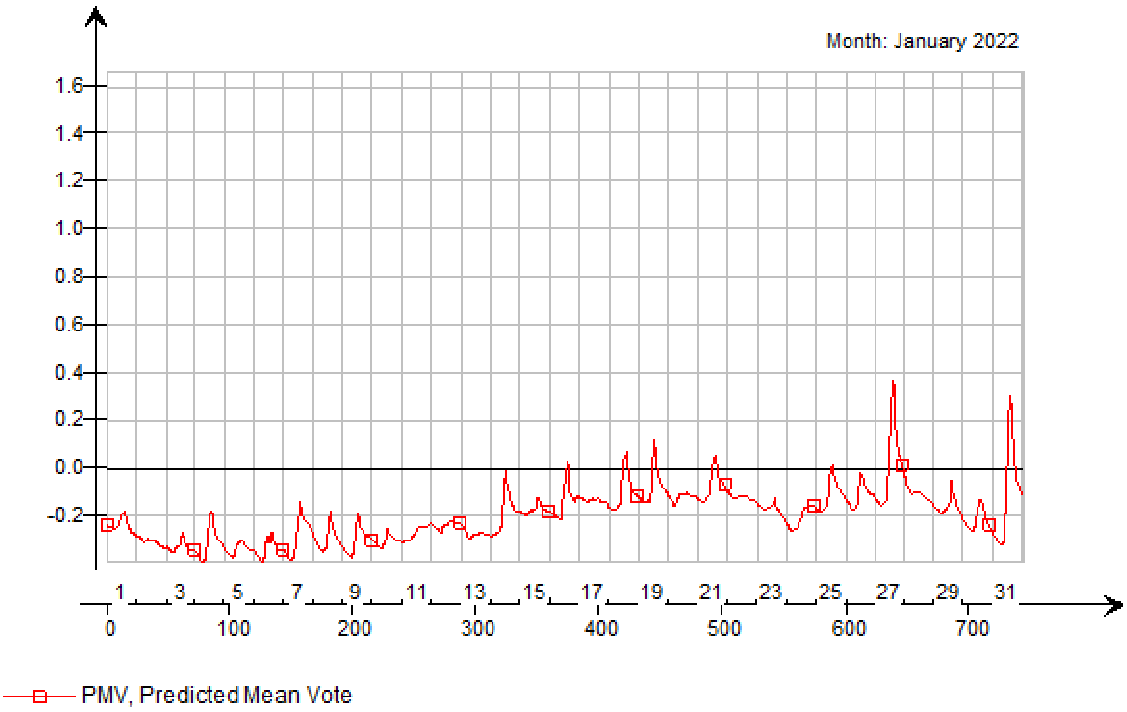


Figure 4-25 Changes in the PMV ranges in the bedroom from the last solution in Table 4-18

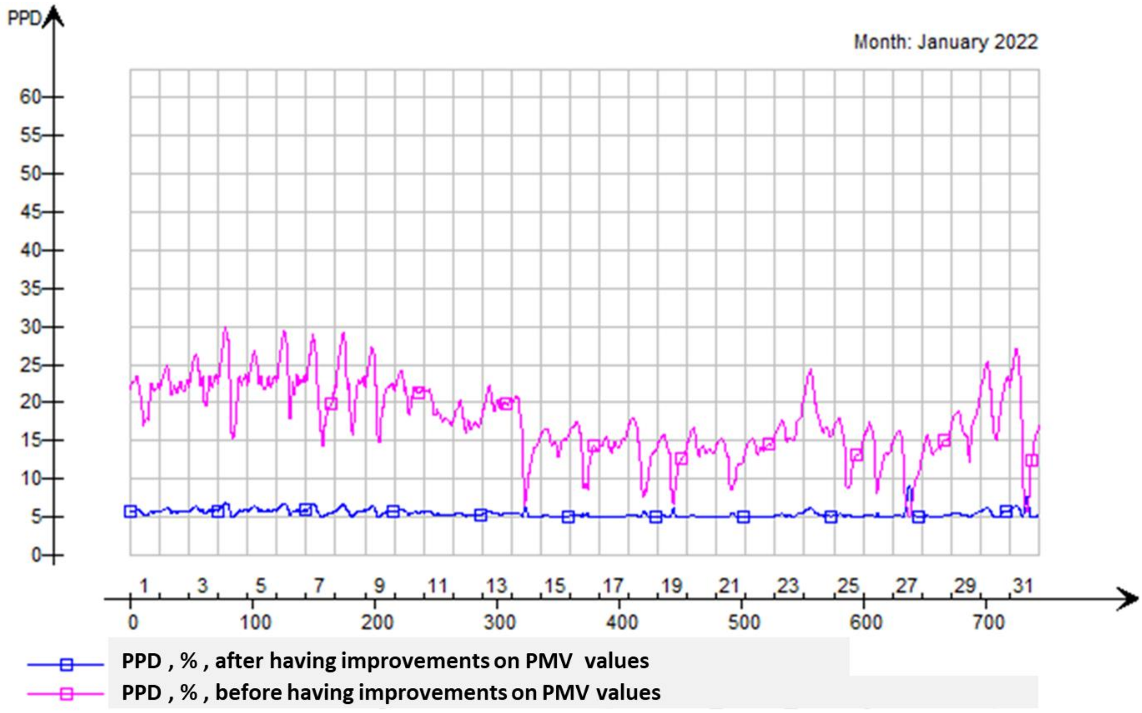


Figure 4-26 changes on the PPD values from the first PMV case to the last PMV case

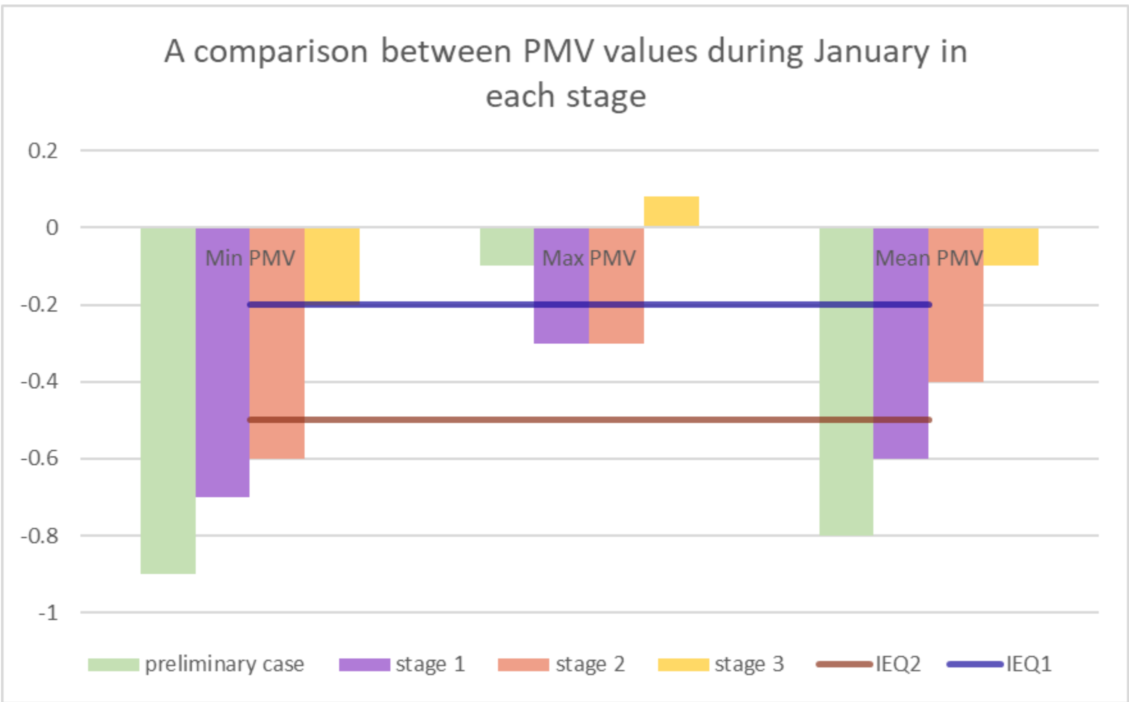


Figure 4-27 A comparison between PMV values in different scenario stages with acceptable categories: stage 1 – changes in CLO values, stage 2- Changes in heating setpoints, Stage 3- changes in MET value

4.3.4 Discussion

> ***Question 3.***
>
> *How would an energy-aware user experience the thermal condition in terms of PMV? How can the user improve the perceived conditions?*

There is not a huge difference between the PMV values in the kitchen/living room and bedrooms. This indicator usually fluctuates between (-0.6) to (–1.0) in both zones. In the bedroom, there is a higher chance for experiencing lower PMV of around (-1.2) in some days. The main reason for lower PMV value in the bedroom is lower temperature set points (+19°C during occupancy).

These results are based on the default Clo value of 0.25 to 0.85 and MET value of 1.0. Therefore, it also shows the high importance of adjusting these values during the simulation process while reducing the heating set points. The poor thermal condition in both zones puts the PMV under the category of IEQ_4 in [Table 4-14]. However, in reality, one would adjust his clothing levels to feel more comfort. Also, it is easier to adjust the clothing levels in a residential building for users than office building. Not adjusting the clo and MET values leads to almost 2 times lower PMV value (-1.0) than the minimum acceptable range of (-0.5).

Changing of the maximum Clo value from 0.85 to 1.0 improves the PMV value in both living room and bedroom by almost between 20-25%. In the kitchen, for example, the "mean PMV" changes from (-0.8) to (-0.6). Having the "Mean PMV" value closer to the minimum PMVs than maximum shows mainly poor thermal conditions. The minimum PMV is (-0.7) and (-0.9) for kitchen/ living room and bedrooms, respectively. For instance, as mentioned previously the "Mean PMV" of (-0.6) is close to the minimum of (-0.7) than maximum of (-0.3) in the kitchen. Thus, the work was followed with 2 more scenarios.

In the next scenario the temperature setpoint was increased by +1°C in both zones. After changing the temperature, the "Mean PMV" increases by almost 35%. This difference in the PMV values illustrates that +1°C has 15% higher impact than (+0.25) change in clothing levels. The "Mean PMV" of (-0.4) in this case is within the required range for IEQ_2 in [Table 4-14]. Moreover, in this case, the mean PMV is even closer to the maximum value of (-0.3) than minimum value of (-0.6). Meaning that mostly user experiences comfort condition. Eventhough both stage 1 (change in the clo) and stage 2 (change in temperature setpoints) show the same maximum PMV value, this maximum value seems to be more influential in the “mean value” of stage 2.

The evaluation process was further followed by change of MET rates in stage 3. In this case, the activity level was changed from 1 MET to 1.2 MET. The change in the metabolic rate contributes to the highest impact compared with temperature setpoint and Clo values. For example, “Mean PMV” in this case increases by 75%, which is more than 2 times higher than the impact of 1°C increase in setpoint. “Mean PMV” also in this case is a number between the maximum and minimum. Even in this case, the maximum PMV shows a positive value. It needs to be mentioned than Met= 1.2 is equivalent to having relaxed standing position and does not refer to a high level of physical activity.

In addition, the net primary energy and heating demand was calculated for the second case with higher temperature and the 3rd case with higher MET rate. The case with higher MET rate has also the higher temperature as inputs.

As [Table 4-17] illustrates, +1°C would only increase the heating demand of the preliminary case by approximately 6%. This change of +0.5 kWh/m2 has even lower share in the scale of total energy demand. Thus, small changes in the temperature will not have a huge impact of the final results of this user profile. The reason is the saved energy by an energy-aware user is a combination of saving in different means of energy indicators. Also, changes in the MET rate increases the internal heat gain from users from 24.30 to 28.04 kWh/m2. This change results in save of energy by 1.6 kWh/m2.

Also, only one PPD chart was exported to show the difference from the preliminary case to the final case. As shown in [Figure 4-26] the preliminary case has mostly PPD ranges between 15% to 30%, while the final case (stage 3) shows ranges around 5%. This way the PPD values also change from low category of IEQ_4 to highly favorable condition of IEQ_1.

4.4 Design options

4.4.1 Evaluation framework

In general, the energy performance of a building can be improved in two ways: 1- further reduction in the energy use by implementing new design options. 2- production of more on-site renewable energy. The first option includes, for example, changes in the building body, envelope, devices, and systems and is the focus in this study.

7 scenarios were simulated as possible design options to compensate for the wasted energy as a result of wasteful behaviors by user. Thus, these options consider the case of energy- unaware user in pandemic. The design alternatives include changes in thermal mass, shading systems, and window properties. [Figure 4-28] summarizes all the scenarios in this part:

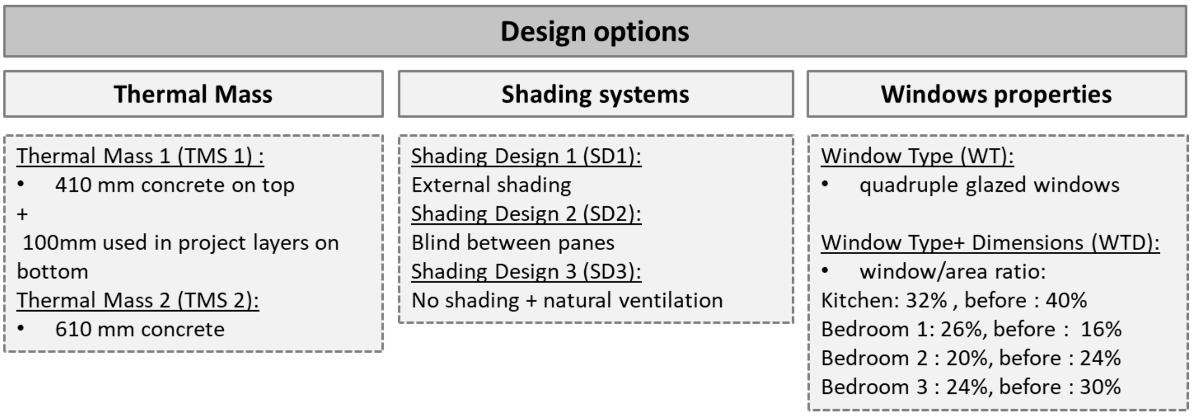


Figure 4-28 Scenarios made for design improvements

4.4.2 Solutions

- **Thermal Mass:**

The two first design options consider adding thermal mass, changing its thickness and exposedness. Use of thermal mass can show how the high heating demand caused by a wasteful user can be addressed through a passive strategy.

TMS 1: The hollow concrete in the base case [appendix 12] was firstly replaced with a massive concrete. The chosen slab is exposed from top, while from bottom it has the same layers as in the base case. Then, the thickness of the top layers were added to the concrete thickness. Therefore, the concrete thickness increased from 265 mm to 410 mm. The layer on the bottom part remains as before and thus, the thickness of the whole slab remains 510mm. The heating distribution system also is also kept as before including ventilative heating and floor heating.

TMS 2:

The whole slab section was assumed to be made of concrete. An additional of 200mm concrete was also added to the slab compared to TMS 1. Thus, the whole slab thickness changed to 610mm. For this case, one additional simulations was done considering only floor heating as the heating distribution source.

- **Shading devices:**

Due to high values of cooling load in section 4.2. for the case of energy-unaware pandemic this section tries to evaluate possible design options to reduce the cooling load in summer. Eventhough, this profile had active use of internal blinds to provide better conditions, the result showed relatively high demand for cooling. The last scenario in this part concentrates more on lowering the heating demand than cooling by evaluating maximum solar gains.

The cooling demand has been only added as ideal coolers to show the difference. So, it does not necessarily mean that the building uses any cooling unit.

SD 1: In this option the internal shading was replaced with external shading. The window opening pattern is as it was in the initial case.

SD2: In this case the shading system has changed from internal shading to blinds between panes. The window opening pattern follows as before.

SD 3: This evaluation mostly concentrates on the heating demand rather than cooling. It is assumed that there is no use of blinds which maximizes the solar heat gains.

- **Window type and properties:**

The last part in the design options shows changes in the window type and properties.

WT: Here changes have been done on the window type. As explained in [74] quadruple glazed windows can reduce the transmission heat loss through the windows by approximately 25% compared to triple glazed windows. In addition, this window typology will maintain maximum daylight levels and solar energy gains. Quadruple glazing are 20% higher in cost compared to triple glazing. [Table 4-20]shows the properties of the chosen window typology

Table 4-20 Examples of quadruple glazed windows and the chosen typology.

Window (Including frame and glazing)	Total window U-value (W/m2k)	G- value
2WS compact	1.10	0.63
3WS compact	0.53	0.53
4WS+ compact (chosen)	0.46	0.50

The light transmittance is 75% and the solar energy transmission is above 50% in quadruple glazed windows.

WTD: In this part in addition to the building typology in the previous option, changes on the window dimensions have been made. The window to floor ratio in different zones is summarized in [Figure 4-28].

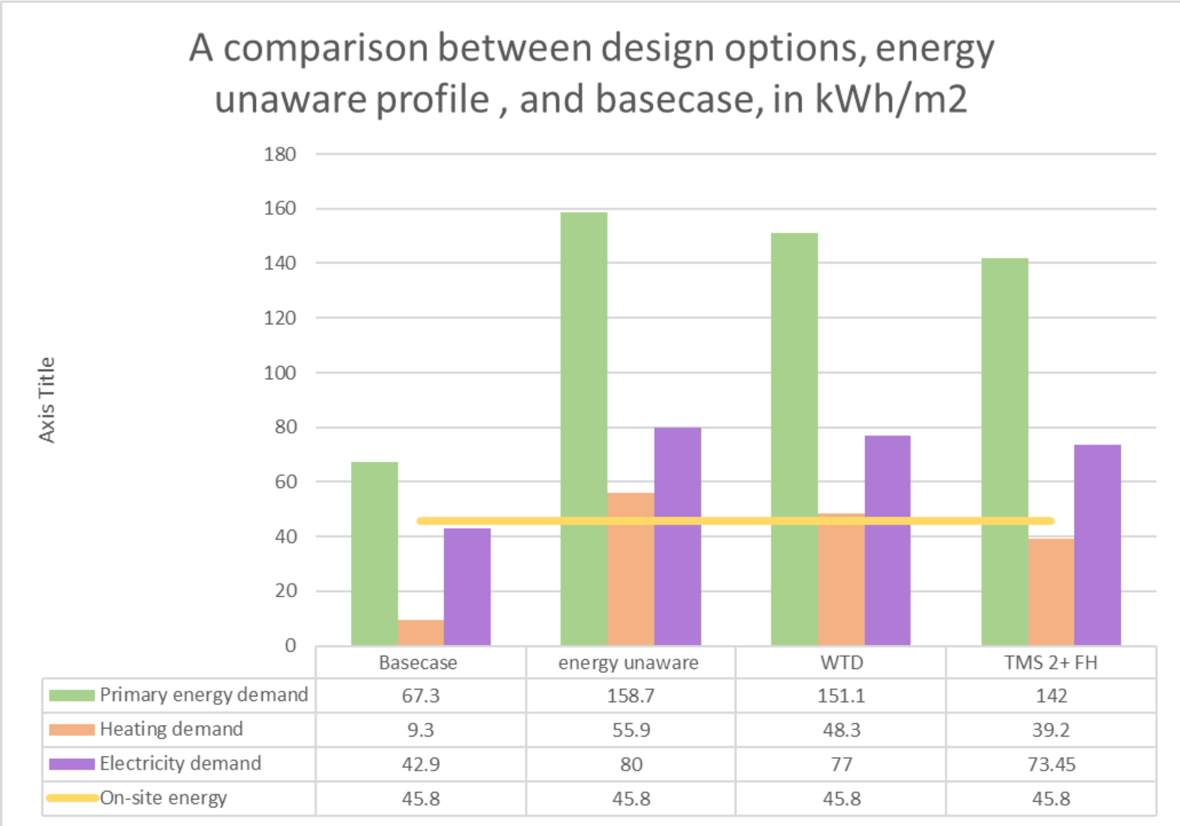
4.4.3 Results

Table 4-21 A summary of results from design options

KPIs Unit: (kWh/m^2)	Energy un-aware	Thermal mass		Window shading			Window properties	
	Pandemic	TMS 1	TMS 2	SD 1	SD2	SD 3	WT	WTD
Heating demand	55.9	52.3	50.6	57.3	56.4	50.5	49.1	48.3
Cooling demand	15.7	-	-	6.2	11.0	25.7	-	-
DHW demand	53.8	53.8	53.8	53.8	53.8	53.8	53.8	53.8
Lighting	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5
Appliances	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1
Fans+ pumps	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4
Total energy demand	158.7	155.1	153.4	160.1	159.2	153.3	151.9	151.1
Electricity for GSHP	31.0	29.8	29.0	31.9	31.3	29.0	28.7	28.0
Total electricity demand	80.0	78.8	78.0	80.9	80.3	78.0	77.7	77
PV production	45.8	45.8	45.8	45.8	45.8	45.8	45.8	45.8

Table 4-22 Results from Thermal mass with 2 difference heating distribution scenarios

	Heating demand	Primary energy demand	Electricity demand
TMS2	50.6	153.4	78.0
TMS2 + FH	39.2	142	73.4



	Basecase	energy unaware	WTD	TMS 2+ FH
Primary energy demand	67.3	158.7	151.1	142
Heating demand	9.3	55.9	48.3	39.2
Electricity demand	42.9	80	77	73.45
On-site energy	45.8	45.8	45.8	45.8

Figure 4-29 Comparison between impact of design options and wasteful user behaviors on energy demands

4.4.4 Discussion

Question 4.

How can design improvements compensate for a wasteful user? Which weighs more, the occupant impact or the discussed design options?

As mentioned previously, a wasteful user can cause around 6 times higher heating demand than the predicted value. While only 15% of this demand can be addressed in the case of best design option (for heating - WTD). Thus, the heating demand would still remain enormously higher than the base case. Combination of thermal mass and only water-based floor heating (TMS+FH) as the heating distribution system would reduce the heating demand by 28%. Even in this case, the heating demand is more than 4 times higher than the base case.

Also, there is only a small change in the electricity demand of both these cases compared to the high electricity demand of a wasteful user. Meaning that the electricity demand would decrease from 80 kWh/m2 to between 74 and 77 kWh/m2. So, it will be about 1.7 times higher than the on-site renewable electricity.

The net primary energy demand in case of an energy wasteful user will increase by approximately 250%. At the same time, the best design option can only improve the situation by 5%. So, the primary energy demand would still remain 245% higher than first calculations.

The choice of thermal mass and the changes on the energy needs is highly dependent on the choice of heating systems. Thermal mass can reduce the total energy demand by 3% in the best case if the heating is to be provided by both ventilative heating and water-based floor heating. Furthermore, changes in the thickness of the thermal mass would not significantly change the heating demand results, as it would differ by only 2 kWh/m2. At the same time, it may increase the structural needs by increasing building's weight. Further studies can probably investigate this issue later. In contrast, the thermal mass can have the best performance if all the heating is to be covered by floor heating system. Close contact between the heating distribution system and the thermal mass increase the chance of heat saving by concrete.

The results from the shading devices show that having external shading can significantly (more than 50%) reduce the cooling load. At the same time, it would not significantly increase the heating demand since heating would change by only 1.5 kWh/m2. Blinds between panes shows better heating performance compared to external shading, while it cause almost two times higher cooling demand. Blinds in all the cases have same control based on solar radiation and indoor temperature.

The last case in the shading devices category shows the impact of maximum solar gains on the heating demand. In this case, the shading devices are assumed not to be used throughout the year. Not use of blinds has more negative impact on the cooling loads than positive impact on the heating loads. Meaning that the heating load in this case would only reduce around 10% (from around 56 kWh/m2 to 50 kWh/m2), while the cooling load would rise up to 60% (from around 15 to 25 kWh/m2. The main reason for this high cooling demand is having more trapped heat indoors, especially during the summer months. Thus, further studies with different use patterns during cold and warm months would be beneficial to come to a better conclusion.

The change of windows properties including size and typology has the highest positive impact compared to the other options. But even this positive impact is very minimal compared to the negative impact of an energy-unaware user.

Another important factor that is not within the scope of this thesis is the cost of design options. For instance, as mentioned before, the case of quadrupled glazing would add around 20% to the window costs compared with triple glazing. At the same time, it would save approximately 5% of primary energy. Hence, a comprehensive future study can help with comparing the costs, different design options and energy demand for a high-energy consumer. Then, one can decide if changes in the design are worth doing or another measurement needs to be done.

All in all, this section shows low impact of possible design options on the building energy compared to the negative behaviors by occupants. The main reason is that this building is already highly optimized and efficient (passive house). For example, if the windows are to be open for some hours during the day, changes in the building body cannot really address the heating need. On the other hand, the only way to cover the energy demand of wasteful user may be production of more on-site energy, which is not within the scope in this study.

5 Discussion

Occupants can cause significant change to the predicted electricity demand by their interaction with the internal loads. Internal loads can also change the level of the heating demand enormously, especially when considering number of users in a dwelling. generally, the internal heat comes from occupants, lighting, appliances and plug loads. The higher internal heat gain due to more occupants can be considered beneficial for the energy demands. While more heat gain due to more use of electrical devices has more negative impact.

Additionally, DHW has the largest energy need compared to lighting and appliances. But having GSHP as the main heating source helps with reducing the impact of this need on the total energy balance. When considering internal loads, it does not differ much if an energy-aware is fully present or not. On the other hand, limited occupancy periods for an energy unaware would save the energy to a considerable amount.

Increase in heating setpoints by 3 to 4 degrees, changes in the ventilation rates, and negative window opening behavior leads to 6 times higher heating demand for energy-unaware users. The ventilation rate itself can also be more than double of the predicted value.

In total, an energy-unaware family has 3 times more net energy need than an energy-aware family. The standard values is closer to energy-aware profile by having a difference of 25%. While in the case of energy wasteful profiles the difference changes to 150%.

As the heating need is considerably higher for energy-unaware, it causes a huge gap between this profile energy needs in summer and winter. In summer, the minimum monthly energy for this user can go to around 9 kWh/m2, while it may reach 18 kWh/m2 in winter. This shows 50% lower demand during summer than winter. Standard and energy-aware has almost the same energy demand pattern throughout a year. for example, for the standard model, the primary energy demand is around 7.5 kWh/m2 during winter and 5.5 kWh/m2 during summer. This shows around 20% less energy demand during summer.

Although there is a high share of energy need for heating and DHW for both user profiles, use of GSHP helps considerably for reducing these energy needs. For instance, the total energy demand of 158.7 kWh/m2 for one of the energy-unaware cases has an electricity demand of 80 kWh/m2. This shows ½ total energy demand for this scenario. Also, around 50 kWh/m2 of this electricity demand is directly for lighting, appliances, fans, and pumps.

Also, as the PMV results showed, energy-aware family can easily reach the thermal comfort conditions. Even small changes in the heating setpoint would not significantly change the net energy demand for this family. In addition, change of MET rate has the biggest impact on reaching the thermal conditions. Then, change of 1°C of temperature set points can be considered as the second influential factor. The clo value can also provide the thermal condition and it is easier to adjust clothing levels in a residential building. All in All, the thermal comfort can be reached by minimum impact on the energy demand in the case of energy-saver users.

On the flip side, the negative impact of an energy unaware family is way higher to be compensated by design options. Especially, when considering high-performance buildings. Maybe reducing energy can help more in the case of less efficient buildings. Another integrated subject to the design options is the cost of them. Further study is required to show if this minimum change is worth spending more.

- ❖ More detailed discussions can be found at the end of each section in chapter 4.

6 Conclusion

- The difference between the pandemic and pre pandemic results are larger in the case of an energy-unaware users than energy-aware. The energy-aware family has almost similar energy demand in both occupancy cases.
- The total primary energy demand of energy-unaware cases are 3 times larger than energy-aware cases. Also, it is almost 150% higher than the standard model. Standard model has closer value to energy saver profile. Hence, the standard model seems to underestimate the impact of users on the energy performance of the buildings.
- More occupancy rate and use of electrical devices results in more internal heat gains and reduces the heating demand.
- Use of external sun protection can help with reducing the overheating periods.
- The poor thermal comfort conditions can easily be addressed by small changes in Clo, MET, and even temperature values. Minor changes in the temperature value for energy-saver profile would not have a large impact on the overall energy demand.
- The design options cannot compensate for the performance gap caused by energy-unaware user in terms of reducing the heating demand. Also, other features like possible costs needs to be investigated when design options are considered.
- DHW and heating demand have the highest share in the primary net energy demand. Having GSHP helps with saving energy for these 2 systems. However, still other means of electricity demand have high shares.

  The results in this study show that a certain number cannot represent the final performance of a building. People can have different needs and may use less or more energy than predicted. The prediction of building's energy should include a range of possible result. Which in this case starts from around 50 kWh/m2 to 160 kWh/m2. Thus, one cannot expect a statical future performance.

  Also, this study has some limitation that should be considered. Different number of users, orientations, and variety of schedules, and behaviors (more discussed in Figure 1-3) can be evaluated, discussed, and integrated to have more accurate result.

7 Future work

Occupants' behavior impact on building's energy and IEQ can be studied in several ways. Many parameters can be included to provide better understanding occupants role in this regard. Possible future works are suggested below:

- Different stochastic models of user's presence and absence patterns. For example, including holidays, difference in occupancy rate during winters and summers, occupancy rate during post-pandemic. The post-pandemic includes flexible working conditions, for instance some days home and some days in the office.
- Comparison of occupants' behavior in different climatic conditions. For example: warm, cold, Mediterranean, and etc. Or comparison of occupant's behaviors and its impact on energy demands in today's climate with future climate condition.
- Comparison of possible design options including costs and on-site energy production with the energy gap caused by a wasteful user. Also, how current design affects the future improvements for these options. For example, in this study the south façade has several balconies which would shade the possible additional BIPVs in future. So, this would limit the options for possible improvements.
- In-depth evaluation of different IEQ indicators including, CO2 concentration, PMV, PPD, relative humidity, air age, and visual comfort for energy-saver case. How would improvement of the situation change the energy demand of this user profile?
- Comparison of different number of occupants (1,2,3,4) in a dwelling and their behavioral impact on the energy demand. This comparison can also include different floor areas and how it would affect both the behaviors and energy performance.
- The possible occupant's behavior in building units with different orientations, and comparison between the energy gaps of each case.
- Simulation and comparison of occupant's role on the energy performance of a passive house, TEK 10 and a conventional building. how much the high-performance buildings already covers for the wasted energy by negative behaviors.

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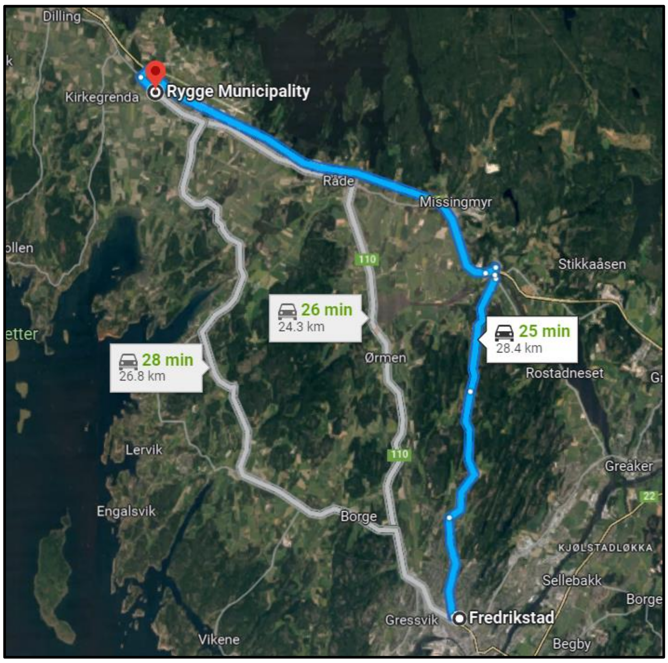
Appendix

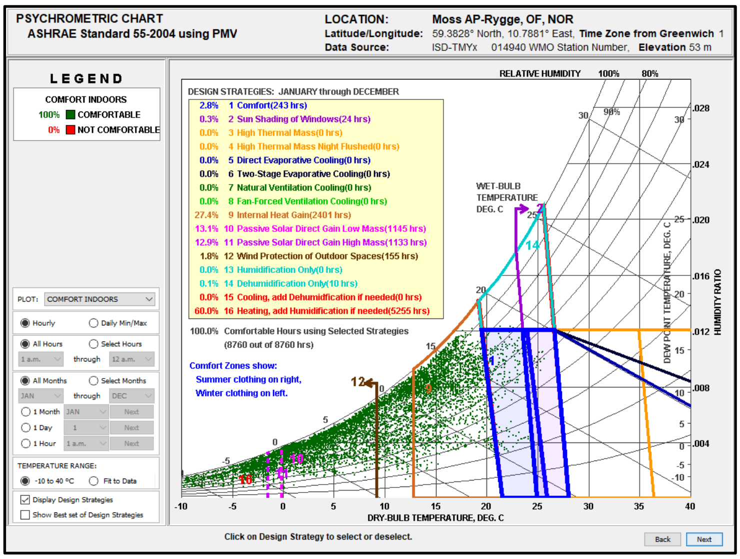
1- The climatic file of the closest climate station called “Rydde” is used for this work as there is no available file for Fredrikstad.



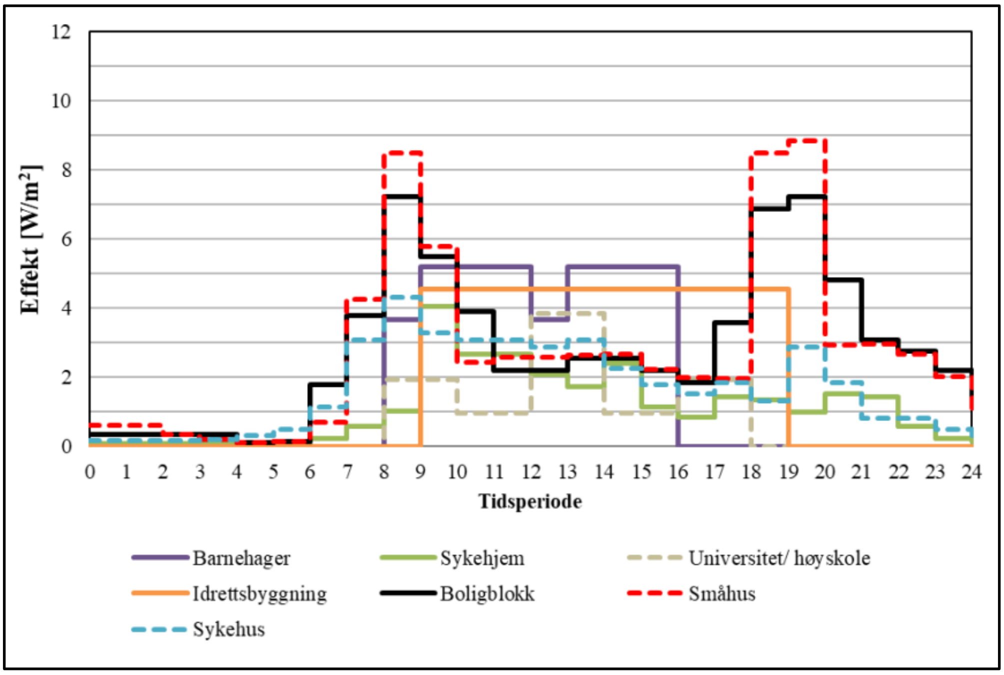
2- Apartment prices for the case study:

125 m2	From: Kr 12 995 000
105 m2	From: Kr 7 895 000
52 m2	From: Kr 3 445 000

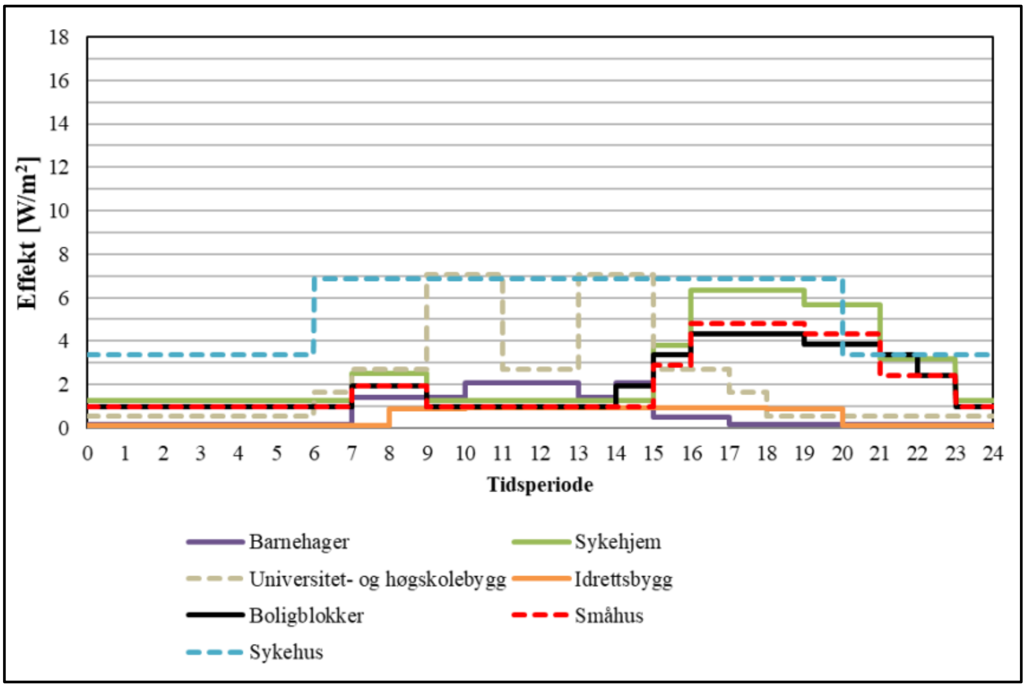
3- Psychrometric chart from the respective climate and comfort conditions: 2.8% in comfort while more than 60% heating is needed



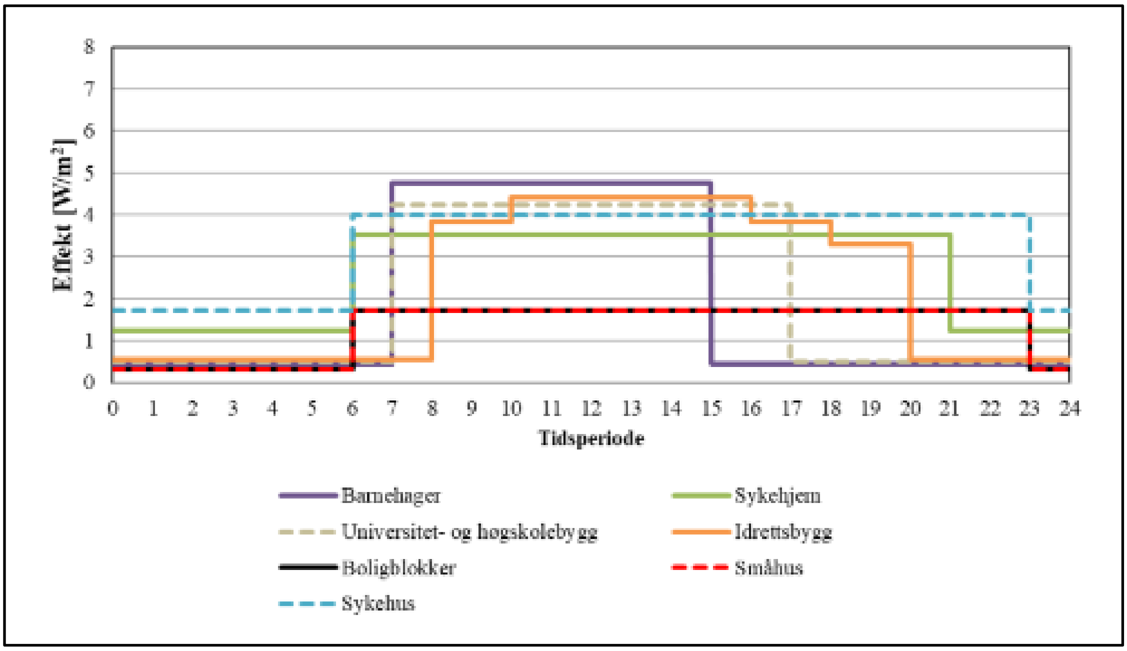
4- The daily pattern of DHW use in SN-NSPEK 3031: 2021



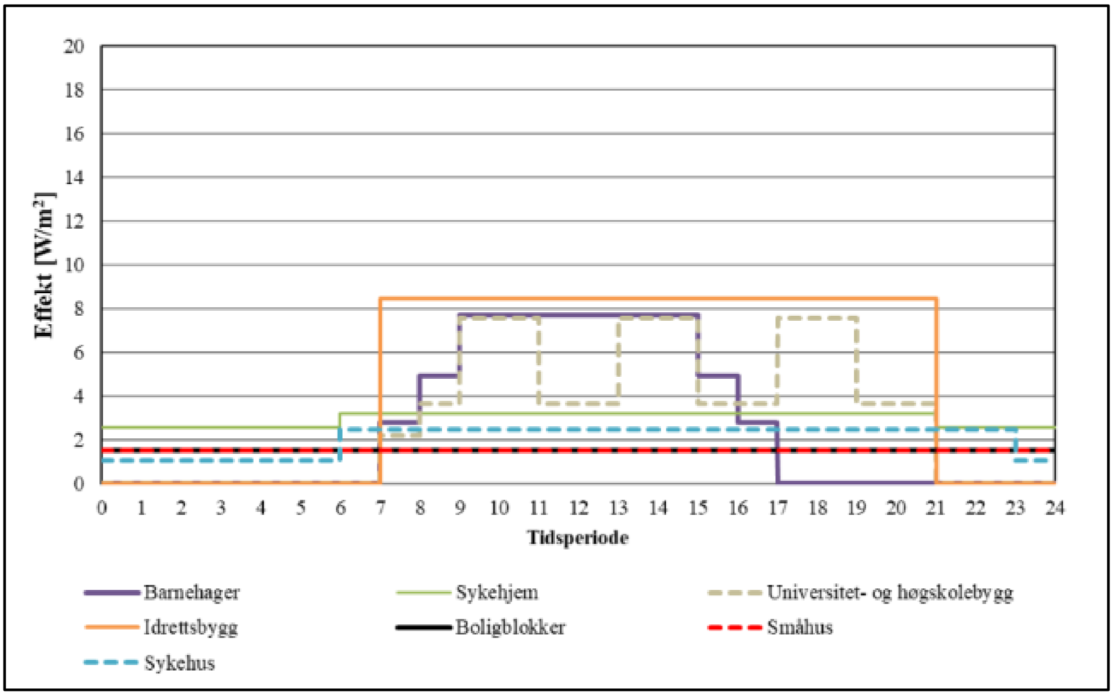
5- The daily pattern of appliances use in SN-NSPEK 3031: 2021



6- The daily pattern of lighting use in SN-NSPEK 3031: 2021



7- The daily pattern of occupancy in SN-NSPEK 3031: 2021



8- Hourly power loads for DHW-

SN-NSPEK 3031:2021

Tidsperiode			Småhus	Boligblokker
			[Wh/m²]	[Wh/m²]
0	-	1	0,6	0,3
1	-	2	0,3	0,3
2	-	3	0,2	0,3
3	-	4	0,1	0,1
4	-	5	0,1	0,1
5	-	6	0,7	1,8
6	-	7	4,3	3,8
7	-	8	8,5	7,2
8	-	9	5,8	5,5
9	-	10	2,4	3,9
10	-	11	2,6	2,2
11	-	12	2,6	2,2
12	-	13	2,6	2,5
13	-	14	2,7	2,5
14	-	15	2,2	2,2
15	-	16	2,0	1,9
16	-	17	2,0	3,6
17	-	18	8,5	6,9
18	-	19	8,8	7,2
19	-	20	2,9	4,8
20	-	21	3,0	3,1
21	-	22	2,7	2,7
22	-	23	2,0	2,2
23	-	24	1,1	1,2
[Wh/m² per døgn]			68,7	68,7
Effekt utenfor driftstid [Wh/m²]			0,0	0,0

9- Hourly power loads for lighting

SN-NSPEK 3031:2021

Tidsperiode			Småhus	Boligblokker
			[Wh/m²]	[Wh/m²]
0	-	1	0,3	0,3
1	-	2	0,3	0,3
2	-	3	0,3	0,3
3	-	4	0,3	0,3
4	-	5	0,3	0,3
5	-	6	0,3	0,3
6	-	7	1,7	1,7
7	-	8	1,7	1,7
8	-	9	1,7	1,7
9	-	10	1,7	1,7
10	-	11	1,7	1,7
11	-	12	1,7	1,7
12	-	13	1,7	1,7
13	-	14	1,7	1,7
14	-	15	1,7	1,7
15	-	16	1,7	1,7
16	-	17	1,7	1,7
17	-	18	1,7	1,7
18	-	19	1,7	1,7
19	-	20	1,7	1,7
20	-	21	1,7	1,7
21	-	22	1,7	1,7
22	-	23	1,7	1,7
23	-	24	0,3	0,3
[Wh/m² per døgn]			31,2	31,2
Effekt utenfor driftstid [Wh/m²]			-	-

10- Hourly power loads for appliances

SN-NSPEK 3031:2021

Tidsperiode			Småhus	Boligblokker
			[Wh/m²]	[Wh/m²]
0	-	1	1,0	1,0
1	-	2	1,0	1,0
2	-	3	1,0	1,0
3	-	4	1,0	1,0
4	-	5	1,0	1,0
5	-	6	1,0	1,0
6	-	7	1,0	1,0
7	-	8	1,9	1,9
8	-	9	1,9	1,9
9	-	10	1,0	1,0
10	-	11	1,0	1,0
11	-	12	1,0	1,0
12	-	13	1,0	1,0
13	-	14	1,0	1,0
14	-	15	1,0	1,9
15	-	16	2,9	3,4
16	-	17	4,8	4,3
17	-	18	4,8	4,3
18	-	19	4,8	4,3
19	-	20	4,3	3,9
20	-	21	4,3	3,9
21	-	22	2,4	3,4
22	-	23	2,4	2,4
23	-	24	1,0	1,0
[Wh/m² per døgn]			48,1	48,1
Effekt utenfor driftstid [Wh/m²]			-	-

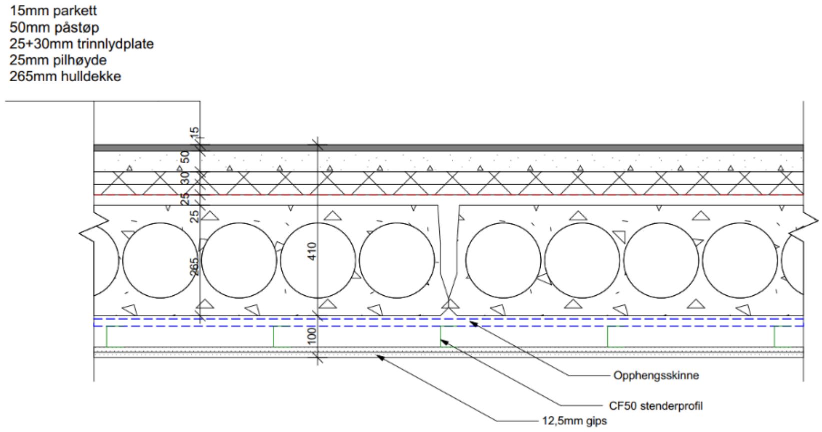
11- Hourly power internal loads for users

SN-NSPEK 3031:2021

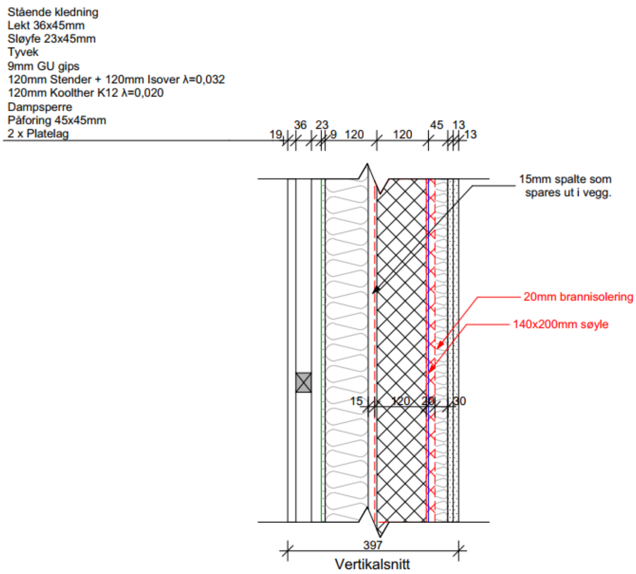
Tidsperiode			Småhus	Boligblokker
			[Wh/m²]	[Wh/m²]
0	-	1	1,5	1,5
1	-	2	1,5	1,5
2	-	3	1,5	1,5
3	-	4	1,5	1,5
4	-	5	1,5	1,5
5	-	6	1,5	1,5
6	-	7	1,5	1,5
7	-	8	1,5	1,5
8	-	9	1,5	1,5
9	-	10	1,5	1,5
10	-	11	1,5	1,5
11	-	12	1,5	1,5
12	-	13	1,5	1,5
13	-	14	1,5	1,5
14	-	15	1,5	1,5
15	-	16	1,5	1,5
16	-	17	1,5	1,5
17	-	18	1,5	1,5
18	-	19	1,5	1,5
19	-	20	1,5	1,5
20	-	21	1,5	1,5
21	-	22	1,5	1,5
22	-	23	1,5	1,5
23	-	24	1,5	1,5
Wh/m² per døgn			36	36
drifsttid			0,0	0,0

The building body properties:

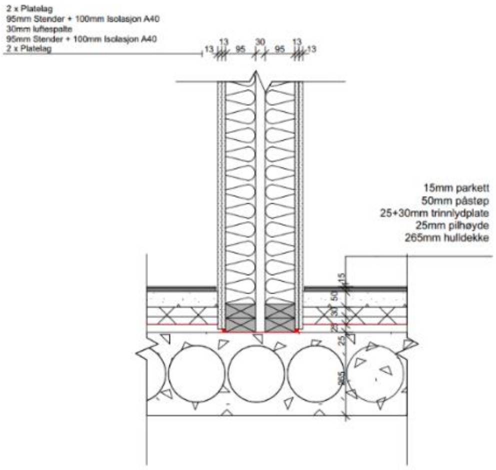
12- Interior slabs, U-value: 0.83 W/m2K



13- Exterior walls, U-value: 0.10 W/m2K



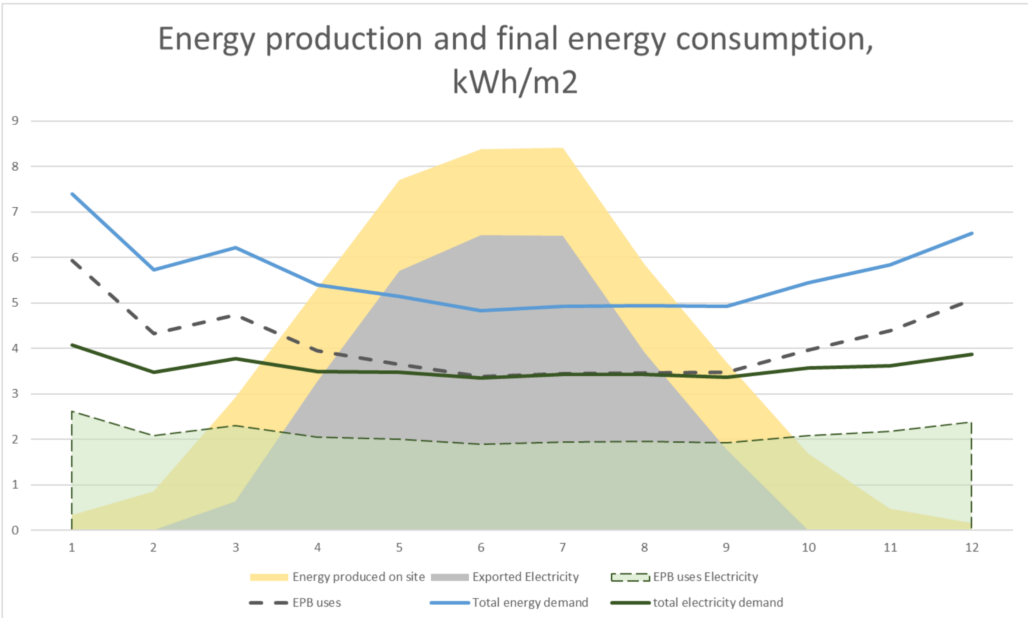
14- Interior walls, U- value: 0.18 W/m2K, λ of A40= 0.040



15- A comparison of energy performance and/or energy balance by including and not including appliances for the BC.

- EPB uses: Heating, cooling, ventilation, lighting, DHW
- Non-EPB uses technical appliances and plug-loads
  The items showed in the graph are hatched in the table.

	Year	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
EPB uses [kWh/m2]	**49.78**	5.94	4.34	4.74	3.95	3.65	3.38	3.44	3.46	3.47	3.96	4.39	5.06
Non-EPB uses [kWh/m2]	**17.50**	1.48	1.39	1.48	1.44	1.48	1.44	1.47	1.47	1.44	1.47	1.44	1.47
EPB uses electricity [kWh/m2]	**25.39**	2.62	2.09	2.29	2.04	2.00	1.90	1.94	1.95	1.92	2.08	2.17	2.39
Energy produced on-site [kWh/m2]	**45.77**	0.33	0.84	2.92	5.32	7.7	8.38	8.41	5.85	3.70	1.69	0.48	0.16
Exported electricity [kWh/m2] - appliances	**28.23**	0	0	0.62	3.27	5.70	6.48	6.47	3.90	1.78	0	0	0
Total energy demand [kWh/m2]	**67.28**	7.39	5.73	6.21	5.39	5.14	4.83	4.92	4.94	4.92	5.44	5.84	6.53
Total electricity demand [kWh/m2]	**42.89**	4.08	3.47	3.77	3.49	3.47	3.34	3.43	3.43	3.36	3.57	3.62	3.86
Exported electricity + appliances	**18.84**	0	0	0	1.83	4.23	5.04	4.98	2.42	0.34	0	0	0



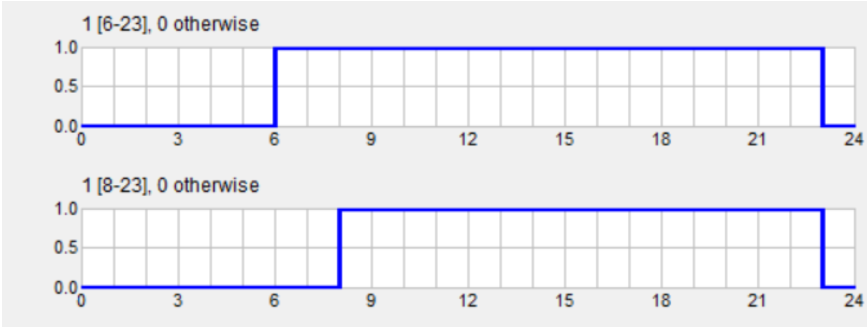
16- Impact of different MET values on internal loads and effect of Clo values on the level of body insulations.

(1 met = 58 W/m²)

AKTIVITETSNIVÅ	STOFFSKIFTE	
	W/m²	met
Sovende	48	0,8
Stillesittende, avslappet	58	1,0
Stående, avslappet	70	1,2
Sittende (kontor, skole, lab)	65–110	1,1–1,5
Stående (forretning, lab, lett industri)	90–120	1,6–2,1
Moderat aktivitet (husarbeid, maskinarbeid)	115–160	2,0–2,8
Middels høy aktivitet (tungt maskinarb, verksted)	165–200	2,8–3,5
Gå (2 km/h)	110	1,9
Gå (5 km/h)	200	3,4
Løpe (9 km/h)	435	7,5
Løpe (15 km/h)	550	9,5
Maks ytelse ved kontinuerlig arbeid	780	13,4
«Topp-idrett»	870	15,0

Bekledning	Arealfaktor f_{cl}	Isoleringsevne I_{CL}	
		clo	(m² · K)/W
Shorts, underbukser, T-skjorter, lette sokker, sandaler	1,10	0,30	0,050
Lett kjole med ermer, underkjole, strømpebukser, truser	1,15	0,45	0,070
Lette bukser, skjorte med korte ermer, underbukser, lette sokker, sko	1,15	0,50	0,080
Skjørt, skjorte, med korte ermer, truser, strømpebukser, sandaler	1,20	0,60	0,095
Skjørt, genser med rund hals, skjorte, truser, tykke knestrømper	1,30	0,90	0,140
Jakke, bukser, skjorte, underbukser, sokker, sko	1,30	1,00	0,155
Frakk, jakke, vest, bukser, skjorte, kort undertøy, sokker, sko	1,50	1,50	0,230

17- Defined lighting schedules for bedrooms

<table>
<tr><td rowspan="2">Energy aware – Bedrooms</td><td rowspan="2">Schedule based control: based on daylight level and active occupancy</td><td>Pandemic</td><td>
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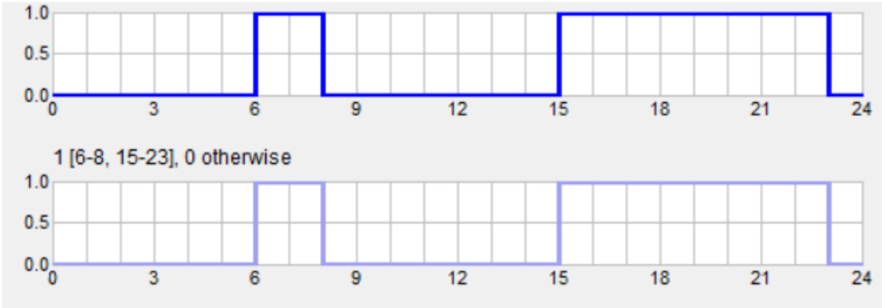
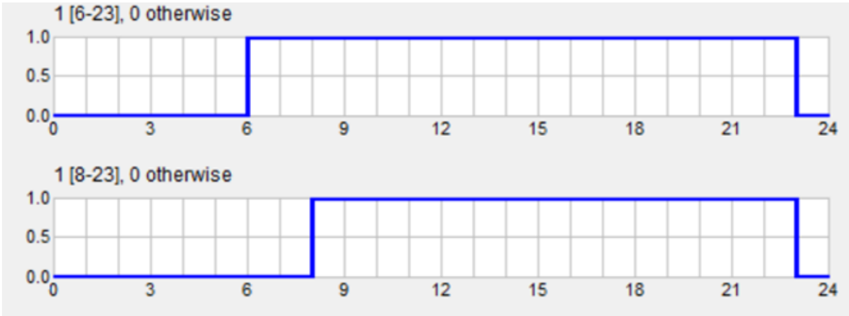
<tr><td>Pre-pandemic</td><td>
</td></tr>
<tr><td rowspan="2">Energy unaware – bedrooms</td><td rowspan="2">Scheduled based control: occupancy >0, some lights on when occupancy =0</td><td>Pandemic</td><td>
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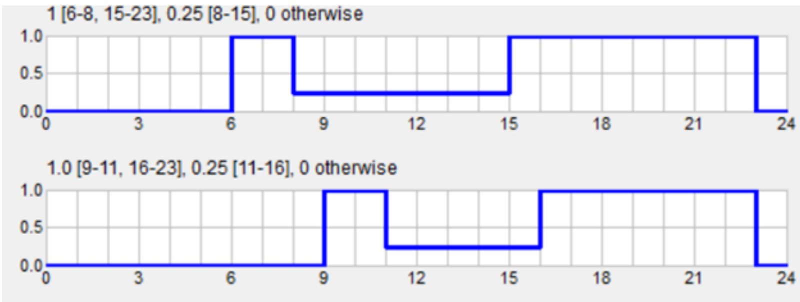
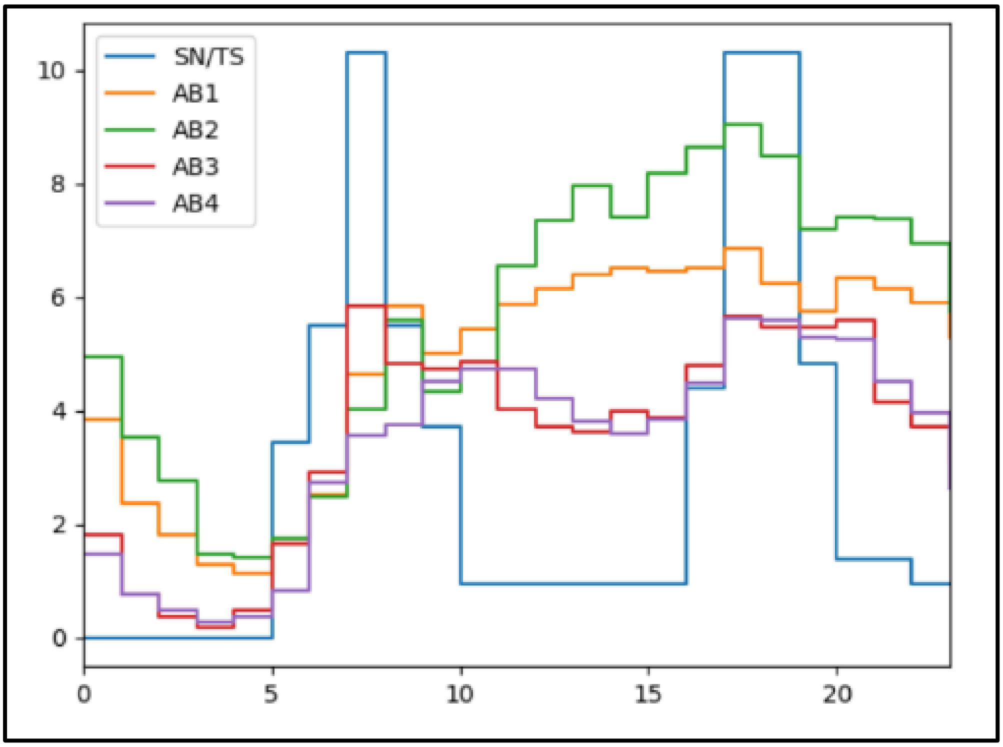
<tr><td>Pre-pandemic</td><td>
</td></tr>
</table>

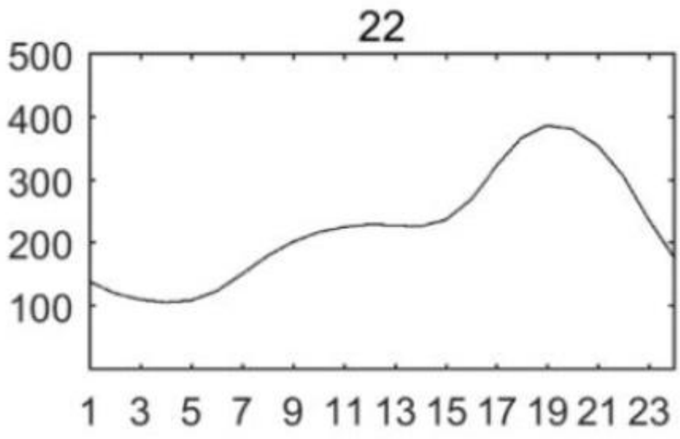
18- Results from "prosjektet varmtvann2030" in [19] :

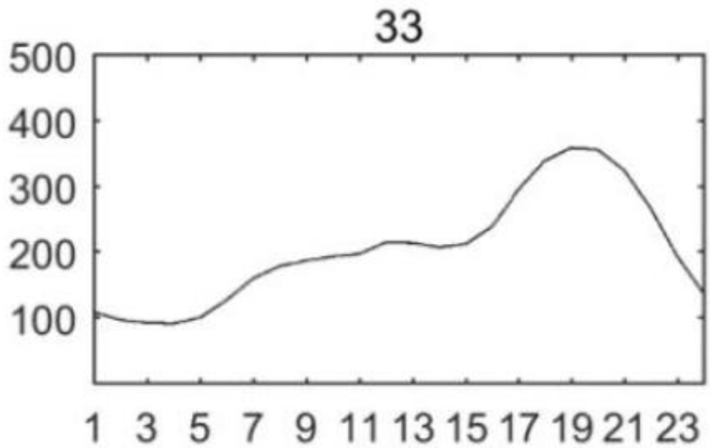
***Tabell 1.** Oversikt over de 4 boligblokkene målt i Varmtvann 2030 – prosjektet. Boligblokkene AB1 og AB2 inneholder kommunale leiligheter. Kilde: Varmtvann2030*

Navn	Areal	Antall leiligheter	Årlig netto energibehov til tappevann, kWh/(m²år)
AB1	4400 m²	96	42
AB2	2700 m²	56	49
AB3	3752 m²	56	31
AB4	5100 m²	86	30



19- Appliances power load throughout a day for the respective profiles in 4.1.4. [63]:

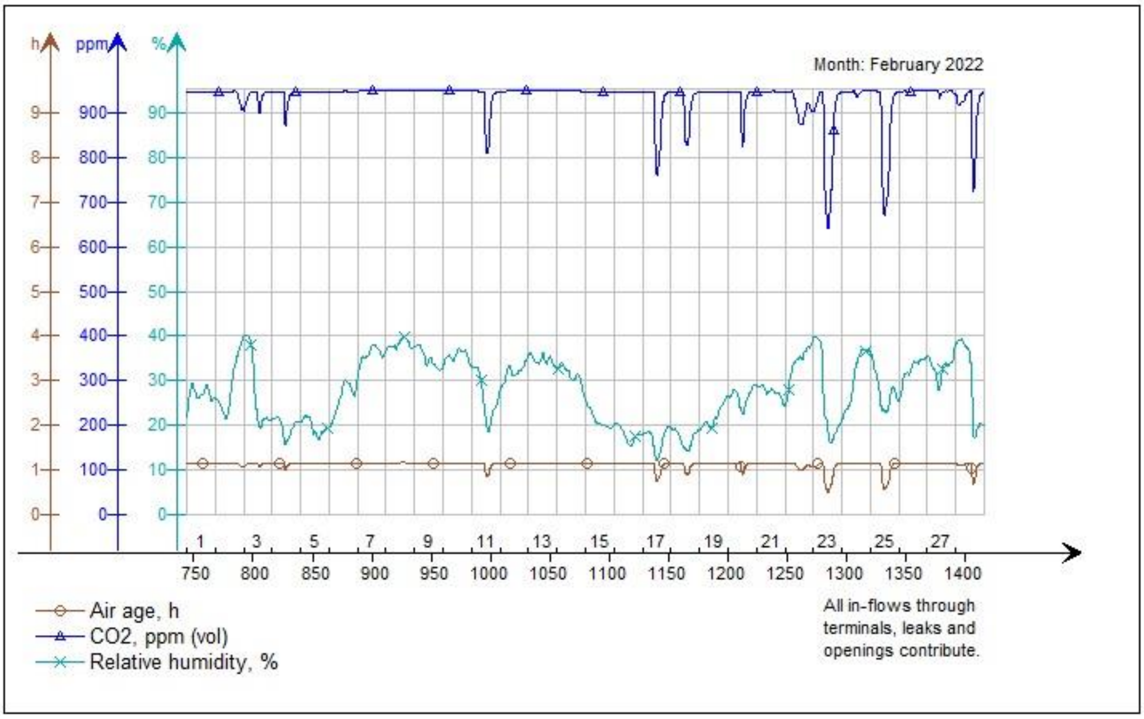




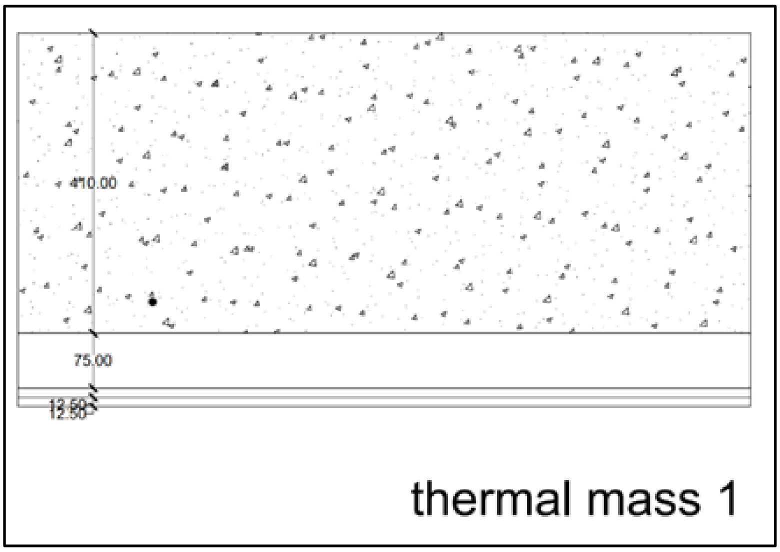
20- Exhaust air flow rates. Main reference of 4.2.2 from [69]:

Number of main rooms in the dwelling	Design extract air flow rates in l/s				
	Kitchen	Bathroom or shower with or without toilets	Other wet room	Toilets	
				Single in dwelling	Multiple (2 or more in dwelling)
1	20	10	10	10	10
2	25	10	10	10	10
3	30	15	10	10	10
4	35	15	10	15	10
5 and more	40	15	10	15	10

21- The highest CO_2 and relative humidity ranges for case of energy aware pandemic during February:



22- Thermal Mass 1



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