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Energy performance analysis of an NZEB

The Danish case in the PRELUDE Project

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A tutte quelle persone che sono state per me
un rifugio o una liberazione.

Summary

List of Figures

List of Tables

Abstract

This thesis focuses on the research and analysis of a real case study in Denmark. The house in question is part of a European project called PRELUDE (Prescient building Operation Utilising Real Time data for Energy Dynamic Optimisation) and represents a building with high-level technological solutions. The building is also classified as an NZEB (Nearly Zero Energy Building) for its energy performance and its use of renewable energy resources.

These types of buildings, despite being equipped with many different energy efficiency solutions, do not perform as expected, and they often demonstrate the highest energy performance gap. So, thanks to measurements and modelling, it can be possible to know whether the selected buildings underperform and to identify the most impactful parameters.

Therefore, within this general framework, this study sought to take a step towards reducing the possible energy performance gap in the building by analysing the behaviour from various points of view.

Firstly, the Be18 model was created. This software is a calculation programme used to document whether a building complies with the energy framework of building regulations and thus to identify the position of the house in terms of primary energy requirements. This analysis made it possible to compare theoretical performance with actual performance and to check whether there were any major differences.

Secondly, the data measured over the past four years were analysed and compared in order to check the efficiency of the systems in operation and to identify possible faults. This also allowed to understand the differences in user behaviour and how this affects energy consumption.

Finally, a model of the building was created to obtain its dynamic simulation in order to reproduce its complex behaviour. A reproduction of this model can help to understand the consequences of each setpoint change and control of the house.

1. Introduction

The European Union and building regulations are increasingly focusing on reducing energy use and greenhouse gas emissions and integrating renewable energy sources into the building sector, especially in new constructions. Indeed, the main goal of the latest Energy Performance of Buildings Directive (EPBD) is to reduce the primary energy consumption of buildings, which is assumed to be 40% of total energy consumption in the European Union (EU). To this end, every new building in every EU Member State must be nearly zero-energy.

The introduction of NZEB reflects the high energy saving potential associated with the design and retrofitting of energy efficient buildings. According to Article 2.2 of the Directive NZEB, it is defined as a building with a very high energy performance, determined in accordance with Annex I. The required amount of nearly zero or very low energy should be covered to a very significant extent by energy from renewable sources produced on site or nearby [1].

However, some studies show that differences between predicted and actual energy performance can be significant in this type of buildings. Research by Zou et al. (2019) identified 8 critical factors that cause an energy performance gap [2]:

- Inaccurate design parameters;
- Failure to account for uncertainties;
- Lack of accountability;
- Poor communication;
- Lack of knowledge and experience;
- Inefficient and overly complicated design;
- Lack of post-testing;
- Lack of feedback.

Liang et al. (2019) found that energy consumption related to user and deficiencies in energy-efficient technologies are also important factors for the gap [3]. According to this research, the main reasons for the energy performance gap are higher energy consumption by occupants than originally planned, higher occupant numbers than originally planned, and deficiencies in energy efficiency technologies.

The influence of occupants, according to Carpino at al. (2020), becomes particularly relevant in low-energy buildings, where the energy requirements for which they were designed are low. Indeed, occupants influence energy use by contributing to internal gains, interacting with systems and modifying internal conditions through their behaviour [4].

Therefore, reconsidering the calculation of energy demand in building regulations can have a significant impact on achieving near zero energy buildings that functioning as intended.

It is, also, necessary to carry out extensive occupant data collection and monitoring of occupied buildings in order to obtain a good insight into the performance gap.

In particular, in this thesis, a real-life case study in Denmark of a building with high-level technological solutions was considered with the aim of analysing and assessing the building's energy efficiency and internal environmental conditions in detail.

The building under analysis is part of a European project called PRELUDE (Prescient building Operation utilizing Real Time data for Energy Dynamic Optimization). The aim of this project is to improve building smartness by minimising energy use, maximising self-consumption and investment in renewable energy sources (RES), reducing the CO_2 footprint and improving indoor conditions.

In the first phase, the buildings are closely monitored to check the efficiency of the systems in operation and detect faults.

In the second phase, the monitored data are used to mobilise tenants for corrective actions and proactive use of available smart solutions. In this case, PRELUDE solutions are used to inform and suggest actions to tenants to ensure indoor thermal conditions and reduce energy demand (use of the 'not at home' function to lower the temperature, opening of windows, night-time temperature lowering, active role in the use of building management system/IoT functionalities).

In the third phase, the energy specialist takes control of the building to optimise its energy performance. In this phase, energy reduction is prioritised and the indoor climate is sacrificed, while user acceptance is monitored.

This study is part of the three phases of the PRELUDE project. First, the data recorded for the reference building were monitored and analysed, comparing the results obtained in terms of primary energy with those obtained from modelling the house on the Danish Be18 legislative software, with the aim of comparing theoretical performance with actual performance.

Secondly, the analysed data were compared with those of the previous three years, when another family lived in the building, with the aim of detecting possible faults in the system and identifying the weight of different occupants' behaviour on consumption, in order to explain and interpret certain energy consumption.

Thirdly, a dynamic model of the building was created in order to reproduce its complex behaviour and thus understand the consequences of each change in setpoint and house control.

As said, in fact, NZEB buildings, despite being equipped with all energy efficiency solutions, often do not perform as well as expected. Before measurements begin, it is not known to what extent and whether the selected buildings underperform, but based on measurements and modelling it will be possible to identify the most impactful parameters.

According to the current danish Building Regulations [5], all new buildings should reach at least the currently mandatory A2015 class. This means that the number of these buildings will increase and that their share of the total residential building stock will increase year by year. Therefore, the replicability potential of the Danish demonstration buildings is very significant and will only increase with time. Within this general framework, this study sought to take a step towards reducing the energy performance gap by analysing building behaviour.

1.1 Policy briefing

In the European Union, energy production and use are responsible for 80% of all greenhouse gas (GHG) emissions. With around 40% of the EU's final energy and 36% of CO2 emissions, buildings have an undeveloped potential for energy savings [6].

In 2007, EU leaders presented the '20-20-20' targets to become an energy-efficient, low-carbon economy. The targets were formulated as:

- A 20% reduction in greenhouse gas emissions compared to 1990 levels;
- Increasing the share of energy from renewable sources to 20%;
- Improvement of energy efficiency leading to 20% primary energy savings in the EU.

In 2011, a new energy roadmap was introduced to move to a competitive low-carbon economy in 2030, introducing new targets to promote energy security, energy equity and environmental sustainability: a 40% of greenhouse gas emissions, a minimum 32% share of renewable energy consumption and at least 32.5% energy savings. Buildings, therefore, could be a key factor in achieving Europe's updated 2030 energy and climate targets [6].

The European Union's desire to achieve the main objectives by 2020 has given rise to Directive 2010/31/EU, also known as the Energy Performance of Buildings Directive (EPBD) recast, in which the concept of Nearly Zero Energy Building (NZEB) is included. The dissemination of this type of building is therefore one of the main aims of the legislation.

The directive also defines the energy performance of a building as the calculated or measured amount of energy required to meet the energy needs associated with its normal use, including energy used for heating, cooling, ventilation, hot water and lighting.

Delegated Regulation (EU) n. 244/2012 and Recommendation (EU) 2016/1318 contain useful information for calculating the energy performance of a building.

In accordance with Part 3 of Annex I to the Delegated Regulation, in order to calculate the energy performance, it is first necessary to calculate the final energy required for heating and cooling and then the net primary energy. The Directive authorizes the Member States to use their national primary energy factors to transform the final energy supplied into primary energy and calculate the performance of buildings [7].

In this perspective, according to the Recommendation, the definition of NZEB shall also include a numerical indicator of the annual primary energy consumption expressed in kWh/m^2, which concerns energy performance [8].

So, the Directive traces the path and objectives that each Member State must follow to identify an NZEB and to get the outlined target. However, it is up to individual countries to define the minimum requirements in terms of energy performance within the perspective of achieving optimal cost levels.

A correct assessment of the energy request is a challenge of primary importance since it influences both the environmental and the economic aspects. To this aim, occupants’ presence and behaviours inside buildings are the main causes of the energy consumption prediction gap.

1.2 NZEB around Europe

In the first place, there is the question of identifying an implementing definition of the concept of NZEB.

According to Article 9 of the EPBD recast, from the beginning of 2021 all new buildings constructed in the EU must be nearly zero-energy, and the same applies to all new buildings publicly owned and occupied from the beginning of 2019.

The Directive also sets a common target in terms of production from renewable energy sources (RES), currently 32% for the amount of renewable energy in EU energy consumption by 2030, but the way these requirements are handled varies widely [1].

However, due to the complexity and variability of how NZEB standards are defined, it is only possible to make a high-level summary of the main achievements in the Member States, illustrated in Table 1.

Table 1 - Summary of energy requirements within NZEB standards around Europe [9]

Country/region	Was NZEB legislation in place for public buildings by January 2019?	Was NZEB legislation in place for all buildings by January 2021?	Is there a numerical indicator of primary energy use expressed in kWh/m²y?	Are renewable energy requirements clearly specified?
Austria	✓	✓	✗	✓
BE – Brussels	✓	✓	✓	✗
BE – Flanders	✓	✓	✗	✗
BE – Wallonia	✗	✗	✓	✗
Bulgaria	✗	✗	✓	✓
Croatia	✓	✓	✓	✓
Cyprus	✓	✓	✓	✗
Czechia	✓	✓	✓	✗
Denmark	✓	✓	✓	✓
Estonia	✓	✓	✓	✗
Finland	✓	✓	✓	✗
France	✓	✓	✓	✓
Germany	✗	✓	✗	✓
Greece	✗	✗	✓	✓
Hungary	✗	✗	✓	✓
Ireland	✓	✓	✓	✓
Italy	✓	✓	✗	✓
Latvia	✓	✓	✓	✗
Lithuania	✓	✓	✓	✓
Luxembourg	✓	✓	✗	✗
Malta	✓	✓	✓	✗
Netherlands	✓	✓	✓	✓
Poland	✓	✓	✓	✗
Portugal	✓	✓	✗	✓
Romania	✓	✓	✓	✓
Slovakia	✓	✓	✓	✗
Slovenia	✓	✓	✓	✓
Spain	✗	✓	✓	✓

Sweden	✓	✓	✓	✗

It can be noted that only eight Member States fulfilled all four requirements: Croatia, Denmark, France, Ireland, Lithuania, the Netherlands, Romania and Slovenia. The others did not adequately address at least one of the provisions.

Regarding the EPBD's requirement that all new publicly owned and occupied buildings should be NZEB as of 1 January 2019, most Member States met this date, according to BPIE (2021), although in some cases the exact implementation date could not be determined. Four countries did not meet the deadline: Germany, Greece, Hungary and Spain.

While all new buildings in the EU, residential or non-residential, publicly or privately owned, from 1 January 2021, had to be built to the national NZEB standard. This requirement has been met in all countries except: Bulgaria and Greece [9].

To determine how ambitious these requirements are, two main parameters were taken into account:

- the energy performance of the building, expressed in primary energy consumed;
- the share of energy needs supplied by renewable sources produced on site or nearby.

1.2.1 Primary energy requirement

Clause 3 of Article 9 of the EPBD requires Member States to define their NZEB requirements in their national plans, including a numerical indicator of primary energy consumption expressed in kWh/m^{2}y.

In some cases (e.g. the Netherlands and the Belgian region of Flanders), the building's primary energy use is assessed through a non-dimensional coefficient, comparing the building's primary energy use with a 'reference' building with similar characteristics (e.g. building geometry). In some countries (e.g. UK, Norway and Spain) carbon emissions are used as the main indicator, while in others (e.g. Austria and Romania) carbon emissions are used as a complementary indicator to primary energy use.

For residential buildings, most jurisdictions aim to have a primary energy consumption of no more than 50 kWh/m^{2}y. Different requirements are often set for single-family houses and residential buildings, and higher values are set for regions with a colder climate (e.g. France and Romania).

For non-residential buildings, requirements may have a wider range in the same country, depending on the type of building. Some jurisdictions set a single target only for offices and schools (e.g. Brussels Capital Region), while others (e.g. Romania and Estonia) also include requirements for hospitals. In general, due to different calculation methodologies, climatic conditions and building type, the maximum primary energy level for non-residential buildings in Europe ranges from 0 to 270 kWh/m^{2}y.

Regarding the methodology of calculating the energy performance of buildings, the EPBD (Annex I) lists the main end uses to be included, such as heating, domestic hot water, cooling, ventilation and (especially in the non-residential sector) lighting. In most jurisdictions, energy requirements for cooling and ventilation are considered for residential buildings, but only a few consider appliances (e.g. Austria) or the energy consumption of lifts and escalators (e.g. for non-residential buildings in Italy).

In addition to requirements for primary energy consumption, most countries also set separate requirements for final energy use, as suggested by the European Committee for Standardisation.

In most jurisdictions, these refer to the final energy required for space heating (e.g. in Cyprus, Latvia, Slovenia or the Brussels-Capital Region) or to the average transmittance coefficient of the building (e.g. in the Czech Republic); in some cases (e.g. in Denmark and the Brussels-Capital Region), an assessment of the airtightness of the building is also included. In some cases (e.g. in France, Denmark, the Brussels-Capital Region and Flanders), additional requirements are set for the performance of technical systems (e.g. heating and ventilation units) and to further reduce the risk of overheating of the building [9].

The European Commission has also considered the EU climate zones. In the 2016 NZEB Recommendations, it published reference thresholds for primary energy in the EU, differentiated according to four main climate zones: Mediterranean, Oceanic, Continental and Nordic [8]. These recommended reference values are summarised below, for single-family houses, as they relate to the case study represented.

Table 2 - European Commission building energy performance and renewables benchmarks

Single family house	**Net primary energy kWh/m2/y**	**Energy supplied from renewable energy sources kWh/m2/y**	**Primary energy threshold including that supplied from renewable sources kWh/m2/y**	**Renewables as % of total primary energy (based on mid-point)**
Mediterranean	0-15	50	50-65	87%
Oceanic	15-30	35	50-65	61%
Continental	20-40	30	50-70	50%
Nordic	40-65	25	65-90	32%

Countries with milder climates should have both the lowest net primary energy demand and the highest share of renewables. However, if the primary energy demand of the building is considered regardless of whether it is supplied by renewable energy sources or not, the range between the 4 climate zones is much narrower (50-90 kWh/m^{2}y).

1.2.3 Renewable energy requirements

The way renewable energy requirements are handled varies widely. Only a few Member States provide for minimum values in legislation, so as to be comparable to the European Commission's benchmarks, and these are: Ireland, France, Hungary, Croatia, Netherlands, Lithuania, Portugal, and Bulgaria. These are expressed as a minimum share of renewable energy contribution to total primary energy demand, ranging from 32% for the Nordic climate zone to 87% for single-family houses in the Mediterranean climate zone (Table 2).

In all cases except Lithuania and Bulgaria, these values are lower than the European Commission's benchmark values for the relevant climatic region.

Other Member States have adopted different ways of specifying renewable energy requirements:

- Austria proposes that 80% of heating and hot water needs be met by renewable sources or 20% by photovoltaic solar energy;
- Denmark has specified a maximum level of 25 kWh/m^{2}y of renewable energy to be included in the energy framework calculation;
- The German requirements are based on 15% for solar thermal or solar photovoltaic and 50% for geothermal energy, waste heat biomass;
- Portugal sets a minimum contribution of renewable energy only for residential buildings (50% of total primary energy consumption);
- Some countries (Greece, Italy, Slovenia, Spain) have only specified minimum shares of domestic hot water to be from renewable energy;
- Sweden stated that the high content of low-carbon sources in its energy mix avoided the need to specify a renewable energy requirement in its ZEB standard [9].

1.3 Italy vs Denmark legislation

By comparing European NZEB policies, it was possible to note the absolute predominance of Denmark in terms of energy efficiency.

For many years, this state has focused on reducing energy consumption in buildings, which has steadily increased since the first energy requirements were introduced in building regulations in 1961.

Since 2006, according to Thomsen et al. (2020), requirements for the total energy consumption of a building have been set in accordance with the EPBD. In 2008, the Danish government signed an energy agreement to reduce the energy requirements of buildings by 25% in 2010, 25% in 2015 and another 25% in 2020, for a total reduction of 75% compared to the 2006 requirements [10].

The thoroughness of Danish legislation in terms of NZEB and, more generally, energy use efficiency, has brought the country a step ahead of the leading European countries. This is also demonstrated by the fact that Denmark introduced the EPBD requirement before the deadline, notably in 2016. In particular, it introduced the requirement for new publicly owned buildings 3 years before the deadline, in 2016, and the same for all other types of buildings, even 5 years before. This state also introduced an even more demanding primary energy requirement value than the benchmark proposed by the European Commission [9].

Summarising the above conclusions, it is possible to note some differences between Italian and Danish NZEB legislation.

In Italy, the European EPBD recast has been transposed through Legislative Decree n. 63 of 4 June 2013, converted into Law n. 90 of 3 August 2013, and made changes to the text of Legislative Decree 192/05, introducing precisely for the first time the definition of an NZEB building in the national legislation. However, the characteristics of a nearly zero energy building were only established by the Ministerial Decree of 26 June 2015 of the Ministry of Economic Development, "Minimum requirements for buildings" [11].

While, in Denmark, the current energy performance requirement methodologies for new residential and non-residential buildings were implemented through the 2006 Danish Building Regulation as an implementation of Directive 2002/91/EC.

Italy certainly appears to be a step behind in terms of building energy efficiency. In addition to the slowness in introducing specific legislation for this type of intervention, Italy has a not inconsiderable historical building heritage - almost two out of ten buildings were built before 1919 - and this is certainly an obstacle to the speed of this technological evolution.

The main difference, however, in term of NZEB legislation, is that in Italy there is no numerical indicator of primary energy consumption, while in Denmark it can be found. An overview of the energy flows included in the national calculations and the allowed maximum primary energy (PE) values to comply with NZEB requirements are given in Table 3. While Table 4 presents the PE factors for energy carriers used in European Commission (EC) [7] recommendations and national energy performance calculations in Denmark and Italy [5] [11].

Table 3 - National and EC NZEB requirements and energy flows included in the PE calculation

	Included energy flows	**PE requirement for NZEB, kWh/(m^{2}y)**
		Single family house

		2015	2020
EC recommendations	HVAC, DHW, auxiliary	Mediterranean: 0-15 (incl. ~50 RES) Oceanic: 15-30 (incl. ~35 RES) Continental: 20-40 ((incl. ~30 RES) Nordic: 40-65 (incl. ~25 RES)	
DK requirement	HVAC, DHW, auxiliary	30 + 1000 / Ag	27
IT requirement	HVAC, DHW	-	-

Table 4 - PE factors used in European Commission recommendations (EC), Denmark (DK) and Italy (IT)

Energy carrier	PE factors		
	EC	DK	IT
Electricity	2.3	1.9	2.42
District heating	1.3	0.85	1.5
Natural gas	1.1	1	1.05

In Denmark the current legislation regarding the energy performance of the building is the "Danish Building Regulations" (BR18). It sets minimum energy performance requirements for all types of new buildings and for a voluntary low-energy class. PE requirements for a building also take into account thermal bridges, solar gains, shading, infiltration, ventilation, heat recovery, cooling, efficiency of boilers and heat pumps, electricity for operation and heat pumps, electricity for building operation and lighting.

On-site produced renewable energy is part of the calculation. The maximum local electricity production to be factored in from RES corresponds to a reduction of the need for supplied PE of 25 kWh/m²y in the energy performance framework.

In addition, buildings that comply with BR18 and the voluntary low-energy class must also have a good indoor thermal climate, and more specifically the indoor temperature of residential buildings must not exceed 27°C for more than 100 hours per year and 28°C for more than 25 hours per year.

The individual elements of the building envelope must be insulated to a level that ensures that dimensional heat losses through them do not exceed predefined values. The calculation of heat loss coefficients must be carried out in accordance with Danish standards. There are also specific requirements for the HVAC system.

The energy requirement for domestic hot water is based on a standard use of hot water (250 L/(m²y) in residential buildings) and calculated according to the efficiency of the technical system installed in the building. The national standard excludes lighting and electricity of private appliances from the calculation of energy performance in residential buildings [5].

In Italy the current legislation for the energy performance of the building is the "Minimum requirements for buildings" Decree. It introduces the 'reference building', by which is meant a building identical to the one under consideration in terms of geometry (shape, volumes, floor area, surfaces of building elements and components), orientation, territorial location, intended use and boundary situation, having thermal characteristics and energy parameters predetermined in accordance with Appendix A of Annex 1 of Ministerial Decree 26/6/15.

In Italian law, in fact, to be defined as NZEB, a building must have energy efficiency indices lower than the corresponding indices calculated on the reference building. These indices are:

- H'_T [kWh/m^{2}K]: overall average heat transfer coefficient for transmission per unit of dispersing surface area;
- $A_{sol,est}/A_{sup,utile}$ [-]: equivalent summer solar surface area per unit of useful surface area;
- g_{gl+sh} [-]: total solar transmission factor;
- η_H [-] :average seasonal efficiency of the winter air-conditioning system;
- η_w [-]: average seasonal efficiency of the domestic hot water production;
- η_c [-]: average seasonal efficiency of the winter air-conditioning system;
- EP_H [W/mK]: useful thermal performance index for heating;
- EP_c [W/mK]: useful thermal performance index for cooling;
- EP_{gl} [W/mK]: overall energy performance index of the building;

In addition, the minimum principles concerning the obligations of integration of renewable sources for summer and winter air conditioning and to produce domestic hot water must also be respected in the following quotas:

- 50% of the planned consumption for domestic hot water (55% for public buildings);

- 50% of the sum of planned consumption for heating, domestic hot water and cooling (55% for public buildings).

In Italy, unlike Denmark, the energy performance of the building changes depending on the location of the house and its S/V ratio, where S is the surface area dispersed to unheated rooms, and V the heated volume enclosed by S [11].

In both countries, energy labelling of buildings is mandatory. The purpose is to promote energy savings by showing the amount of energy consumed by a building and outlining energy saving possibilities. In Denmark it is mandatory to have an energy performance certificate (EPC) when selling or renting buildings. The energy labelling scale ranges from A to G, where A is divided into A2020, A2015 and A2010. A2020 concerns low-energy buildings, which consume only a small amount of energy, while G-labelled buildings consume the most energy [12].

The same applies to Italy, where the assignment of the energy class is done by taking the reference building as a model (class A4). The better the match with this model, the higher the energy class of the house [13].

It is difficult to compare the building's energy consumption due to the climatic zone assigned to the two countries, Denmark with an Oceanic climate and Italy with a Mediterranean/Continental climate, but the table below provides a comparison.

Table 5 - Building energy class table

Denmark		**Italy**	
kWh/m^2		kWh/m^2	
A2020	27	A4	(< 0.40) · EP_{gl} (<15)
A2015	<30.0 + 1.000/Area	A3	(0.40-0.60) · EP_{gl} (15-30)
A2010	<52.5 + 1.650/Area	A2	(0.60-0.80) · EP_{gl} (15-30)
B	<70.0 + 2.200/Area	A1	(0.80-1.00) · EP_{gl} (15-30)
C	<110 + 3.200/Area	B	(1.00-1.20) · EP_{gl} (31-50)
D	<150 + 4.200/Area	C	(1.20-1.50) · EP_{gl} (51-70)
E	<190 + 5.200/Area	D	(1.50-2.00) · EP_{gl} (71-90)
F	<240 + 6.500/Area	E	(2.00-2.60) · EP_{gl} (91-120)
G	>240 + 6.500/Area	F	(2.60-3.50) · EP_{gl} (121-160)
-	-	G	(>3.50) · EP_{gl} (>160)

1.4 Residential or non residential house

The number of NZEB and high-performance buildings in Europe, as shown by D'agostino et al. (2021), increased significantly from 2012 to 2016. In total, 1.238.184 NZEB buildings were constructed or renovated during this period. Most of them (22%) were built in 2014. The share of NZEBs in the total construction market increased from 2012-2016 (from 14% in 2012 to 20%).

In particular, residential buildings, divided into newly constructed residential buildings and residential renovations, represent the largest share (95.6%) over the total NZEBs in almost all European states [14]. For this reason, a single-family house was examined in this project.

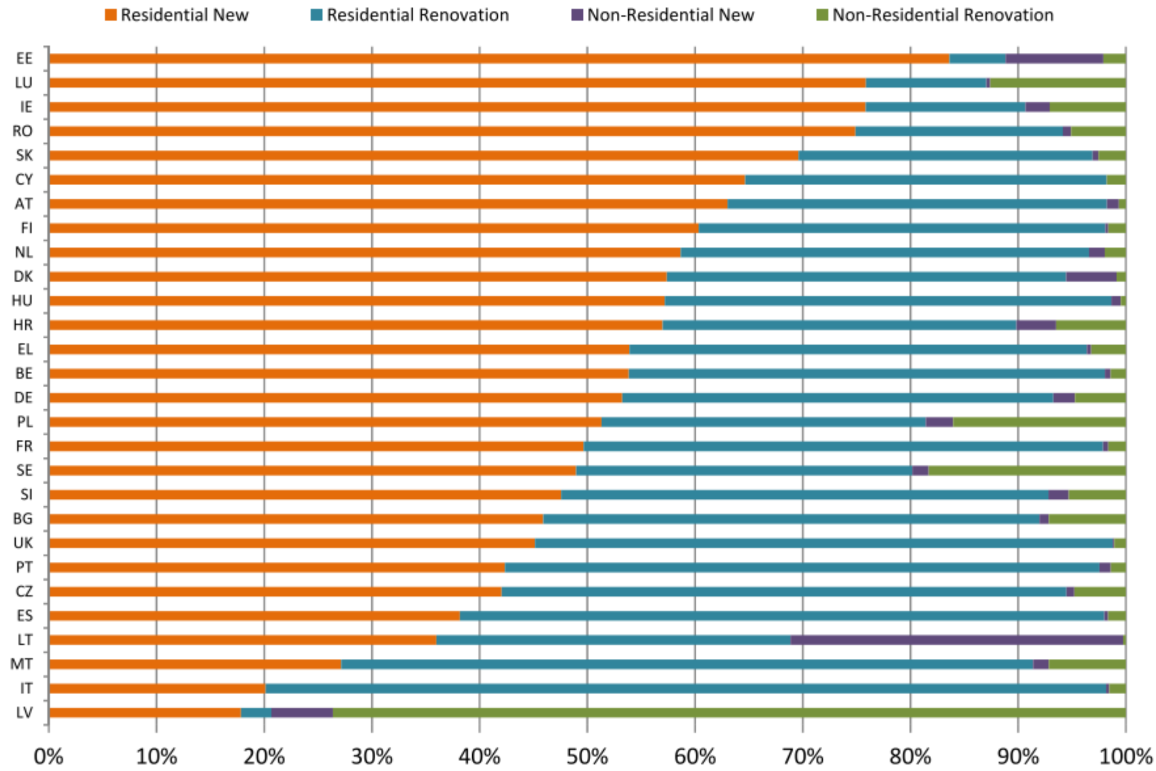

Figure 1 - NZEBs in 2016 in new residential and non-residential, existing residential and non-residential buildings per Member State

2. Case study

The following analysis concerns a residential one-storey detached house situated in Ry, a town in central Denmark. It is occupied by a young Danish couple with a toddler. They bought the house and moved in December 2021, but the year of construction is 2017. Before them, another family, also consisting of a young couple and a child, lived in the building.

The house was built as part of an EUDP (Energy Technology Development and Demonstration Programme) project called: Dwelling2020 with good indoor environment and high user comfort [15]. The aim of the project was to develop and demonstrate a second generation of low-energy housing after the Danish Building Class 2020.

2.1 Building description

The building consists of two volumes with a height difference of 0.53 m, designed to adapt the fabric to the gently sloping terrain. It is composed of 11 rooms: 1 dressing room, 2 bathrooms, 1 master bedroom, 3 rooms (bedrooms or offices), 1 kitchen-dining room, 1 living room, 1 technical room and 1 utility room. There is also an unheated space used as a storage room (warehouse). The total gross area is 160 m^2 and the treated volume is 360.6 m^3.

Figure 2 shows the floor plan and section of the house, while Figure 3 shows exterior views of the building.

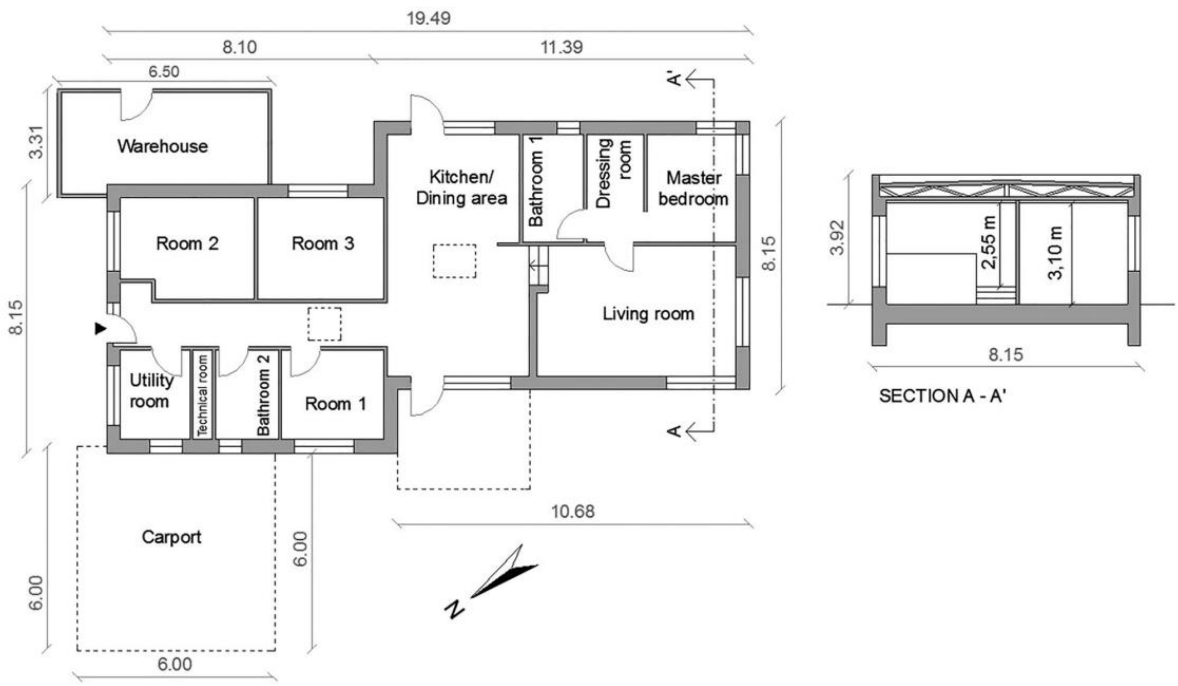

Figure 2 - Floor plan and section of the house

Figure 3 - External views of the house in Ry

The external walls have brick as layer and an inner layer of aerated concrete blocks, with a layer of mineral wool insulation in between. The roof is flat, and is made of reticular beams, OSB (Oriented Strand Board) panels and 41 cm of paper wool insulation. The inner side of the flat roof is finished with an acoustic plaster ceiling. The internal partitions are in aerated concrete blocks and have a thickness of 10 cm. The ground slab is in concrete, with 32 cm of EPS and a wooden floor.

The windows have a 48 mm triple pane glazing with argon, and composite aluminium and wood frames with thermal break. Table 6 summarises the transmittance values of main components.

Table 6 - Thermal transmittance of the opaque components of the building envelope

Building components	**U [W/m^{2}K]**
External walls	0.15
Flat roof	0.09
Ground slab	0.08

The main appliances are: 2 ovens, cooker plate, cooker hood, refrigerator, freezer, dishwasher, electric water heater, washing machine and dryer.

Artificial lighting consists of integrated LED spots throughout the house. There are also exterior façade lights and LED spots in the terrace and carport roof.

The house is also equipped with photovoltaic panels on the roof of the carport, with an output of 1.55 kWp.

2.2 System description

The house is equipped with a radiant floor heating system divided in 11 zones fed by district heating.

An Air Handling Unit (AHU), integrating an air-water heat pump, provides ventilation with heat recovery (86%) and the production of domestic hot water. More in the specific there is a Nilan Compact P with passive and active heat recovery, DHW heat pump system, bypass, and active cooling.

The integrated heat pump uses energy from the extracted air, not recovered by the heat exchanger, to produce domestic hot water.

When the heat pump integrated in the ventilation part does not produce domestic hot water, it can additionally heat the supply air and thus contribute to heating the house. This only occurs when the indoor temperature or the supply air temperature falls below the value specified in the settings.

The heat pump in the ventilation part is also reversible. This means that it can both heat and cool the supply air. When the outside temperature is above 14 °C, the unit operates in summer mode. If the indoor temperature becomes too high, the unit cools the indoor air according to the values specified in the settings. When cooling, the unit first attempts to do so via the bypass function. If this proves insufficient, it starts actively cooling via the heat pump.

The following figure shows the scheme of the ventilation and domestic hot water system.

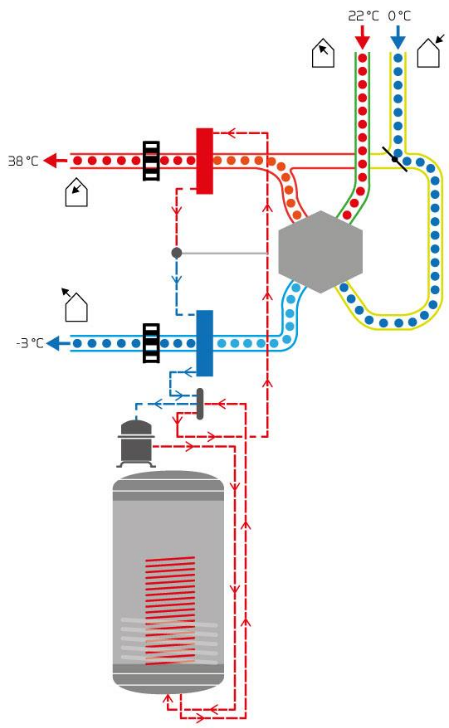

Figure 4 - Integrated heat pump that additionally heats the supply air and contributes to heating the house

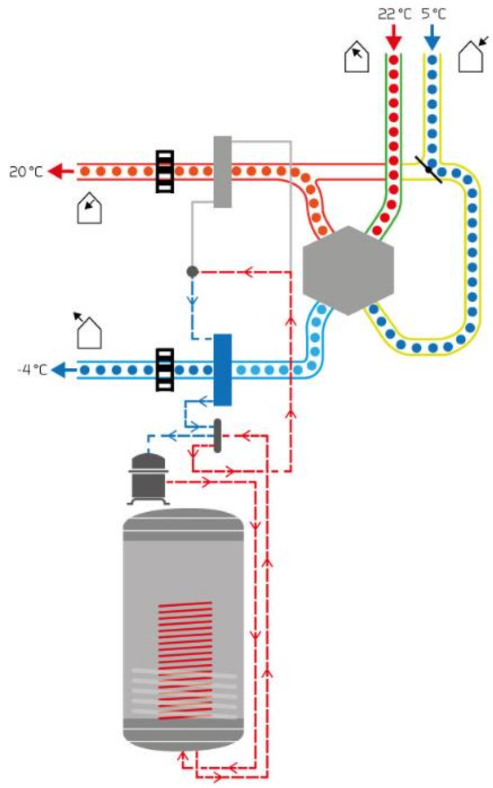

Figure 5 - Nilan AHU Compact scheme focuses on the heat pump that utilises energy from extracted air

The house is equipped with solar shading (4 horizontal shutters), with manual on/off controlled by IHC (Intelligent House Control).

The shutters are automatically controlled by the room temperature in the bedroom and living room, there is also the possibility of controlling them manually. Two roller shutters in the bedroom are controlled as one, while the two living room shutters are controlled individually.

The IHC, in addition to controlling the solar shading shutters, also controls underfloor heating actuators in each room and skylight openings based on temperature setpoints.

Two skylights with automatic mechanical opening are installed on the roof, one at the corridor and the other at the kitchen/dining room. They are automatically controlled by IHC according to temperature setpoints or they can also be controlled by the user.

Lights can be manually controlled on/off by the Intelligent Control in its.

Concerning the natural ventilation, five openings with fixed shutters were installed on the façades and the opening areas are controlled by the opening of a hatch behind the shutters. In the previous research project, the openings were controlled automatically. However, due to the noise of the mechanical chain actuator, the actuators were removed and the openings are controlled manually in the facades.

Figure 6 - Shutters and skylight of the building

The Schneider PLC (Programmable Logic Controller) registers all the parameters like temperature, CO2, relative humidity, water volume flow, air volume flow, etc. While the ventilation system's air volume flow rate (0-100 %) is controlled by the Nilan control.

The following table shows each type of sensor and the number of those currently installed in the house, the parameters monitored and their acquisition rate are also indicated.

Number	Kind	Acquisition rate	Measures	Manufacturer
1	Day/night switch	-	Illuminance (lux)	LK IHC
6	IE sensor GMW95R	5 minutes 2 minutes from 3/6/22	Temperature (°C), CO_2 (ppm), and RH (%)	Vaisala
10	IE sensor IHC Control LK Fuga	5 minutes 2 minutes from 3/6/22	Temperature (°C), and RH (%)	Schneider
1	Water volume meter – Multical 62, Domestic cold water	5 minutes 2 minutes from 3/6/22	Water volume flow (l/h)	Kamstrup
4	Energy meter – Multical 603, District heating in total, for DHW production and floor heating shunt. One for DHW	5 minutes 2 minutes from 3/6/22	Water volume flow (l/h), supply and return temperature (°C)	Kamstrup
2	Ultralink, Total air supply and extraction	5 minutes 2 minutes from 3/6/22	Air volume flow (m3/h)	Lindab

1	Compact P AHU	5 minutes 2 minutes from 3/6/22	Air temperatures (°C), Relative Humidity (%) and Fan Speed (%)	Nilan

3. Be18 model

Danish legislation requires that new buildings calculate energy consumption using Be18. It uses monthly quasi-steady state calculations and is developed to be used for conformity verification and energy certification of Danish buildings.

This analysis was done to identify the position of the house within an energy framework, despite its known high technological performance. In addition, by deriving the energy requirements of the house, it is possible to make a comparison with current consumption and investigate the reasons for any differences in energy use.

3.1 Input data

The following table shows the main input data of the house typed into the software.

Type	**Detached house**
Heated floor area	157.74 m^2*
Heat capacity	47 Wh/m^2K
Normal usage time	168 h/week
Rotation	56°
Heat supply	District heating
Other contributions	Solar cells, heat pump for DHW
* In the calculation of the heated area, there is no storage area because it is an unheated space	

For residential buildings it is assumed that the occupancy time is 24/7. Furthermore, lighting is not taken into account for residential houses, it is only included for buildings other than residential. The energy performance framework of the Building Regulations, in fact, indicates an upper limit for a newly erected building's total need for supplied energy to heating, ventilation, cooling, and domestic hot water.

The thermal capacity was calculated according to the SBi 2013 instructions, a guide from the Danish Building Research Institute at Aalborg University in Copenhagen for calculating the energy requirements of a building [16]. It is mainly the interior wall, ceiling, and floor surfaces that are important for the thermal capacity of the building, while windows, doors, and fixtures are of less importance.

In particular, the compactness of the building can be small, medium, or large and has respectively 0.65, 0.45, 0.25 that are obtained by the external wall area, includes windows and doors, per floor area. In this case, due to the fraction of the external wall area and the heated floor area, the building has small compactness.

$$\frac{External\ wall\ area}{Heated\ floor\ area} = \frac{166.31}{157.74} = 1.05$$

Also, the room sizes can be small, medium, or large and correspond respectively to 2.00, 1.00, and 0.60 m^2 partition area per m^2 floor area. The house has a medium room size.

$$\frac{Internal\ wall\ area}{Heated\ floor\ area} = \frac{230.54}{157.74} = 1.46$$

For the examined house, the values are:

External walls	Aerated concrete	10 Wh/m^{2}K
Floor	Wooden floor with fiber on concrete	17 Wh/m^{2}K
Partition wall	Aerated concrete	7 Wh/m^{2}K
Roof/ceiling	Gypsum boards	3 Wh/m^{2}K
Fixtures	-	10 Wh/m^{2}K

The total heat capacity of the building is, therefore, $10 + 17 + 7 + 3 + 10 \ = \ 47$ Wh/m^{2}K.

3.1.1 Weather data

The programmes use the average outdoor conditions for each month. The weather data come from the Danish design reference year, DRY, updated in autumn 2013.

With regard to dimensioning temperature, the outside temperature is normally -12 °C. In the calculation, the same ambient temperature is used everywhere, normally 20 °C, even, for example, in bathrooms.

The design floor temperature used for underfloor heating is 29°C. International standards recommend a floor temperature between 19°C and 29°C in the occupied zone for rooms with sedentary and/or standing occupants wearing normal shoes. While the floor dimensioning temperature is 10°C.

The temperature factor, b, takes into account two conditions:

- The difference between the annual mean external temperature and external design temperature;
- The difference between the temperature of the unheated space and the external design temperature.

The temperature factor is 1.0 for most buildings, but for new buildings with a design flow temperature for underfloor heating of approximately 35 °C, the temperature factor correction b = + 0.3, so the resulting temperature factor becomes b = 1.0. Thus, the ground floor has a temperature factor of 1 instead of 0.7.

3.1.2 External walls, roofs, floors and foundations

This section considers the heat loss caused by the building's external walls, roof and floor. The area and thermal transmittance values of each surface were entered into the Be18 software in order to calculate the loss dispersed to the outside, as shown in Figures 7 and 8. As might be expected, the greatest heat loss is caused by the outer walls of the building.

The detailed construction of each surface of the building is shown in Appendix A.

	External walls, roofs and floors	Area (m²)	U (W/m²K)	b	Ht (W/K)	Dim.Inside ((	Dim.Outside	Loss (W)
		481.79		CtrlClick	51.7623			1769.97
1	Exterior wall	166.31	0.15	1.00	24.9465			798.288
2	Roof/ceiling	157.74	0.09	1.00	14.1966			454.291
3	Ground deck	157.74	0.08	1.00	12.6192	29		517.387
4		0	0	0.00	0			0

Figure 7 – Transmission loss exterior wall, roof, ground floor

The 'Foundations' module concerns the transmission loss of the foundations of the external walls and the joint at the windows. In this part, the thermal bridge loss [m] of these elements and, in addition, the linear loss [W/mK] must be calculated.

The temperature factor for the foundation is 1.3 due to the heated floor and its linear loss is 0.13 W/mK.

As stated in the Danish Building Regulations 2018, the linear loss due to joints between external walls, windows, external doors, glazed external walls, gates and hatches is 0.06 W/mK, and the linear loss due to joints between roof construction and skylights or skylight domes is 0.2 W/mK.

The following figure shows the total transmission losses.

	Foundations and joints at windows	l (m)	Loss (W/mK)	b	Ht (W/K)	Dim.Inside ((	Dim.Outside	Loss (W)
		176.562		CtrlClick	15.5791			493.242
1	Foundation	67.8	0.13	1.30	11.4582	29		361.374
2	Joint between window at the bottom and wall	100.962	0.03	1.00	3.02886			96.9235
3	Joint between roof construction and skylight	7.8	0.14	1.00	1.092			34.944

Figure 8 - Transmission loss foundation and joints

3.1.3 Windows and external doors

The windows are of the VELFAC 200 Energy type with triple glazing. In this module, it is important to calculate the orientation of the window, its inclination, surface area, and various other factors as:

- Ff [-]: indicates, in fraction, how large the total transmission area of the glass is;
- g factor [-]: is the solar thermal transmittance;
- Shading: the shadows of windows and external doors are determined by reference to the Shadows table.
- Fc [-]: is the sun shading factor. If there is no solar shading, the factor is 1.0. For windows with solar shading, the factor is less than 1.0. In particular, the windows in the bedroom and living room have automatically controlled external solar shading, so the Fc is of 0.13. The rest of the building have manually controlled internal solar shading with an Fc = 0.8, while the skylight has no solar shading.

The considered area is without the width of the frame.

	Windows and outer doors	Numbe	Orient	Inclinatio	Area (m²)	U (W/m²K)	b	Ht (W/K)	Ff (-)	g (-)	Shading	Fc (-)	Dim.Insid	Dim.Outs	Loss (W)	Ext
		18			37,26		CtrlClick	32,4073			CtrlClick				1037,03	0/1
1	Door Hallway NE	1	NE	90	2	0,64	1,00	1,28	0	0		1			40,96	0
2	Door Hallway Glass NE	1	NE	90	0,74	1,22	1,00	0,9028	0,65	0,49		0,8			28,8896	0
3	Door kitchen Glass SE	1	SE	90	1,87	0,81	1,00	1,5147	0,83	0,49		0,8			48,4704	0
4	Door dining room Glass NW	1	NW	90	4,41	0,85	1,00	3,7485	0,84	0,49		0,8			119,952	0
5	Door utility room NW	1	NW	90	1,99	0,64	1,00	1,2736	0	0		1			40,7552	0
6	Window living room NW	1	NW	90	4,42	0,84	1,00	3,7128	0,85	0,49		0,13			118,81	1
7	Window living room SW	1	SW	90	4,42	0,83	1,00	3,6686	0,81	0,49		0,13			117,395	1
8	Window bedroom SW	1	SW	90	2,51	0,94	1,00	2,3594	0,74	0,49		0,13			75,5008	1
9	Window bedroom SE	1	SE	90	1,96	0,88	1,00	1,7248	0,78	0,49		0,13			55,1936	1
10	Window bathroom NW	1	NW	90	0,72	0,95	1,00	0,684	0,75	0,49		0,8			21,888	0
11	Window bathroom SE	1	SE	90	0,72	0,95	1,00	0,684	0,75	0,49		0,8			21,888	0
12	Window kitchen SE	1	SE	90	1,61	1,01	1,00	1,6261	0,71	0,49		0,8			52,0352	0
13	Window Room 1 NW	1	NW	90	2	0,87	1,00	1,74	0,79	0,49		0,8			55,68	0
14	Window Room 3 SE	1	SE	90	2	0,87	1,00	1,74	0,79	0,49		0,8			55,68	0
15	Window Room 2 NE	1	NE	90	2	0,87	1,00	1,74	0,79	0,49		0,8			55,68	0
16	Window Utility room NE	1	NE	90	2	0,87	1,00	1,74	0,79	0,49		0,8			55,68	0
17	Skylight Hallway	1		0	0,81	1,2	1,00	0,972	0,67	0,54		1			31,104	0
18	Skylight Dining room	1		0	1,08	1,2	1,00	1,296	0,67	0,54		1			41,472	0

Figure 9 - Transmission loss windows and outer doors

From the entered information about the building components, Be18 calculates the specific transmission loss [W].

3.1.4 Ventilation

The house has a mechanical ventilation system composed of Nilan AHU Compact P with heat recovery, active heating, DHW heat pump system, bypass, and active cooling.

A housing unit is generally considered to be a ventilation zone, although air mainly enters the occupied rooms and leaves the kitchen, the utility room and the bathrooms.

Regarding input data, there is:

- F0 [-]: is the operating time and for a house is 1, because it indicates the operating time of the ventilation system of the building;
- q_n [l/m^{2}s]: is the outside air flow rate in the supply system divided by the surface area of the served area during the period of use in winter;
- ηvgv [-]: is the temperature efficiency of the heat recovery and it corresponds to 0.86 as indicated in its technical schedule;
- ti [°C]: is the supply temperature, and in ventilation systems with both a temperature-regulated heat recovery unit and a temperature-regulated heating surface, like in this case, a supply temperature of 18 °C is assumed;
- q_n [l/m^{2}s]: is the infiltration in winter during the period of use;
- EL-HC [-]: there isn't an electric heating system in the ventilation unit, so there is 0 in the board;

- SEL [kJ/m^3]: is the specific electricity consumption for air transport for the fans, including control equipment and the like, divided by the external air flow rate transported. For this system, the SEL at average airflow (275 m^3/h) is 800 J/m^3;
- $q_{m,s}$ [l/m^{2}s]: is the maximum ventilation that the mechanical ventilation system can provide during hot summer days. This should be 0.3 $\frac{l}{s \cdot m^2}$ since the system use natural ventilation if the temperature is too high in summer periods.
- $q_{n,s}$ [l/m^{2}s]: is the maximum natural ventilation in summer during the period of use;

In all rooms of a building, during winter, ventilation of at least 0.3 liters/sec per m^2 of heated floor area is assumed.

Furthermore, in all rooms, even those that do not face outside, an infiltration of 0.13 liters/sec per m^2 of the heated surface area during the period of use.

The value for summer must normally be at least the same as the value for winter.

In homes with manually controlled windows can be assumed a ventilation of 2 liters/sec per m^2 of the heated surface, as an average during the hottest summer periods. This value was chosen to avoid overheating of rooms during critical periods.

	Ventilation	Area (m²)	Fo, -	qm (l/s m²)	n vgv (-)	ti (°C)	El-HC	qn (l/s m²)	qi,n (l/s m²)	SEL (kJ/m³)	qm,s (l/s m²	qn,s (l/s m²)	qm,n (l/s m²	qn,n (l/s m²
	Zone	157,74		Winter			0/1	Winter	Winter		Summer	Summer	Night	Night
+1	Whole house with mechanical ve	157,74	1	0,3	0,86	18	0	0,13	0	0,8	0,3	0,9	0	0

Figure 10 - Input data for ventilation

3.1.5 Internal heat supply

The internal heat supply form includes the heat generated by people and all kinds of machines inside the house. The area of the zones is calculated in the same way as the heated floor area of the building.

In homes, it is assumed an average heating contribution from people of 1.5 W per m^2 heated floor area, and an average heat gain from equipment, without lighting, is assumed to be 3.5 W per m^2 heated floor area.

Since homes are assumed to be in use all the time, there isn't equipment consumption outside the period of use.

	Internal heat supply	Area (m²)	Persons (W/m²)	App. (W/m²)	App.night (W/m²)
	Zone	157,7	236,6 W	552,1 W	0,0 W
1	The whole building	157,74	1,5	3,5	0

Figure 11 - Internal heat supply

3.1.5 Heating system

In whole the building there is underfloor heating (UFH) that is supplied by district heating. The supply temperature is set to 47 °C, while the return temperature is approx. 36°C. These values are obtained by averaging the data measured by the house sensors during the analysed period, from December 2021 to the end of May 2022. In the building there is a dual plant.

In this case, there is only one pump for the underfloor heating, which is time control. The nominal power, P_{nom}, is the electrical power used by the pump at its maximum level, including control and automation equipment. It is assumed a value of 34 W, as suggested in the Grundfos circulation pump data sheet.

The reduction factor, Fp, indicates the ratio between the electrical power input, averaged over the running time of the pump compared to the nominal power of the pump itself. The reduction factor is typically 0.8 for multistage pumps with manual settings of the operating stages.

3.1.6 Domestic hot water and heat pump

In homes, annual consumption of domestic hot water of 250 liters per m^2 heated floor area is assumed to be evenly distributed over the year, and it is also assumed to be heated to at least 55 °C. But the actual consumption of this house is 15.90 m^3 for six months, which corresponds approximately to 200 l/m^2 per year.

The DHW tank, installed in the house, has a volume of 180 liters.

The average measured value of the domestic hot water flow temperature over the six months analysed, based on the measurements, is approximately 55 °C. As a rule, the temperature difference to generation is 5-10 °C, so, the supply temperature from the heat pump (central heating) becomes 60-65 °C depending on the heat transfer efficiency. It is assumed a value of 60 °C.

The hot water, as said, is produced by an air to water heat pump system, so the hot water tank is electrically heated. It is in the technical room, so the temperature factor can be considered as 1.

For heat pumps supplying heat to a ventilation system, a negative number below the surface share if there is also another heating system in the room. In fact, in this case the ventilation covers only parts of the heated floor area, so the value is -1.

In domestic water heating, the nominal effect is the power that the heat pump provides to the domestic hot water. While the nominal COP is the efficiency of the heat pump at maximum output and at the same test temperatures used to determine the nominal output.

The heat pump installed has a rated heating capacity of 40 kW and a COP of 3.2.

There is the section specifies the test temperatures used to determine the heat pump's performance and efficiency.

The integrated heat pump uses the energy of the extracted air, that has not been recovered by the heat exchanger, to produce domestic hot water. For the selected system, as specified in the guide, the heat pump has:

Heat pump type	Cold side	Warm side
Outside air	7 °C	60 °C

The power consumption of the condenser water pump is 100 W.

The temperature efficiency of the heat recovery unit in the ventilation system before the heat pump is of 86%. Considering the winter ventilation air flow, it is:

$$0.3\ \frac{l}{s \cdot m^2} \cdot 157.74\, m^2\ =\ 48\ \frac{\mathrm{l}}{s}$$

$$\frac{48\ \frac{l}{s}}{1000\ \frac{l}{m^3}}\ =\ 0.048\ \frac{\mathrm{m}^3}{s}$$

So, this means an average value of $172.8\ \frac{m^3}{h}$.

3.1.7 PV panels

The house has also electricity production from horizontal photovoltaic panels. They have 1.55 kWp and are installed on the carport roof, with an NW orientation. The panel area is of 13,5 m^2, because there are 9 solar panels each of 1.5 m^2.

The efficiency of the solar panel system, that takes into account losses from cables and inverter, is supposed to be of 75%.

3.1.9 Results

The form contains information on the energy picture, energy requirements, and key figures of partial consumption. The table of key figures contains the most important results of the calculation.

The energy framework corresponds, respectively, to:

- Renovation class 2;
- Renovation class 1;
- Energy framework BR18;
- Energy framework low energy.

The total energy demand of the building is the energy demand for the operation of the building divided by the heated surface area. It is this value that must comply with the energy framework of the building regulations.

From the analysis with be18, the building in question obtained the following results in terms of total energy requirement:

	Total energy frame [kWh/m^2 y]	Total energy requirement of the house [kWh/m^2 y]
Renovation class 2	83.9	17.1
Renovation class 1	63.0	17.1
Energy frame BR 2018	36.3	17.1
Energy frame low energy	27.0	17.1

The house, therefore, meets the energy limits imposed by the latest legislation and is also a low-energy house with a total energy requirement of 17.1 kWh/m^2 y.

4. Comparison of energy consumption

This chapter is an analysis of the actual energy consumption of the building, regarding electricity, district heating and the indoor climate of the house. In addition, a comparison was made with the consumption of the previous three years, when another family lived in the house.

The purpose of this chapter is to carry out an in-depth analysis of the energy consumption of the house, which was found to be in the lowest consumption class. In this way, it is possible to detect possible system failures related to out-of-scale consumption and to see the impact of different occupants' behaviour over the years, given also the alternation of two different households.

4.1 Actual family consumption

The cumulative log data were available with the recording occurring every 5 minutes in all rooms of the house. The file was changed to an hourly dataset using the maximum value of each hour, then calculated their differences to obtain the actual consumption and not the cumulative result.

There were about 70 parameters recorded, covering energy consumption, hot water quantity, air flow rate, indoor conditions.

There are sensors for measuring temperature, CO_2, and RH in all the rooms. The measured temperature is used by the IHC to control the underfloor heating for each room, solar shading, and skylight openings.

The current family moved into the house in December 2021, so this first month will probably not be very representative because the new tenants were moving in.

The following table shows the habits of current tenants in a normal week.

Table 7 - Occupancy schedule of the actual family

Time	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
05:00 - 06:00	X	/	X	X	X	X	X
06:00 - 07:00	X	/	X	X	X	X	X
07:00 - 08:00	X	/	/	/	/	X	X
08:00 - 09:00	X	/	+	+	+	X	X
09:00 - 10:00	X	/	+	+	+	X	X
10:00 - 11:00	X	/	+	+	+	X	X
11:00 - 12:00	X	/	+	+	+	X	X
12:00 - 13:00	X	/	+	+	+	X	X
13:00 - 14:00	/	/	+	+	+	X	X
14:00 - 15:00	/	/	+	+	+	X	X
15:00 - 16:00	/	X	+	+	+	X	X
16:00 - 17:00	/	X	/	/	/	X	X

17:00 - 18:00	/	X	/	/	/	X	X
18:00 - 19:00	/	X	/	/	/	X	X
19:00 - 20:00	/	X	X	X	X	X	X
20:00 - 21:00	/	X	X	X	X	X	X
21:00 - 22:00	/	X	X	X	X	X	X
22:00 - 23:00	X	X	X	X	X	X	X
23:00 - 24:00	X	X	X	X	X	X	X
- Both home = X - One home = / - Both out = +							

It can be seen that on Mondays they both work from home during the morning and in the afternoon only one of them does, while on Tuesdays the opposite happens, and both usually spend the weekend at home. Then, on the other days, they return home in the afternoon but at different times.

For the former family, on the other hand, it is known that they usually spent most of their time away from home, also because each of them worked in an office. So, in practice, it was assumed that they were at home from 5pm to 8am.

In this analysis, the period from the beginning of December 2021 until the end of May 2022 will be analysed, as the current family moved in at the very end of the year 2021. Furthermore, in June 2022 the HVAC system had problems with active cooling, so the data cannot be considered realistic.

4.1.1 Actual energy consumption for heating

Heat energy meters are installed in the technical room to measure the flow rate, supply temperature and return temperature for:

- Total district heating;
- District heating with derivation from underfloor heating;
- District heating for domestic hot water production;
- Domestic hot water (the measured temperature is that of cold and hot water and the volume flow is that of domestic hot water);
- Domestic cold water (volumetric flow only).

In this analysis, it was considered the consumption due to the Total district heating.

The accuracy of the meters does not allow a result below kWh, unlike electricity consumption.

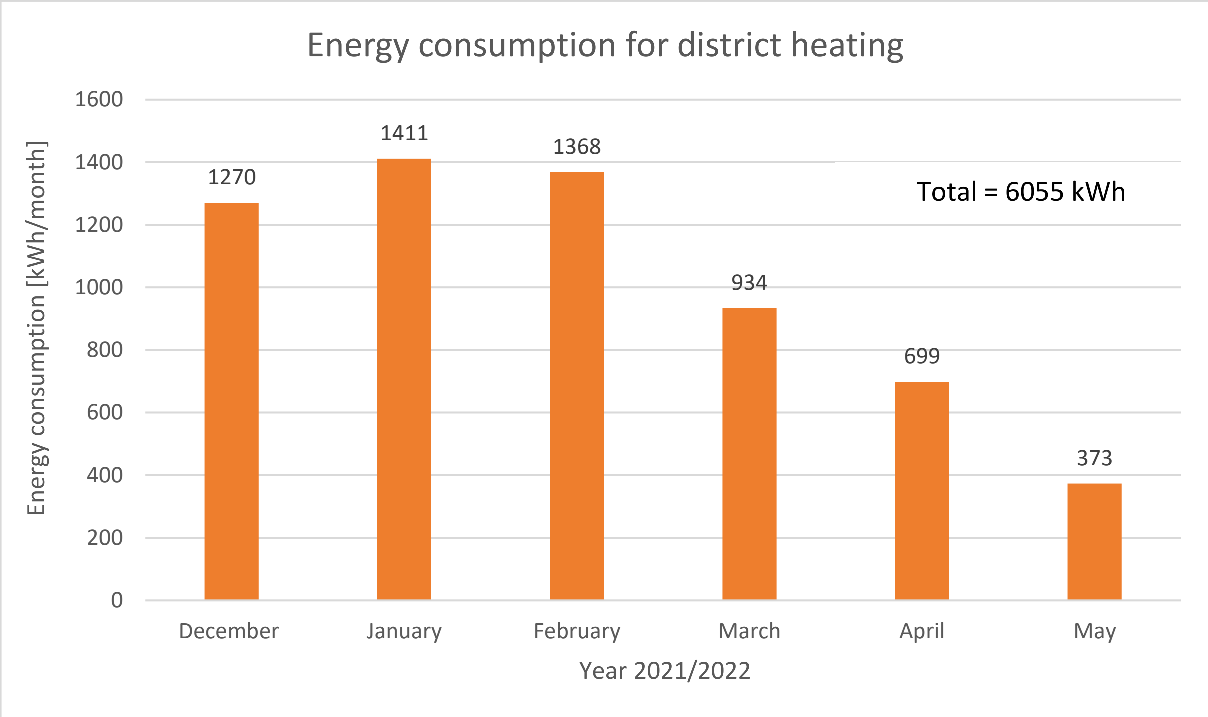

Figure 12 - Energy consumption for district heating

As was to be expected, in the winter months (December, January, February) we see the highest consumption due to heating, which is the period when there is normally a higher utilisation of the heating system.

4.1.2 Actual energy consumption for electricity

The house has several electricity meters, either covering the entire use of this carrier or broken down by individual device. In particular, electricity consumption is divided into:

- Nilan Compact P ventilation unit (including the heat pump for domestic hot water production);
- Household appliances;
- Control system: solar shading, skylight openings, IHC, PLC, circulation pump for underfloor heating, and IE sensors;
- Floor heating pump.

Household appliances are in turn subdivided into:

- Cooking plate + 2 ovens;
- Fridge + cooker hood + wine cooler;
- Washing machine;
- Dryer;
- Dishwasher;
- Electric water heater;
- Other consumption: lighting and plug loads.

This is the total electricity that the dwelling demands from the grid, which will be called 'measured'. The single meter used for this measurement considers the entire demand of the house.

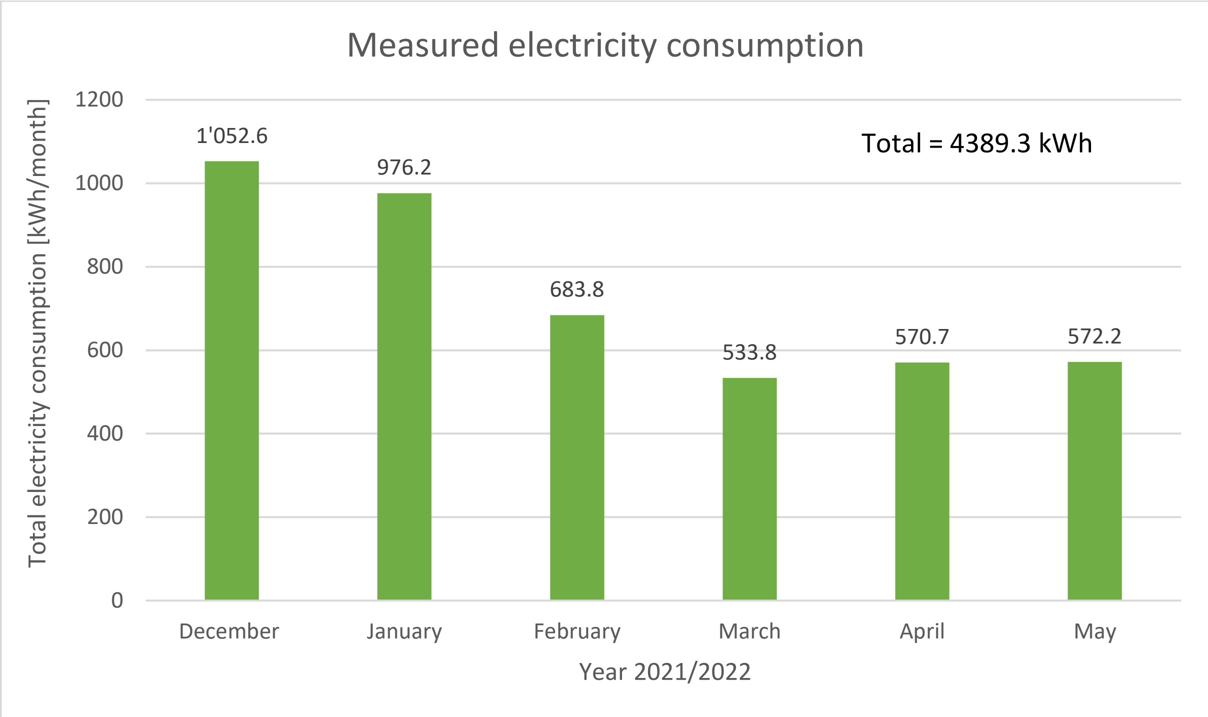

Figure 13 – Total electricity consumption measured by individual meter

The bar graph below (Fig. 14), on the other hand, shows the result of the total electricity consumption obtained by summing up the contribution of all electrical appliances in the house via each meter, which will be called calculated. This includes: Nilan Compact P ventilation unit (including the heat pump for domestic hot water production), household appliances, control system and floor heating pump.

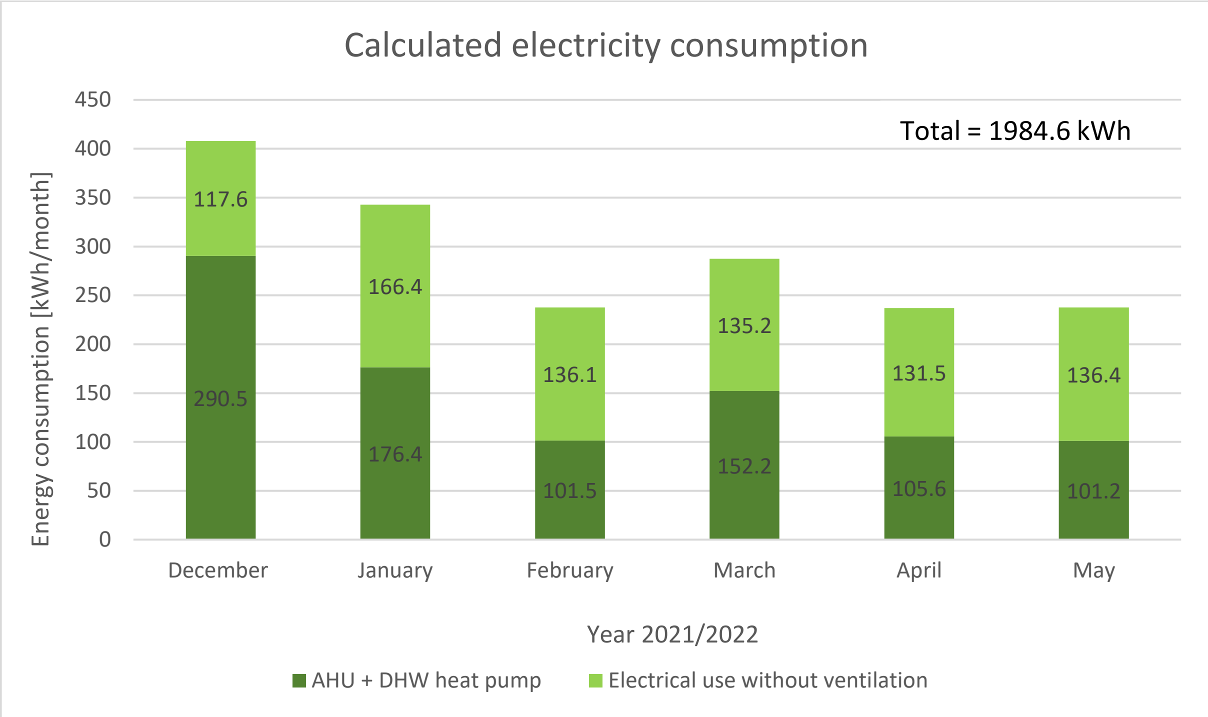

Figure 14 - Total electricity consumption summing Nilan ventilation unit with DHW heat pump, white goods, system control, floor heating pump

There is a huge difference between the total electricity consumption and the sum of the electricity contribution of each item; a fuller explanation is given in the paragraph 4.2.1.

However, December and January turn out to be the months with the highest electricity consumption, mainly due to the use of the AHU system.

4.1.3 Actual energy consumption for ventilation and DHW

It is interesting to analyse the electricity consumption due to the Air Handling Unit in more detail, especially considering the trend of electricity used during the analysed period. The AHU of the house, as mentioned, consists of a heat recovery system, active heating, heat pump for domestic hot water, bypass and active cooling.

It is not possible to distinguish between electricity to produce domestic hot water and to the fans of the ventilation, so the following results for electricity represent both.

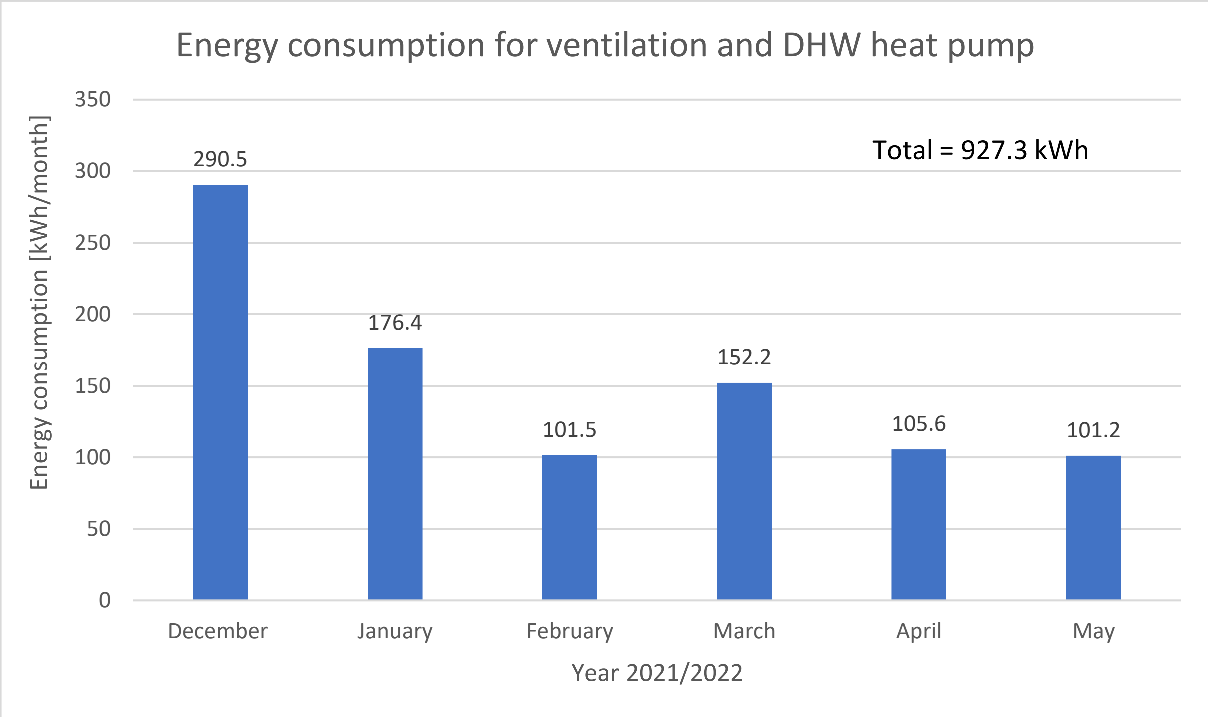

Figure 15 - Energy consumption for ventilation and domestic hot water heat pump during the selected period

As it is possible to see from the graph above, the consumption in December is quite higher than in the other months. This difference in consumption could be due to both the higher utilisation of the AHU and the higher consumption of domestic hot water, and thus the higher electricity consumption of the heat pump. For this reason, it is useful to analyse the use of DHW during this period.

4.1.4 Actual water consumption

Cold water consumption is the total amount of water supplied to the household. Part of the total amount of cold water is heated, resulting in hot water consumption.

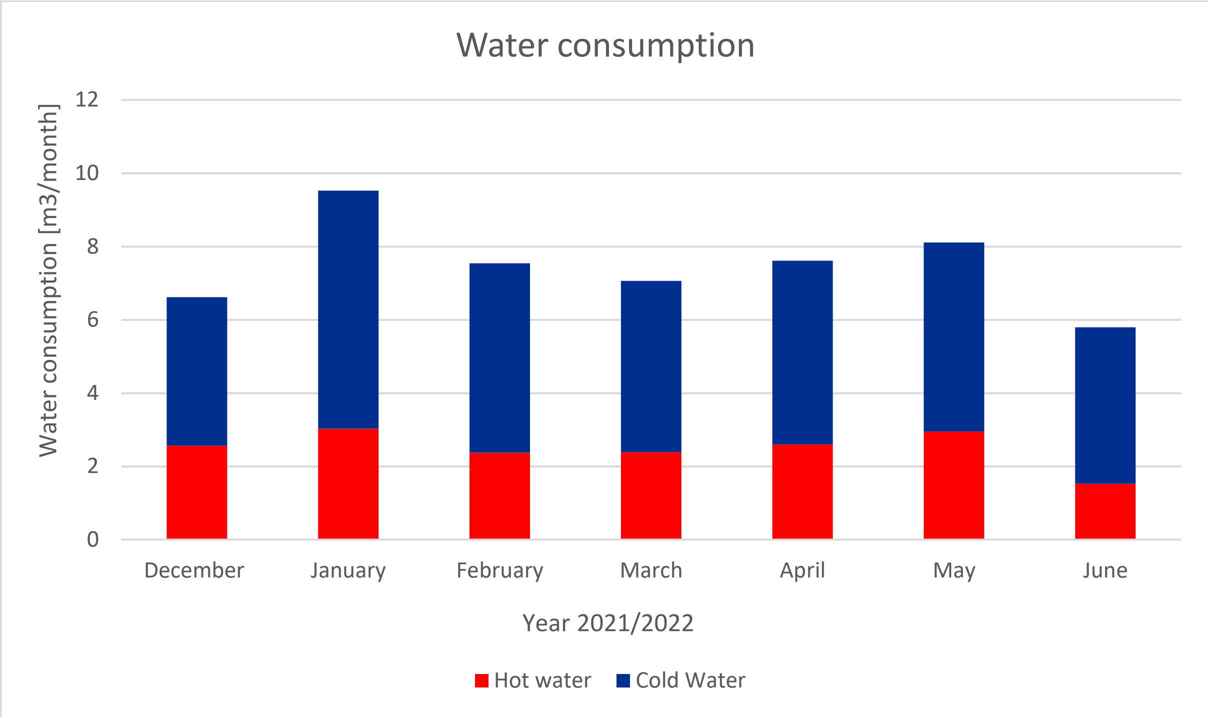

Figure 16 - Water consumption

The consumption of domestic hot water in December was in line with other monthly consumption. This means that the higher electricity consumption in December is only due to the higher use of the AHU.

In turn, this can be caused either by a direct household need, such as to increase the indoor climate of the house, or by a system failure.

4.1.5 Primary energy consumption

The following figures illustrate the primary energy consumption, expressed in [kWh] and [kWh/m^2]. The values are calculated from the energy consumption for heating and electricity, multiplied by the primary energy factors used in Denmark, 0.85 and 1.9 respectively.

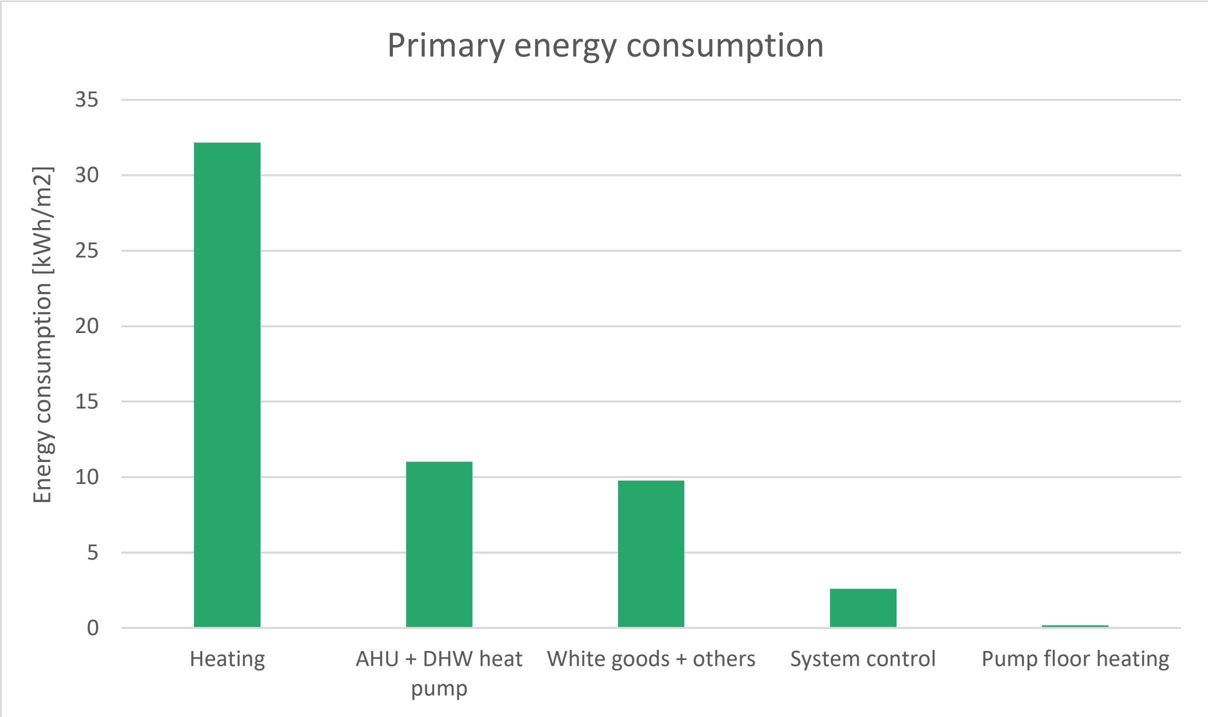

Figure 17 - Yearly primary energy consumption for heating and electricity (December – May)

The model in Be18 provided a value of primary energy required by the house of 17.1 kWh/m^{2}y, which puts the building on the voluntary 'low energy' line of the BR 2018 (PE < 27 kWh/(m^{2}y)).

This value, however, is due to the installation of 13.5 m^2 of photovoltaic system. Using Be18 without the addition of photovoltaics results in an energy requirement of 42.1 kWh/m^{2}y.

The comparison, therefore, was made between the latter result and the sum of the primary energy shown in Figure 27, because in the logfile with the measured consumption there is no contribution from the photovoltaic panels, assuming that the final value of the primary energy required by the building is double that calculated in the first six months, excluding the consumption of the white goods and control systems which are not considered in the Be18 software.

Primary energy consumption [kWh/m^2]	
Be18	Actual
42.1	86.7

Although this analysis is only an estimate, one can see the significant difference between the two results. This result demonstrates the possible discrepancies between the expected NZEB building energy performance and the actual performance. The gap between expected and actual energy consumption may be due to several factors, the most important of which are occupancy profiles, differences in internal heat gain and possible system failures.

4.1.6 Indoor environment analysis

The indoor environmental quality is evaluated by the thermal and atmospheric indoor climate. More specifically, the examined parameters are the room temperature [°C], CO2 level [ppm], and relative humidity level [%]. The rooms are examined on a daily level (24 hours).

The thermal criteria are assessed according to the comfort categories given by the standards EN 16798-1:2019 [17]. It assumed an activity level of 1.2 met (sedentary activity).

For the adapted approach, the criteria for the operative temperature categories are taken from Figure B.5 in EN 16798-1.

The standards recommend that the heating season is defined with mean running mean outdoor temperature below 10 °C, while the cooling season is defined with mean current outside temperatures above 15 °C. However, it is questionable whether heating-cooling should be assumed in the transition period between winter and summer. Therefore, in this analysis, May is calculated for the summer comfort zone, while winter conditions are assumed for December-April.

The following graphs shows the temperature ranges for the hourly calculation of cooling and heating energy in four indoor room categories, according to the adapted approach. The following tables also show the percentage of hours in each category for the different months.

In Denmark, thermal comfort criteria are mandatory for residential buildings. In particular, the internal temperature of residential buildings must not exceed 27 °C for more than 100 hours per year and 28 °C for more than 25 hours per year.

Table 8 - Temperature ranges for hourly calculation of cooling and heating energy in four categories of indoor environment [17]

<table>
<tr><th>Type</th><th colspan="2">Category</th><th>I</th><th>II</th><th>III</th><th>IV</th></tr>
<tr><td rowspan="2">Residential buildings, living spaces</td><td rowspan="2">Operative temperature [°C]</td><td>Winter</td><td>21.0-25.0</td><td>20.0-25.0</td><td>18.0-25.0</td><td>17.0-25.0</td></tr>
<tr><td>Summer</td><td>23.5-25.5</td><td>23.0-26.0</td><td>22.0-27.0</td><td>21.0-28.0</td></tr>
</table>

Internal temperatures above the setpoint indicated in the standard are reported as category II+, III+, IV+ and V, also to identify whether the building exceeds the temperature limits.

Table 9 - Adjustment of temperature intervals suggested by the standard to check exceeding of limits

	IV	III	II	I	II+	III+	IV+	V
Winter	17 ≤ t < 18	18 ≤ t < 20	20 ≤ t < 21	21 ≤ t ≤ 25	25 < t ≤ 26	26 < t ≤ 27	27 < t ≤ 28	t > 28
Summer	21 ≤ t < 22	22 ≤ t < 23	23 ≤ t < 23.5	23.5 ≤ t ≤ 25.5	25.5 < t ≤ 26	26 < t ≤ 27	27 < t ≤ 28	t > 28

Three rooms, bedroom, kitchen and living room, representative of the entire building, are shown below.

The distribution of hours in each category is shown in percentages, in the form of bar charts and tables.

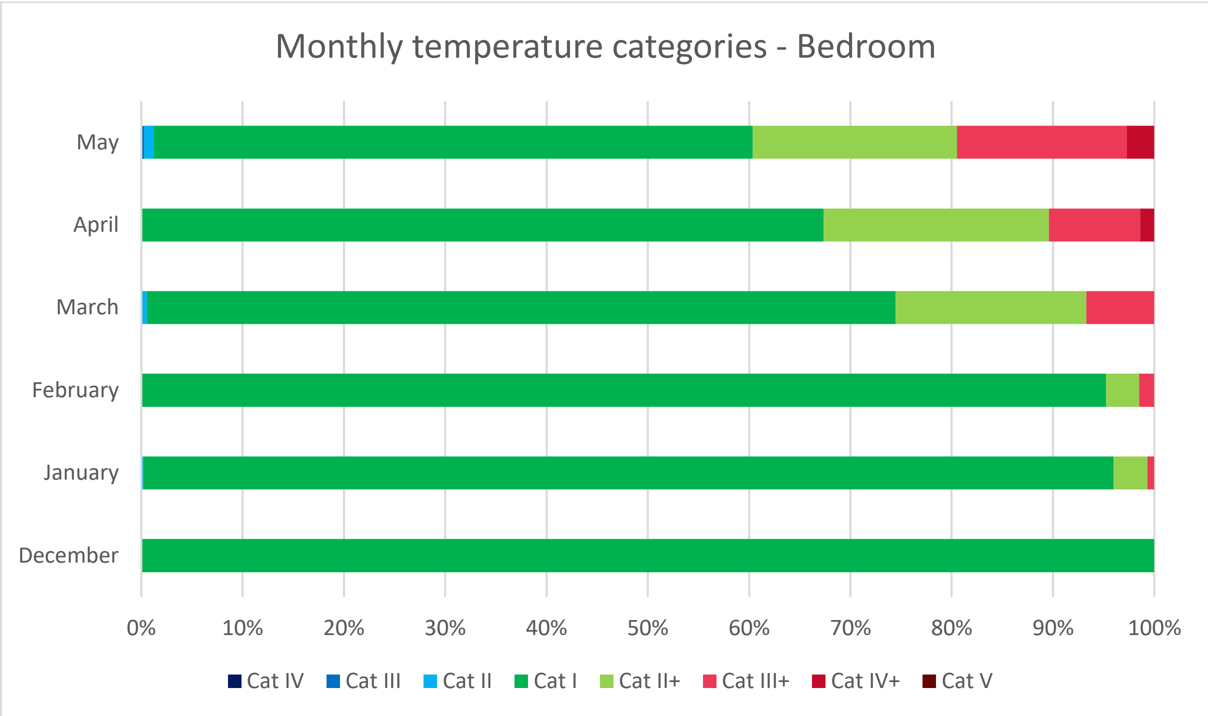

Figure 18 - Time distribution in thermal comfort categories (Master bedroom)

Table 10 - Percentage of internal temperature hours in each comfort category (Master bedroom)

	Cat IV-	Cat III-	Cat II-	Cat I	Cat II+	Cat III+	Cat IV+	Cat V	Hours per month
December	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	744
January	0.00	0.00	0.27	95.70	3.36	0.67	0.00	0.00	744
February	0.00	0.00	0.00	95.24	3.27	1.49	0.00	0.00	672
March	0.00	0.00	0.54	73.92	18.82	6.72	0.00	0.00	744
April	0.00	0.00	0.00	67.36	22.22	9.03	1.39	0.00	720

May	0.00	0.27	0.94	59.14	20.16	16.80	2.69	0.00	744
Total [h]	0.00	2	13	3571	497	255	30	0	

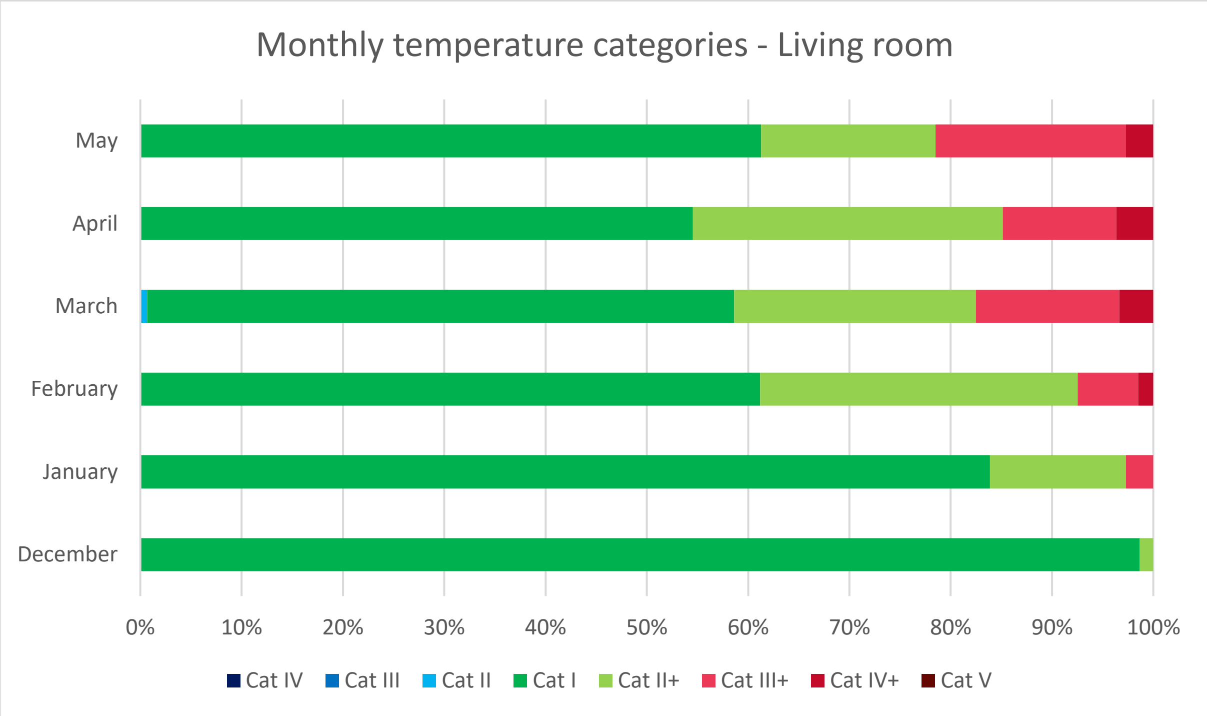

Figure 19 - Time distribution in thermal comfort categories (Living room)

Table 11 - Percentage of internal temperature hours in each comfort category (Living room)

	Cat IV	Cat III	Cat II	Cat I	Cat II+	Cat III+	Cat IV+	Cat V	Hours per month
December	0.00	0.00	0.00	98.66	1.34	0.00	0.00	0.00	744
January	0.00	0.00	0.00	83.87	13.44	2.69	0.00	0.00	744
February	0.00	0.00	0.00	61.01	31.25	5.95	1.49	0.30	672
March	0.00	0.00	0.67	57.80	23.79	14.11	3.36	0.27	744
April	0.00	0.00	0.00	54.03	30.28	11.11	3.61	0.97	720
May	0.00	0.00	0.00	61.29	17.20	18.82	2.69	0.00	744
Total [h]	0	0	5	3043	843	385	81	11	

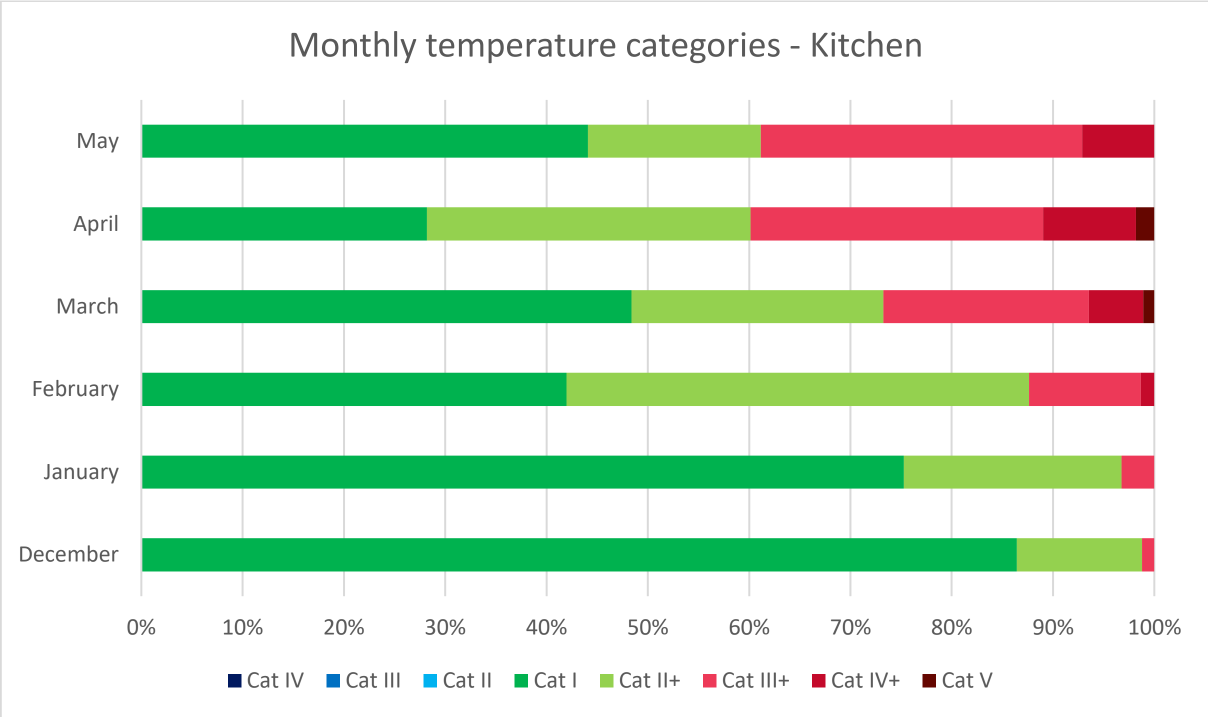

Figure 20 - Time distribution in thermal comfort categories (Kitchen)

Table 12 - Percentage of internal temperature hours in each comfort category (Kitchen)

	Cat IV	Cat III	Cat II	Cat I	Cat II+	Cat III+	Cat IV+	Cat V	Hours per month
December	0.00	0.00	0.00	86.42	12.37	1.21	0.00	0.00	744
January	0.00	0.00	0.00	75.27	21.51	3.23	0.00	0.00	744
February	0.00	0.00	0.00	41.96	45.68	11.01	1.34	0.00	672
March	0.00	0.00	0.00	48.39	24.87	20.30	5.38	1.08	744
April	0.00	0.00	0.00	28.19	31.94	28.89	9.17	1.81	720
May	0.00	0.00	0.00	44.09	17.07	31.72	7.12	0.00	744
Total [h]	0	0	0	2376	1101	702	168	21	

These graphs and tables show that, especially in the living room and kitchen, the temperature is often above 27 °C, sometimes even as high as 28 °C. Despite the fact that the period calculated is not over the whole year, but over the first six months, it can be seen that the temperature inside the house exceeds the limits suggested by the standard. In fact, the hours calculated with an internal temperature greater than 27 °C, as well as those with a temperature greater than 28 °C, are in fact greater than 100 and 25 respectively, even if only part of the calendar year is considered.

The following tables show the acceptable ranges for CO2 level and relative humidity, respectively. The kitchen was considered as the living room for the CO2 level. They correspond to the values in table B.12 of EN 16798 for CO2 level, and table B.16 for relative humidity [17].

Table 13 - Acceptable ranges for CO2 from the Standard

Category	Design ΔCO2 concentration for living rooms (ppm above outdoors)	Design ΔCO2 concentration for bedrooms (ppm above outdoors)
I	550	380
II	800	550
III	1350	950
IV	1350	950

Table 14 - Acceptable ranges for relative humidity from the Standard with the addition of category IV to assess the exceeding of limits

Type of building/space	Category	Design relative humidity for dehumidification, %	Design relative humidity for humidification, %
Spaces where humidity criteria are set by human occupancy	I	50	30
	II	60	25
	III	70	20
	IV	>70	<20

Therefore, class IV was added for the classification of the relative humidity percentage of the dwelling to determine the values above the threshold, because values were recorded below the 20% threshold.

This can be explained by the fact that sometimes the temperature inside the house is high and therefore the relative humidity can be so low.

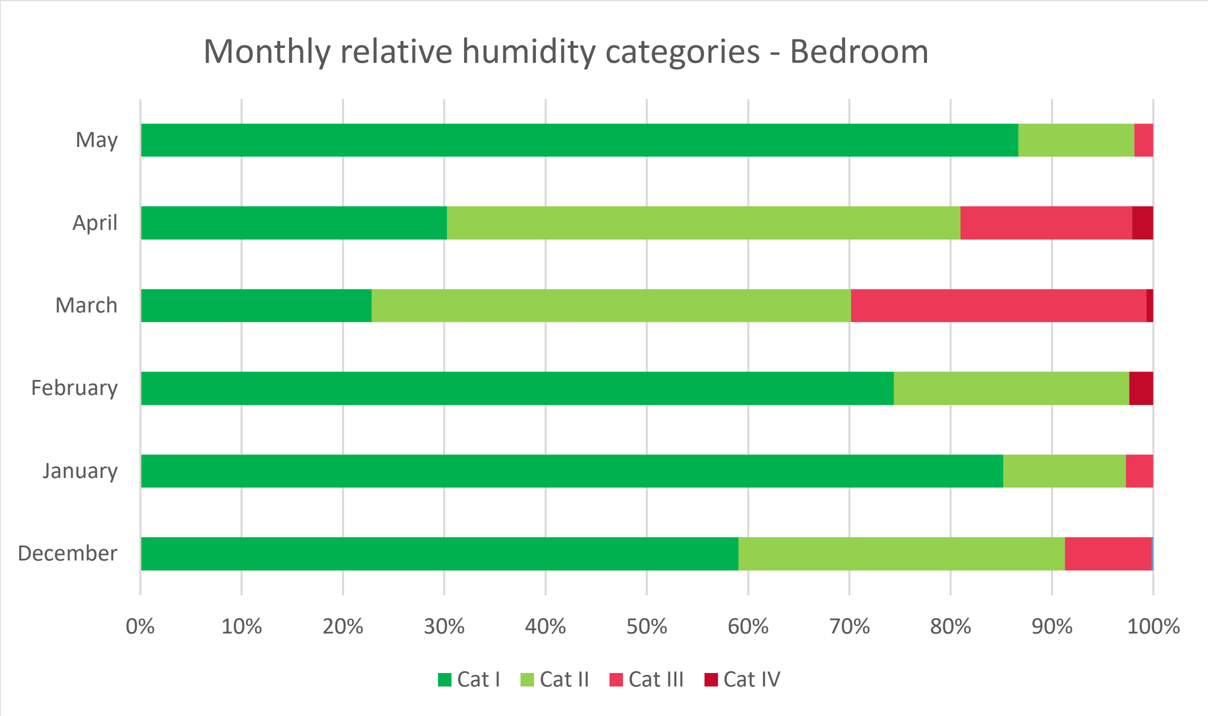

Figure 21 - Time distribution in relative humidity categories (Master bedroom)

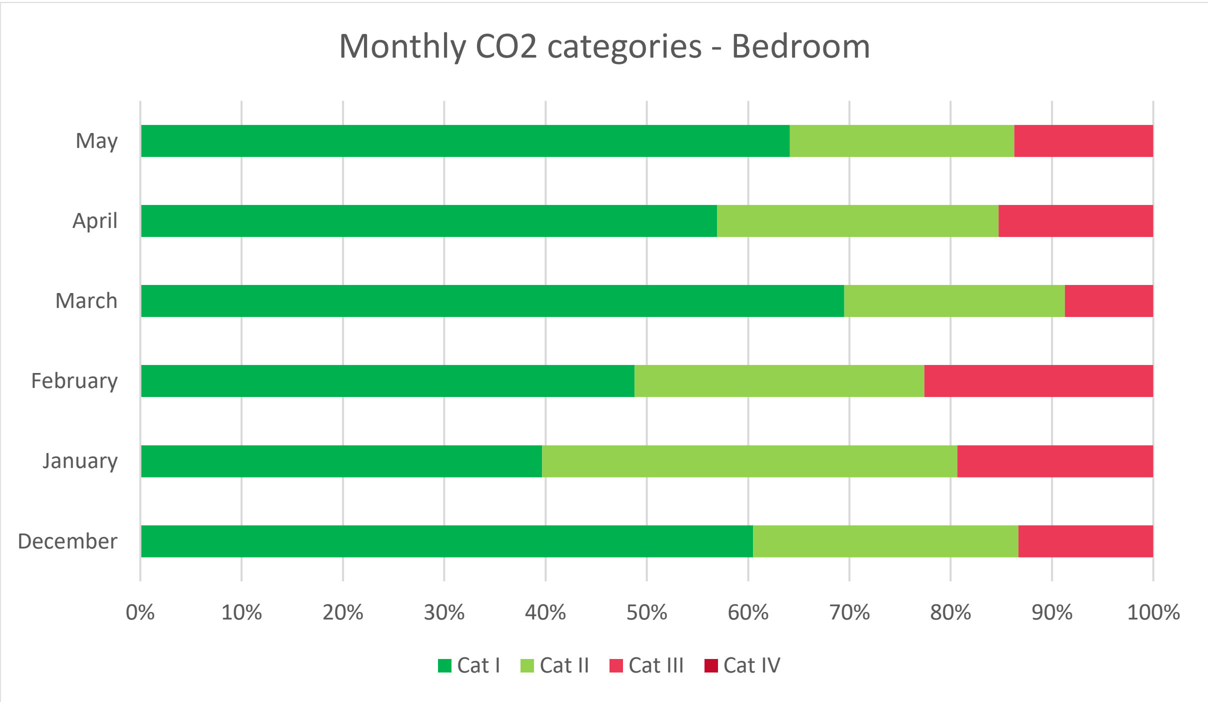

Figure 22 - Time distribution in CO2 categories (Master bedroom)

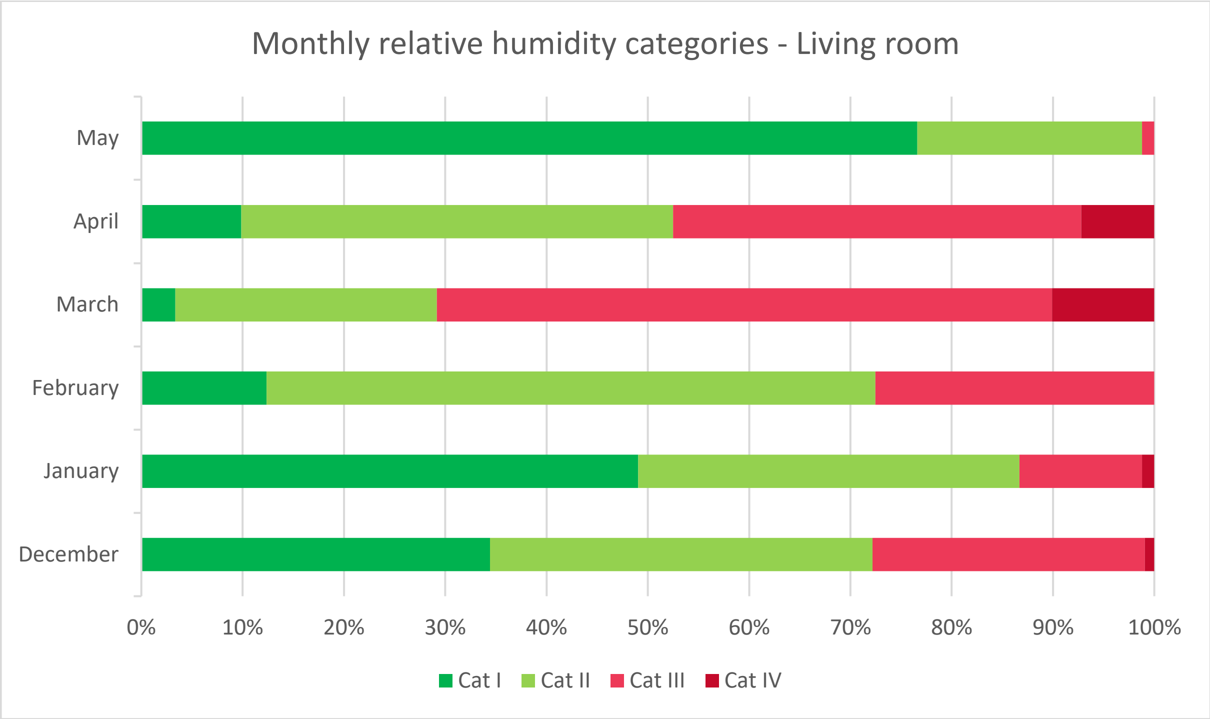

Figure 23 - Time distribution in relative humidity categories (Living room)

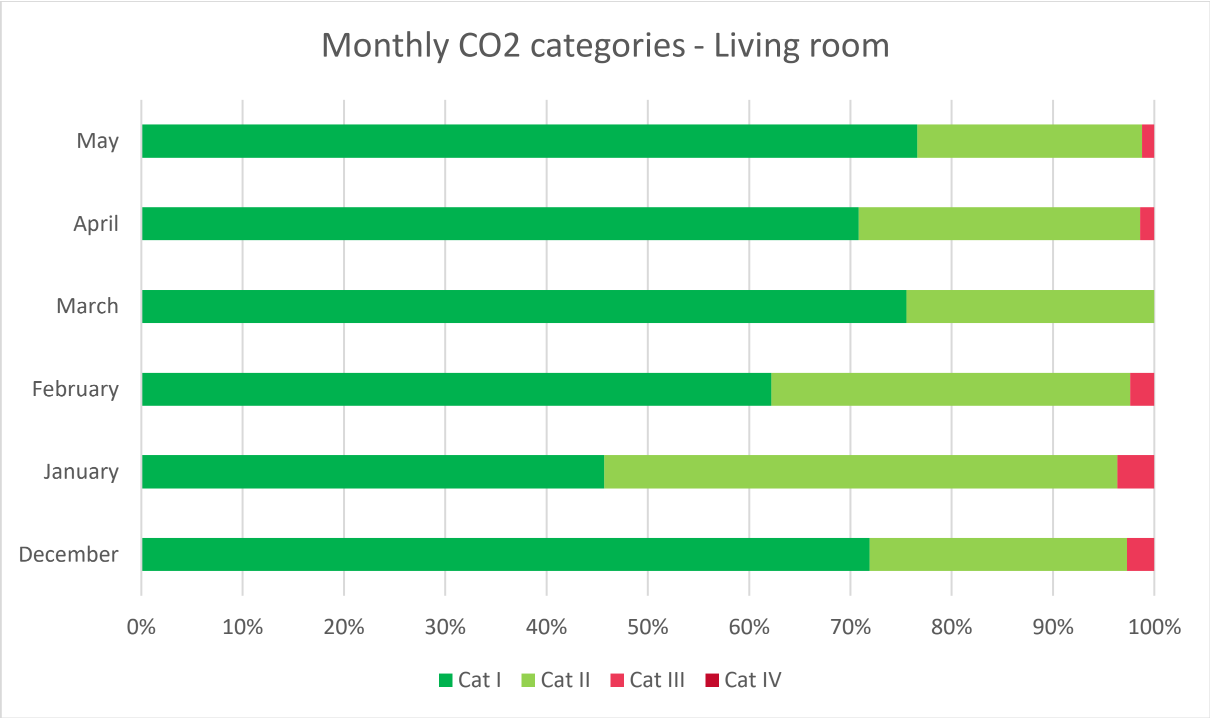

Figure 24 - Time distribution in CO2 categories (Living room)

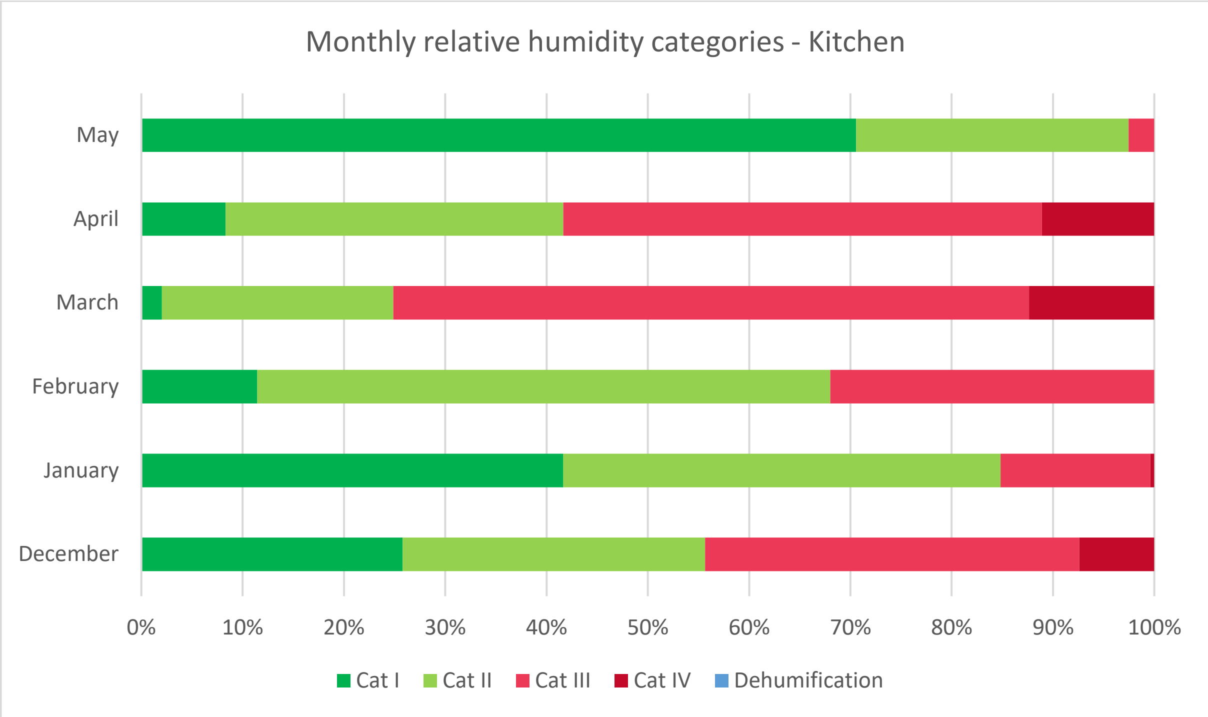

Figure 25 -- Time distribution in relative humidity categories (Kitchen)

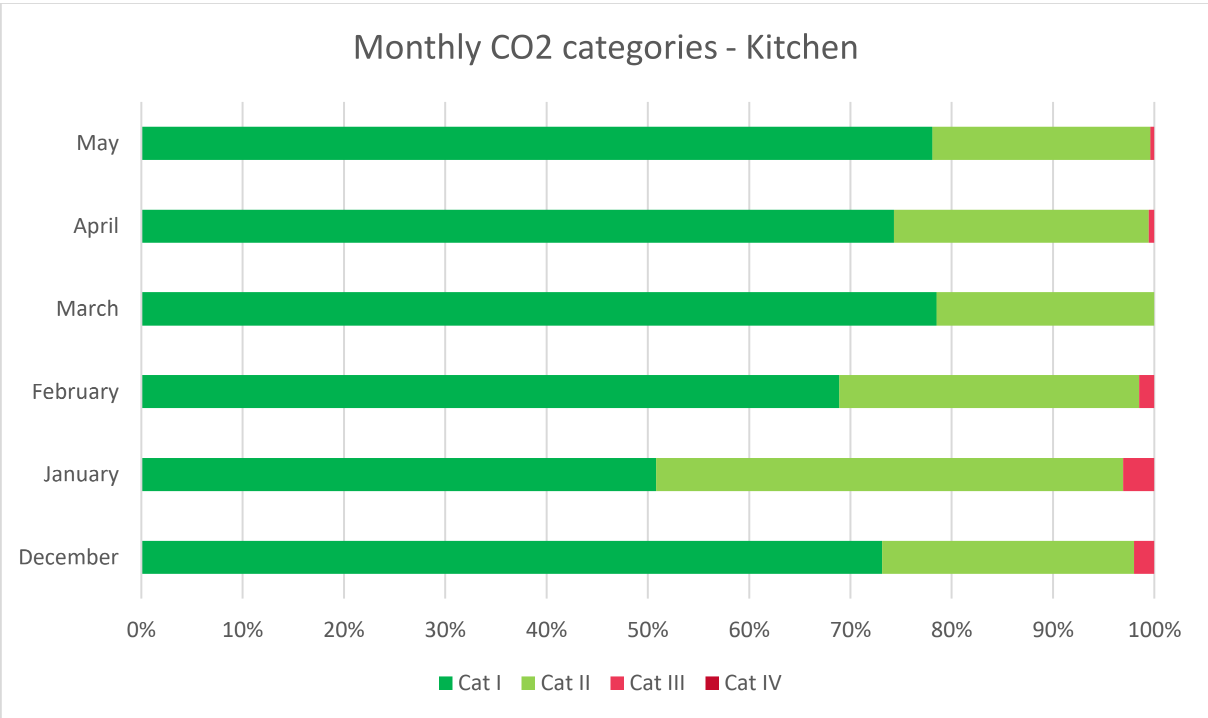

Figure 26 - Time distribution in CO2 categories (Kitchen)

Relative humidity appears to be quite low, reaching values below 20%, especially in the living room and kitchen in April and March, while CO2 emissions are within limits most of the time.

4.2 Fault detection and analysis of occupant behaviour

This analysis contains a comparison of the measured energy consumption data of this building over three different periods. This is useful for carrying out an analysis to detect possible faults and to compare the behaviour of the two different families.

- Period 1: 01/12/2018 - 31/05/2019 (previous family)
- Period 2: 01/12/2019 – 31/05/2020 (previous family)
- Period 3: 01/12/2021 – 31/05/2022 (actual family)

These are the main differences in the control system for the two families:

- Period 1/2: automatic control of solar shading, natural ventilation (skylights and façade windows), and mechanical ventilation with variable air volume.
- Period 3: manual control of the façade windows, the opening of skylights and sunscreens were transferred to another control system. The mechanical ventilation has no damper on each diffuser, which means a fixed flow of air in each room.

More specifically, each change during the period under review is shown in the table below.

Table 15 - Technical changes made in the building during the period of analysis

02/2020		CO2 sensors were replaced with better equipment in February 2020.
17/06/2020	02/06/2022	Nilan AHU stops to communicate device values to the PLC.
12/07/2020		Stop of measurement period in Bolig2020 project. The damper opening was dismounted and will not be mounted again. Automatic and manual openings of natural ventilation openings in the facade are disconnected and will not be connected again.
12/07/2020	16/06/2022	Logging of automatic and manual Skylight opening, and solar shading status is not monitored. 16-06-22 this was fixed due to a change in the control system.
01/12/2021	Now	Start of measurement period PRELUDE.
30/03/2022	30/03/2022	Replacement of electrical energy meter. The old energy meter was a phase meter, the new is a summation meter.

4.2.1 Total electrical consumption

This is the comparison between the total electrical use for the selected periods, determined by the individual meter, that considers all electricity consumption of the house, which will be called ‘measured’, and the total electricity consumption obtained from the sum of Nilan AHU, DHW heat pump, cooking plate, refrigerator, washing machine, dryer, dishwasher, electric water heater, system control, pump floor heating, and other consumption (lighting + plug load), which will be called ‘calculated’, as done in the paragraph 4.1.3.

In the following analysis, the data for 2021 were excluded because there is a gap in the log file between August 2020 and March 2021, so it is impossible to calculate the other consumptions.

In February 2019, furthermore, five days were not recorded, from 6th to 11th February, so the consumption for this period is slightly underestimated.

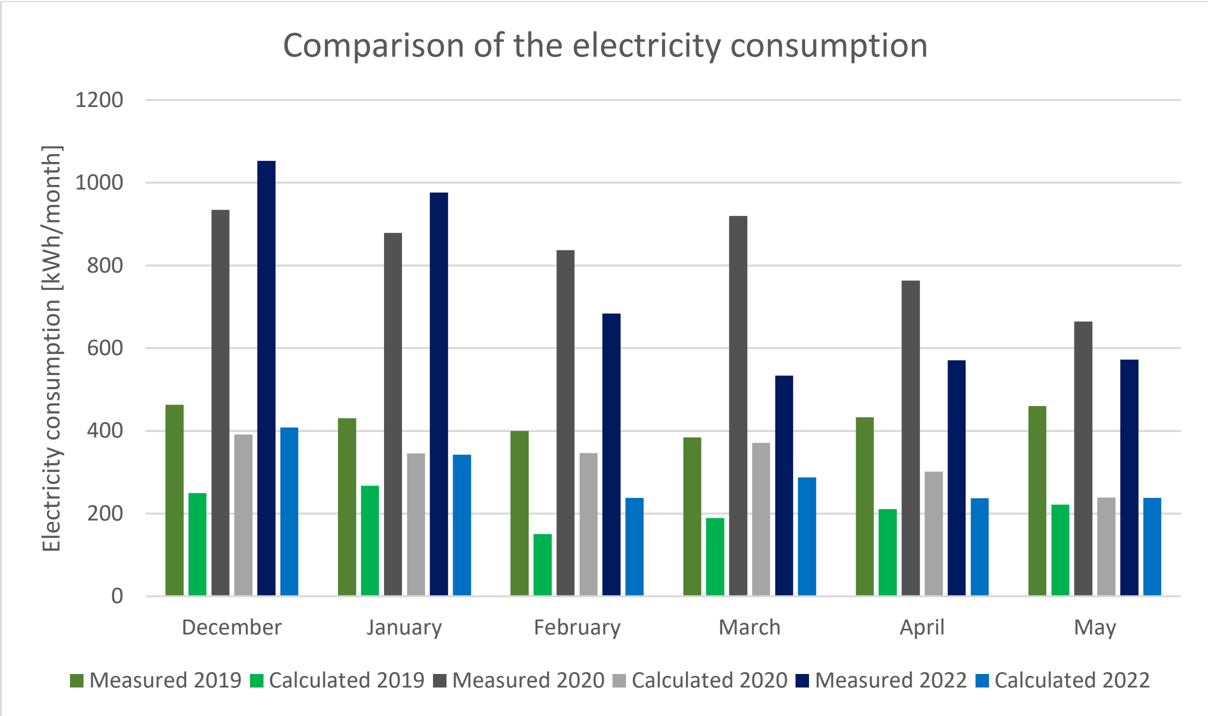

Figure 27 - Comparison of total electrical use

In Figure 27, it is possible to see very different measured and calculated electricity consumption, the reason could be that different meters measure these quantities. There is an external one that measures the building's electricity consumption and other specific meters for:

- AHU Nilan Compact P (including heat pump for DHW production)
- Appliance: cooker plate, cooker hood, ovens, washing machine, dryer, dishwasher, electric water heater, others.
- Control system
- Circulation pump floor heating
- Other: power sockets and lighting.

Therefore, there is probably something in the building that was not recorded or could be due to a fault in the external meter. In this analysis, the consumption resulting from the sum of each device was chosen as the term of comparison, as its composition is more explicit.

More in general, an upward trend is shown over the years. It can be seen that electricity consumption in 2020 and 2022 is quite comparable, while for the first year of this analysis, it was rather lower. In some months, for 2020 and 2022, is more than double that of the previous year.

It is also possible to analyse the specific consumption due to each electrical element in the building, to better understand the impact of each on the results.

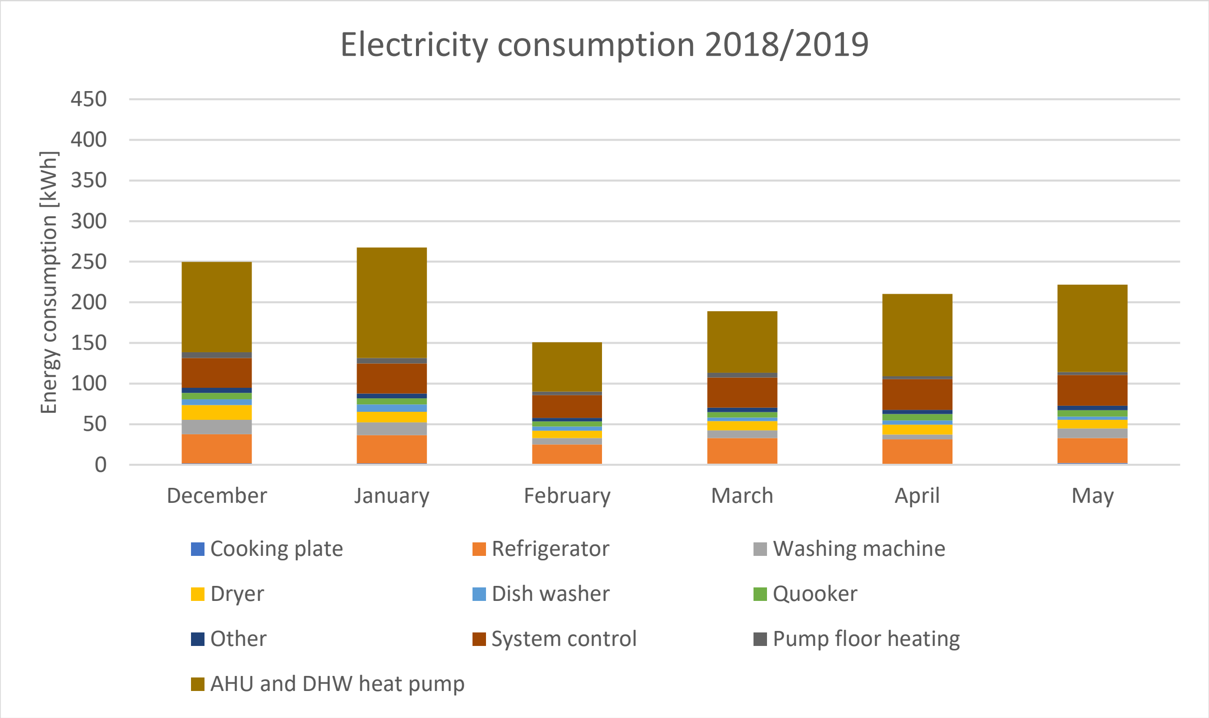

Figure 28 - Electricity consumption of each item 2018/2019

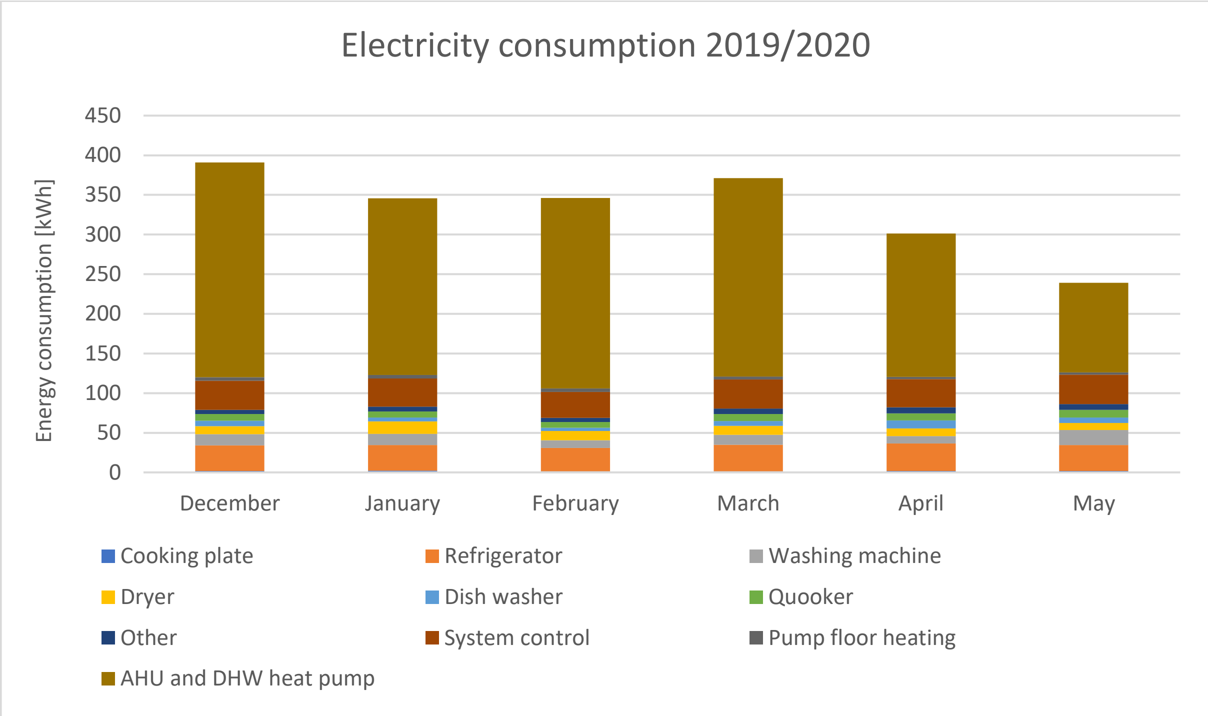

Figure 29 - Electricity consumption of each item 2019/2020

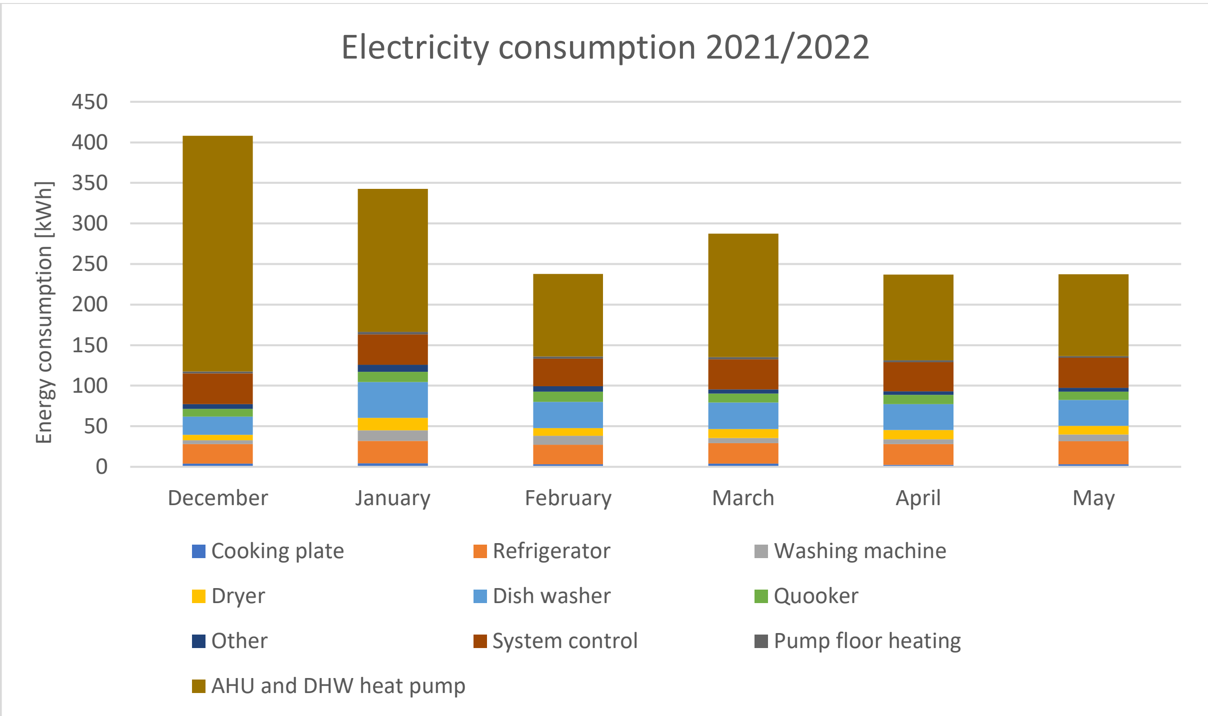

Figure 30 - Electricity consumption of each item 2021/2022

The most significant consumption, as expected, is that of the ventilation system and the heat pump for domestic hot water. It is evident that in the years 2020 and 2022 there is an increasing trend in its use, especially in the winter months.

Table 16 - Summary table of monthly energy consumption over the three periods analysed due to the AHU system and DHW heat pump

	2019	2020	2022
Month	AHU + heat pump [kWh]	AHU + heat pump [kWh]	AHU + heat pump [kWh]
December	111.44	270.50	290.49
January	136.31	222.81	176.36
February	60.68	239.91	101.49
March	75.78	261.74	152.22
April	101.42	180.86	105.63
May	107.73	113.19	101.15

The bar chart below shows a direct comparison between the energy consumption for the ventilation system and the DHW heat pump during the three years.

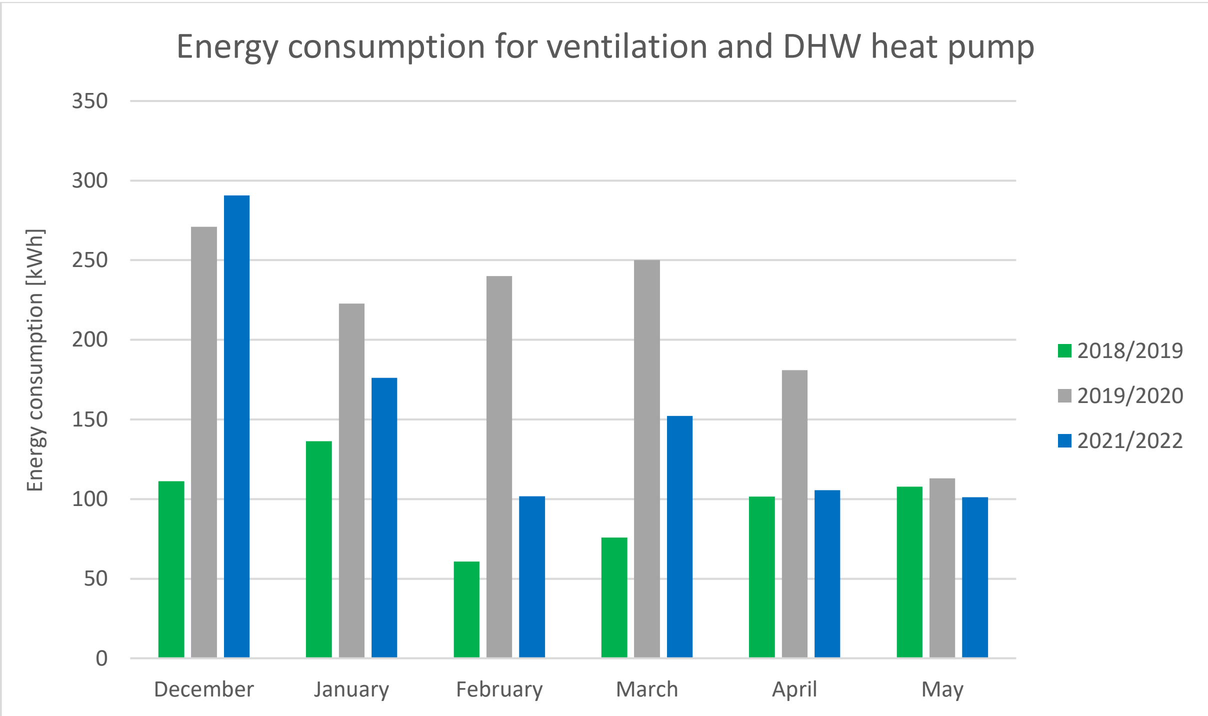

Figure 31 - Comparison of the energy consumption for ventilation and DHW heat pump system

The maximum electricity consumption due to ventilation and the heat pump for domestic hot water occurred in 2019/2020. The most significant differences compared to the other two periods in terms of electricity consumed occur in December, February and March.

This year and 2018/2019 year had the same ventilation system with VAV control and the same household lived in the house, but the consumption was markedly different.

As of 2021, mechanical ventilation has become without dampers on each diffuser, which means a fixed air volume flow for each room. This could lead to a higher air volume flow and consequently higher energy consumption of the AHU to heat it.

In the following analyses, some aspects of electricity consumption will be analysed in more detail to try to explain the differences highlighted.

4.2.1.1 Domestic water consumption

One aspect to be analysed is the water consumption measured between years, because the house has a direct electric hot water heating system and this could be a risk in case of high usage.

In Figure 32, it is possible to see the quantity of domestic water during the three periods, compared with the electricity consumption due to ventilation and the heat pump for domestic hot water.

No information is available on the quantity of domestic hot water in February 2020, so the total amount for this year is slightly underestimate.

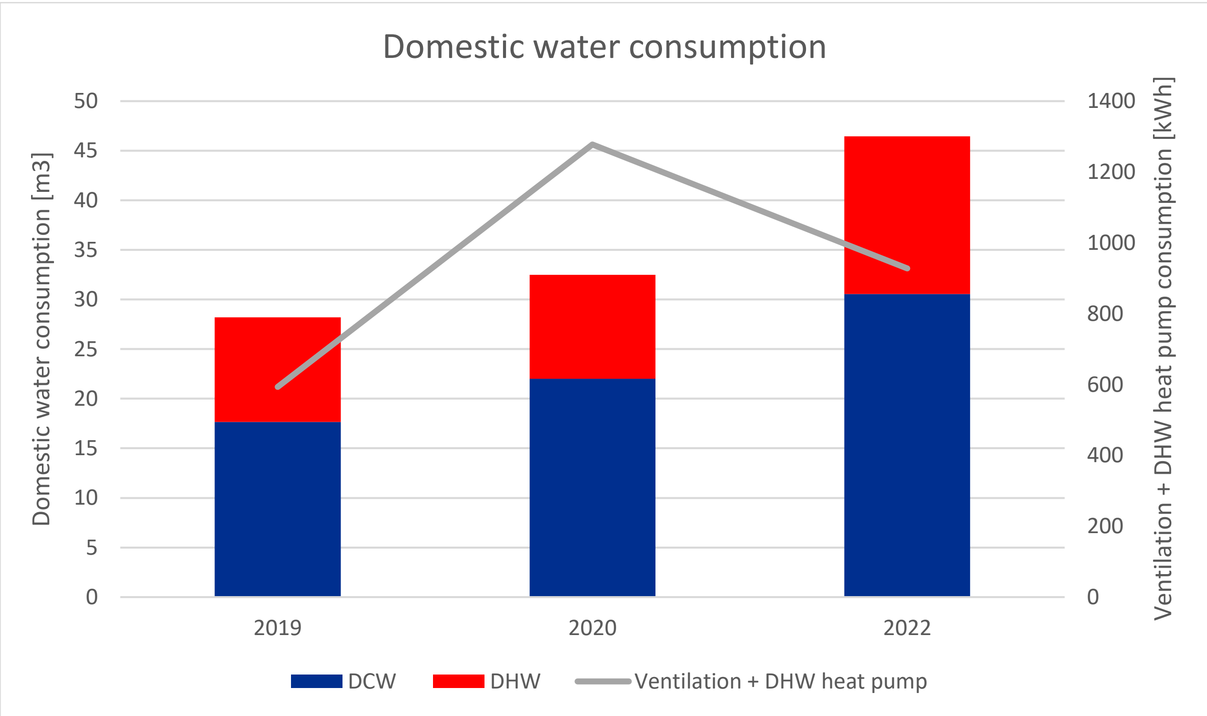

Figure 32 - Domestic water consumption and ventilation + DHW heat pump consumption

The trend of the use of domestic water is increased over the years, until reach the highest value with the actual family. This could be because in the previous household one member used to shower in the gym locker room, being a football player, so in the years 2019 and 2020 we find a lower demand for domestic water and consequently lower electricity heat pump consumption.

Another thing to note is that, in general, water consumption is rather low, especially in the first two years. The average value in Denmark is about 250 l/m^2 per year, with a total water consumption of about 120 m^3/year. The following table shows the results for six months.

Table 17 - Summary table of the amount of water consumed on a six-monthly basis over the three periods analysed

	Year 2018/2019	Year 2019/2020	Year 2021/2022
DHW for six months [l/m^2]	65.9	65.5	99.4
Total domestic water for six months [m^3]	28.2	32.5	46.5

The use of domestic hot water in the 3 periods, however, has no connection with the significant difference with electricity consumption.

For the year 2019/2020, a sharp increase in the consumption of ventilation and heat pump for domestic hot water is evident, one explanation could be related to the Covid19. Especially in 2020, there were many restrictions due to the pandemic, and this certainly affected consumption. In Denmark, the first lockdown took place on 11th March 2020, and this could partially justify the high ventilation consumption that it is possible to see in March and April. The previous family, in fact, spent much more time at home in that year and therefore may have used the ventilation system more.

4.2.1.2 Electrical device consumption

It is also useful to compare only the total consumption given by each electrical device over the three periods in order to assess it in detail.

The only significant difference between the two households seems to be the use of the dishwasher. But since there are no particular discrepancies in total consumption, it can be deduced that any differences are only determined by the habits and behaviour of the occupants.

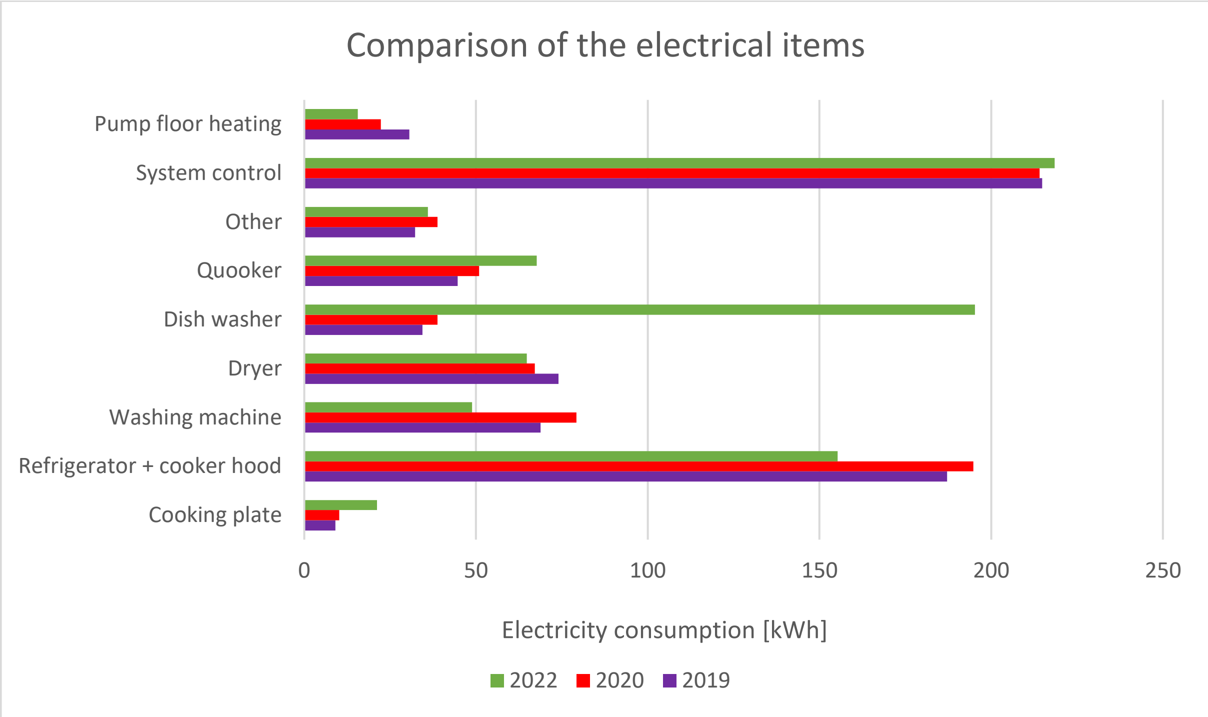

Figure 33 - Comparison of the electrical item's consumption

4.2.1.3 Supply temperature

The Air Handling Unit has passive and active heat recovery, this means that when the integral heat pump in the ventilation part is not producing domestic hot water, it can heat the supply air even further and thereby help heat the dwelling. This only happens when the indoor temperature or the supply air temperature falls below the value specified in the settings.

This analysis, therefore, aims to investigate the supply and return temperatures of indoor air in order to assess possible faults and try to explain the reason for certain differences in the house's electricity consumption over the three periods.

When analysing the supply air temperature, it is possible to see some correlations between it and the consumption of the AHU. For example, in December 2019 and 2021, the consumption of the ventilation and heat pump for domestic hot water is considerably higher than in 2018, and at the same time the recorded air temperature is also considerably higher than the normal setpoint values of an house.

Figure 41 shows the flow temperature in December for the three periods, although there are some missing values, this helps to understand the big picture.

In the first period, the temperature did not reach values above 22 °C, whereas in the last two years, values of even more than 50 °C can be seen.

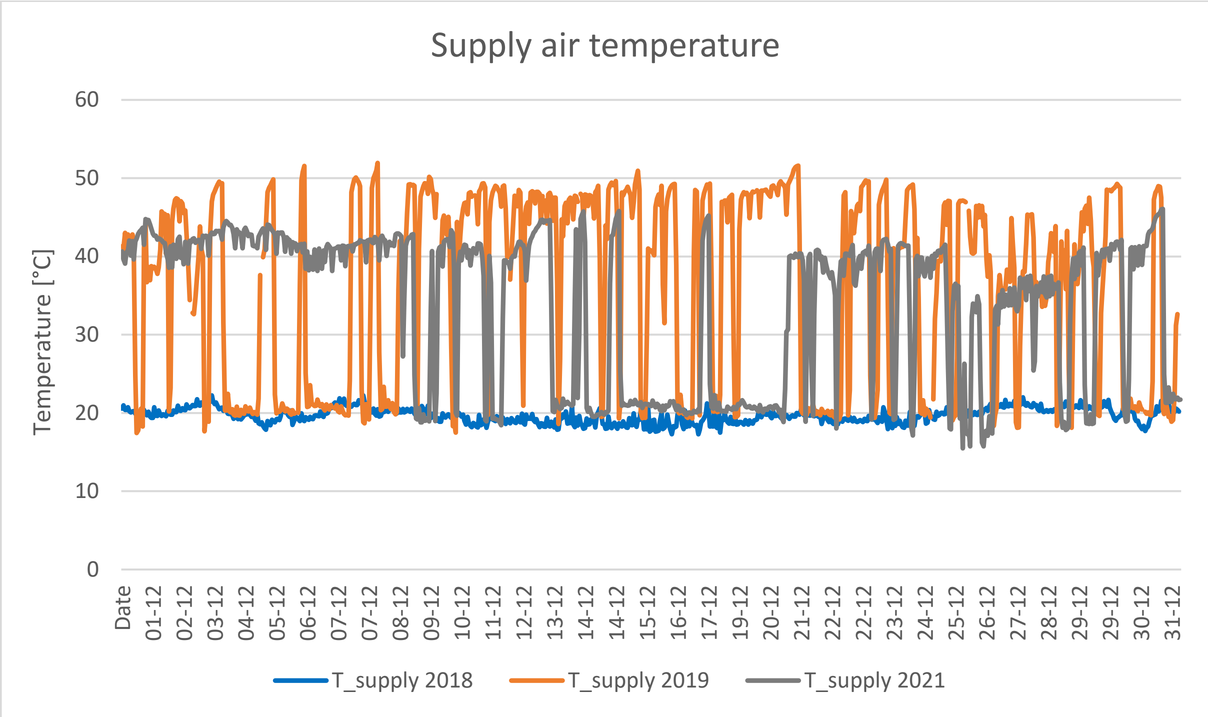

Figure 34 - Supply air temperature trends in December for the three periods

The correlation between the supply air temperature and the energy consumption of the heat pump for ventilation and domestic hot water is also evident in the other months, so it is very likely that the reason for the difference in electricity consumption over the three periods is due to a fault in the building's supply air temperature sensors.

Taking a shorter period relating to February 2019 as an example, the first five days, Fig. 42, where the difference in household electricity consumption is even more pronounced, the temperature trend was compared with that of electricity consumption.

As expected, there is a strong correlation between the supply temperature and the trend in electricity consumption for ventilation and the heat pump for domestic hot water.

The analysis performed on the supply air temperature explains the high consumption recorded, in particular, in December, February and March 2020 and December 2021.

Therefore, one of the causes of the high energy consumption is the malfunctioning of the supply air temperature sensors, and this is one of the reasons for the difference between the assumed and actual performance.

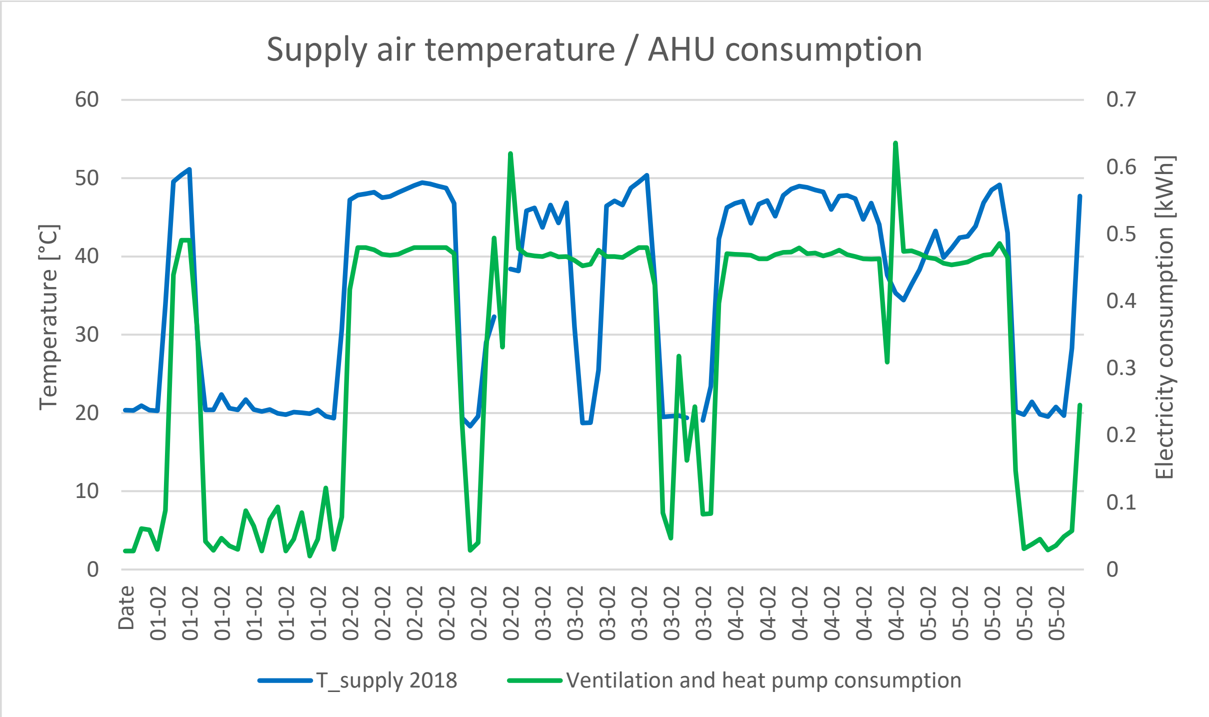

Figure 35 - Supply air temperature compared with the ventilation and DHW heat pump consumption of the first five days of February 2019

4.2.1.4 Air flow rate

In order to keep the building slightly depressurised, the rule of thumb usually used is to extract approximately 5% less supply air.

The values recorded for the air flow in the house show that the mechanical ventilation system is not balanced, and indeed the return air flow is significantly higher than the supply air flow.

This happens in all months of the three selected periods, so in all likelihood it could be due to an incorrect position of the exhaust airflow sensors, perhaps too close to an opening, so the recorded results may not be reliable.

4.2.2 Total heating consumption

The building is equipped with an underfloor heating system in all rooms, supplied by district heating. In the bar graph below, one can see the differences between energy consumption for underfloor heating and the average monthly outdoor temperature in the three different periods.

This comparison was made with the aim of understanding whether the energy consumption due to heating was due to the low outside temperatures during the winter months and thus the increased effort by the heating system to maintain the building at setpoint temperatures.

Even if considering the monthly temperature loses most of the daily differences, it is a good representation of the period to show the main differences.

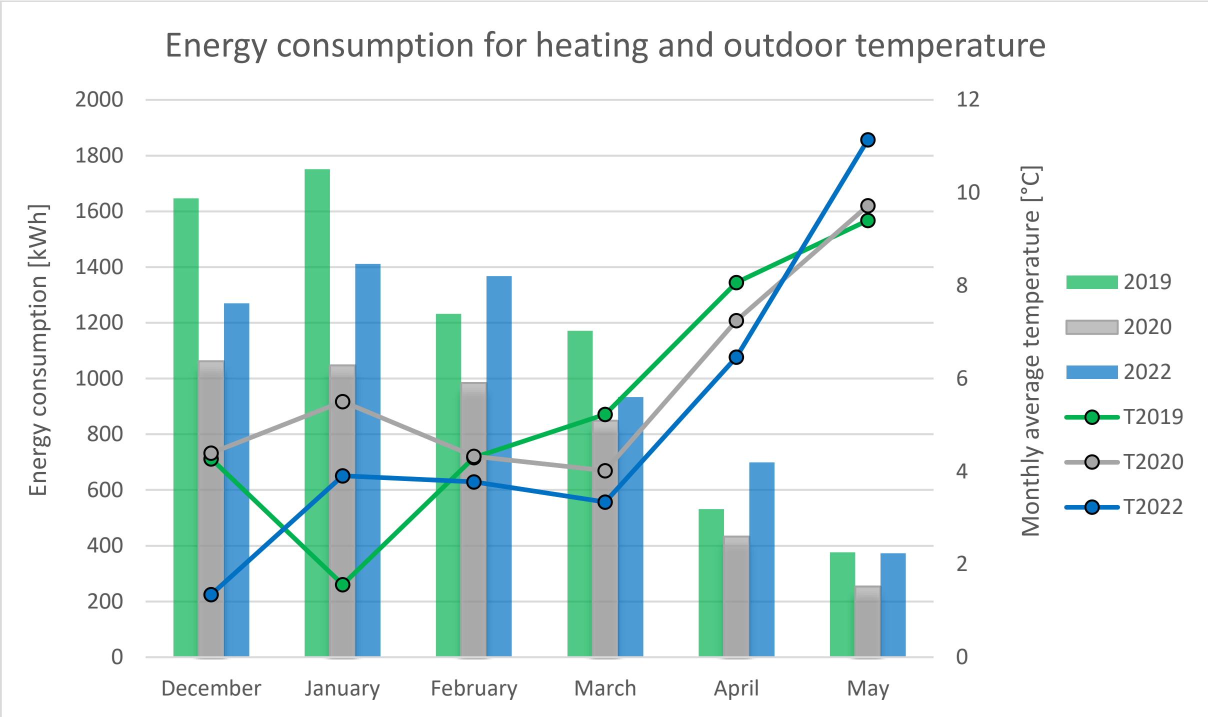

Figure 36 - Energy consumption for underfloor heating compared to average monthly outdoor temperature

In general, it is possible to see that the evolution of heating consumption follows the outside temperature. The higher energy consumption during the first year is evident, especially during the winter season; in January the trend may be justified by the very cold outside temperature, which may have led to an increase in heating consumption.

A similar trend can be seen for the last period, while heating consumption is lower for the year 2019/2020. In the second part of December 2022, we have the coldest outside temperature but not a large consumption for heating, and this could be due to the fact that the family was just moving into the house at that time and therefore probably did not spend every day at home.

4.2.2.1 Indoor temperature

Differences in heating consumption could also be related to a different setpoint temperature of the house. By converting the data into daily values, the indoor temperature trend for each room in the house was verified.

The following figures show the indoor temperature of the living room during the winter months (December, January and February) and spring months (March, April and May) and it is representative of the general behaviour of the building.

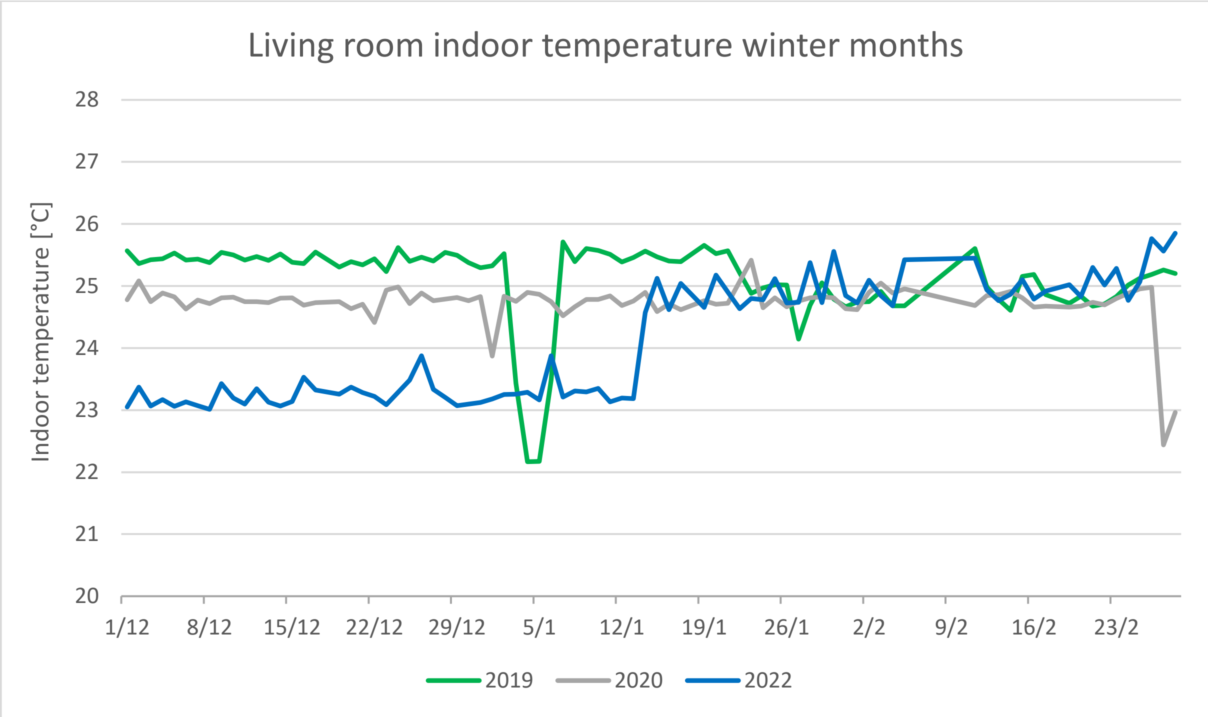

Figure 37 – Living room indoor temperature during winter months (December, January, February)

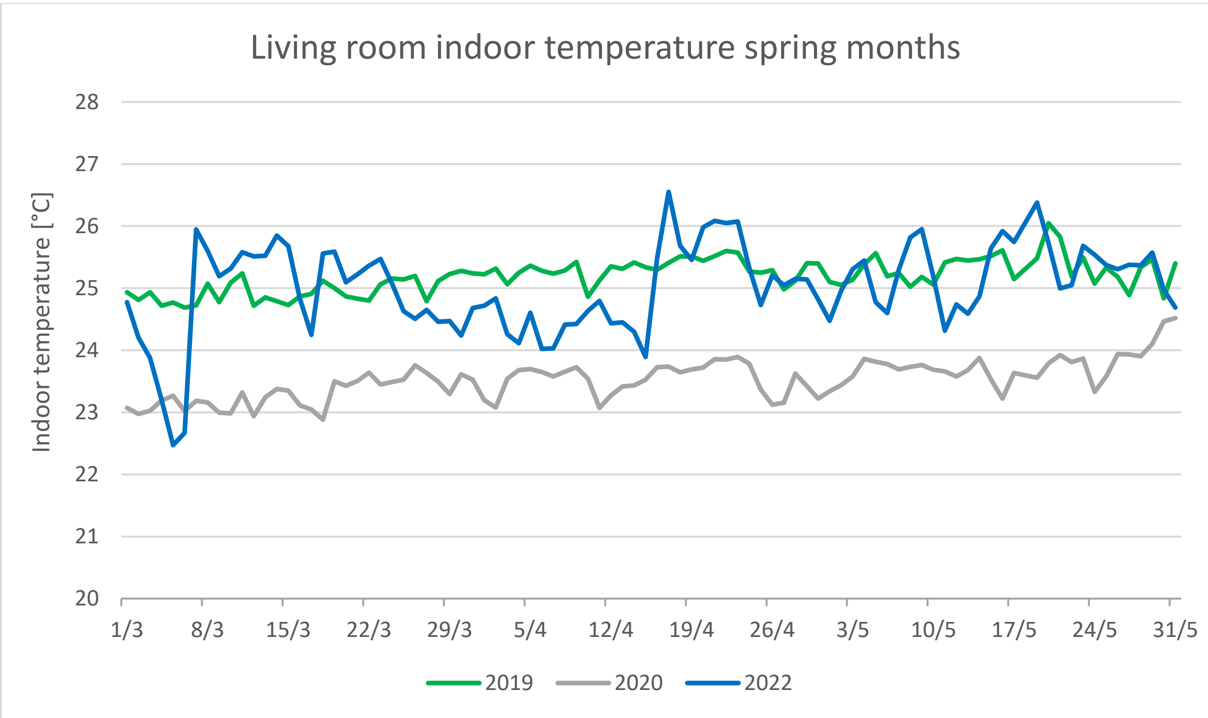

Figure 38 - Living room indoor temperature during spring months (March, April, May)

December 2018 and January 2019 represent the months with the highest energy consumption for heating. This result is partially satisfied by the analysis of the building's internal setpoint. In these two months, in fact, the indoor temperatures in almost each room are higher than in the other two years.

Indeed, it is true that a very relevant factor in energy consumption due to heating is the individual comfort of each inhabitant of the house.

The feeling of well-being, in fact, varies from person to person and depends on factors such as: metabolism, temperature, sex, clothing, age and activity.

Therefore, the differences in consumption could be due both to different external climatic conditions and to the different feeling of comfort of the households.

4.2.2.2 Hot water tank

In the Logfile of the registered parameters of the house there is a column which corresponds to the district heating to support the production of domestic hot water. The valve connecting the district heating to the tank has been closed for some years. The purpose of this analysis is to find the time when this valve was closed, which means the time when domestic hot water started to be produced by the heat pump connected to the ventilation system.

In the beginning, in fact, district heating also supplied the domestic water tank, so the energy needed to heat the storage tank was included. Then the valve has been closed because now it is the ventilation with his heat pump system that supplies the heating for water.

The search for the time of valve closure was done in order to understand the distribution of energy, and thus whether a part of district heating or a part of heat pump electricity was used for heating the domestic water tank during the periods analysed.

The period under analysis is from December 2017 to August 2020.

The consumption of domestic hot water tank is measured by meter B, shown in Figure 37. So, it is possible to separate the total energy of district heating (A) from the consumption for underfloor heating (C) and the energy needed to heat domestic water.

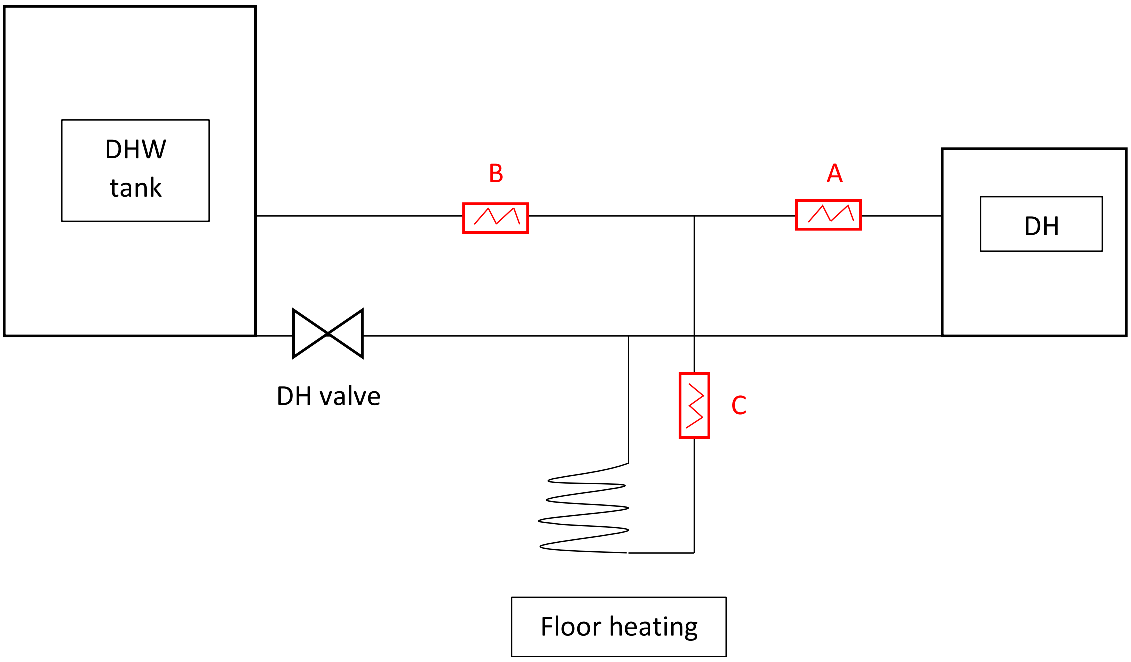

Figure 39 - District heating distribution scheme

The recording of the meters took place every 5 minutes, so in order to better represent the heating consumption trend, the data was first set to current consumption and not cumulated, subtracting the maximum value of each recording and then transformed into an hourly dataset using the average value of each hour.

By analysing the hot water tank consumption graph for each month, it was possible to identify when the valve was closed. It is evident, in fact, by looking at the following line graphs, the change in heating consumption since 12 June 2018, starting at 10.00 a.m., which is therefore considered to be the time when the valve was closed.

Cumulative consumption is also shown in the same graphs because the variation in the trend is even more evident.

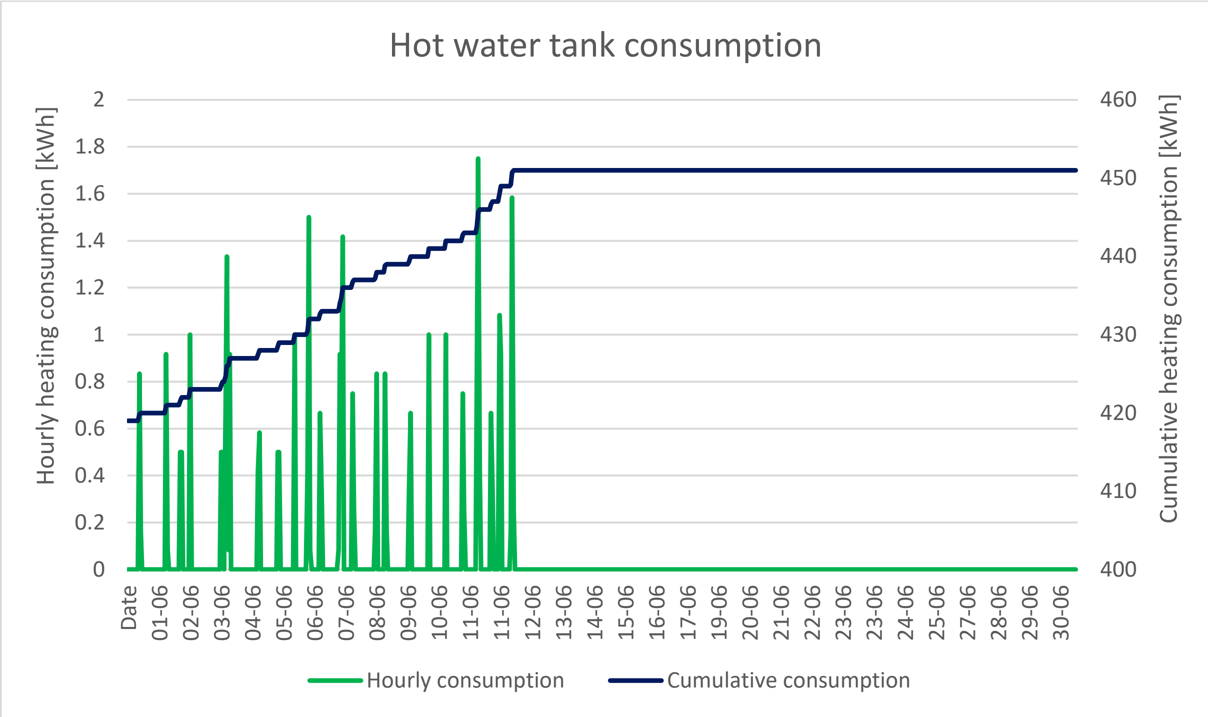

Figure 40 - Hot water tank heating consumption June 2018

From December 2018 to March 2019, there are some peaks in the heating consumption trend, but these are significantly lower than in the first part of 2018 and cannot be connected with the re-opening of the valve.

At that point, no more consumption is measured. Only in March and April 2020 does the meter take some readings. In the current household data, there is no more heating consumption due to the use of the hot water tank.

In the line graphs below, it is shown the month of December, which is a representative example of the entire period.

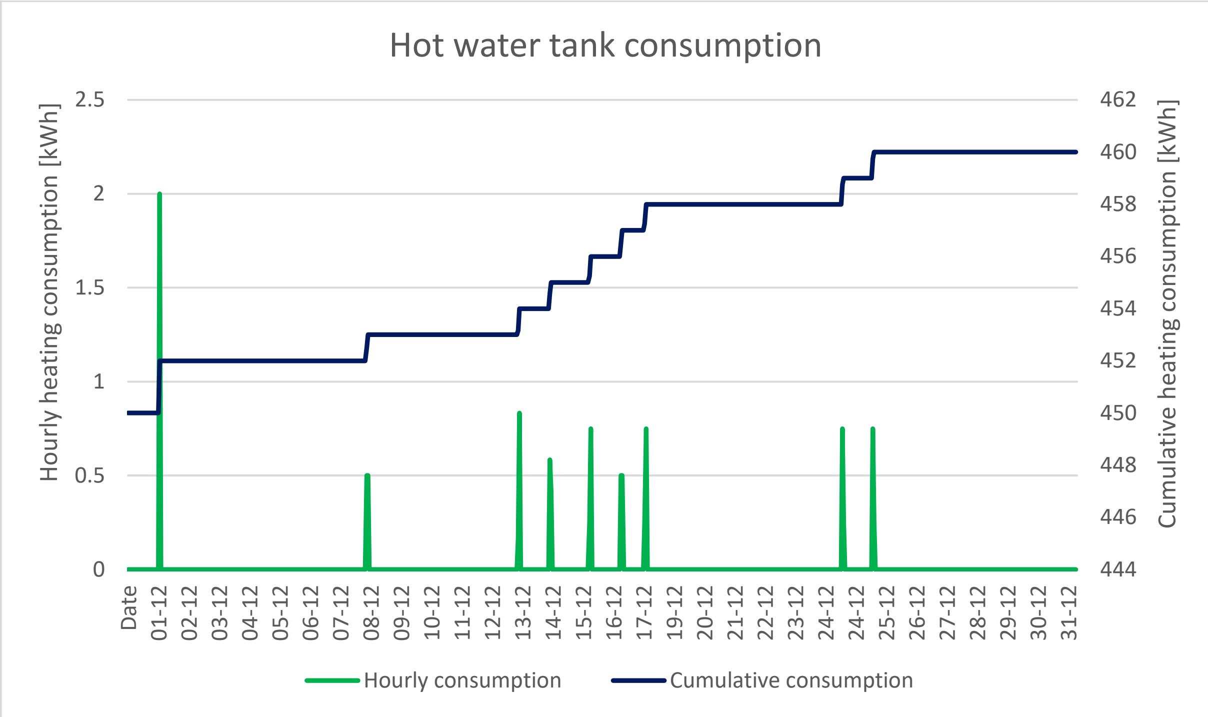

Figure 41 - Hot water tank heating consumption December 2018

The reason of these peaks is probably because the valve is controlled by a thermostat that measures the temperature in the hot water tank. The lowest setting point of the thermostat is 20 °C. In winter, when the temperature in the house is lower and the heat pump has difficulty keeping up with the production of hot water, the temperature in the hot water tank may be so low that the valve opens. This may explain the spikes that are present for some periods even after the valve is closed.

In general, throughout the selected period, the heat pump heats the hot water tank, so the differences in consumption of district heating and electricity over the 3 years are not due to storage as both households were using the same system.

Furthermore, although some heat consumption due to the hot water tank is noticeable, especially in the year of highest heating consumption (2018/2019), for the reasons explained above, it is almost insignificant compared to the total amount of district heating. The hot water tank consumption trend is shown below.

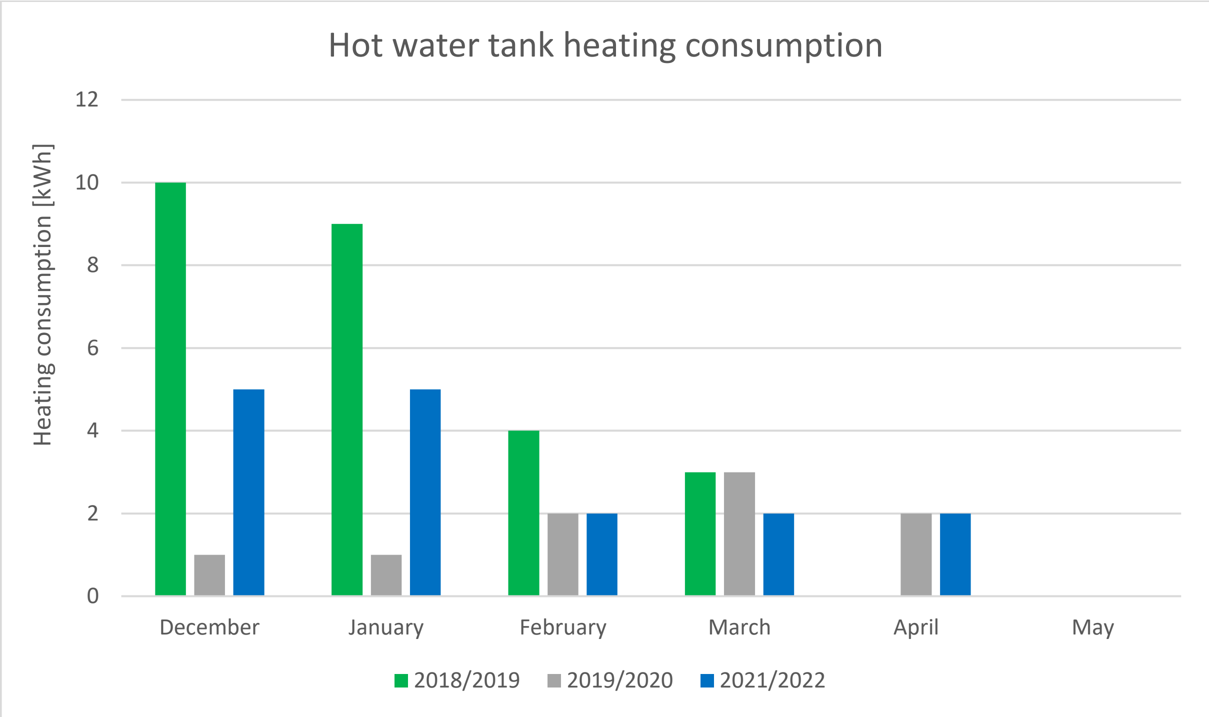

Figure 42 - Hot water tank heating consumption in the three periods

5. Design Builder model description

A true understanding of building behaviour, also supported by a reliable numerical model, can enable feasibility studies and proposals for energy efficiency measures.

Indeed, once the model has been properly calibrated against real measured data, it could be a reliable tool for testing energy efficiency measures and assessing their impact on indoor comfort, energy demand and overall profitability.

Building energy simulation models can be generally classified as physical energy models - 'white box' - that are based on heat and mass balance equations, presenting the dynamic thermal behaviour of buildings, data-driven models using machine learning algorithms - 'black box' - that rely on historical data to infer the hidden relationship between output (i.e. building energy consumption) and input variables (i.e. characteristics such as weather building information, occupant behaviour and equipment programming) using mathematical methods, and hybrid models - 'grey boxes' - that use a simplified physical model and easily accessible data to simulate the building's energy demand, thus combining the advantages of both white and black boxes.

In general, a large amount of information is required to construct a physical energy model of the building, such as building envelope parameters, HVAC systems, internal thermal gains, equipment and occupancy schedules, thermal zones, location and weather data, so they represent a huge challenge for building energy operators. For this reason, they require a great deal of computational efficiency, in terms of time and cost, but if constructed rigorously, accurate and precise results can be obtained that are often generalisable.

On the other hand, data-driven models have gained increasing interest in the energy prediction of buildings due to their simplicity and flexibility, as they are easy to develop and do not require an understanding of the physics of the system to be modelled, but huge historical data and a lot of time are required to train the model and obtain accurate predictions under different conditions.

Grey box models, therefore, represent a middle ground in that they are models based on simplified physics with first-order algebraic and differential equations, the parameters of which can be determined from time series of data. The advantages are that the equations and parameters are physically interpretable, unlike black-box models, and have a simpler implementation than white-box models. However, they are not as accurate and precise as white-box models and are difficult to generalise [18].

In this project, a physics-based building model was realised using the open-source programme Energy Plus with the graphical interface of Design Builder. It is a dynamic simulation tool that provides access to all simulation capabilities most commonly required in building design. For example, it provides advanced dynamic thermal simulation at sub-hourly time intervals, data on environmental performance such as energy consumption, carbon emissions and environmental comfort at annual, monthly, daily, hourly and sub-hourly intervals, reports on surface temperatures and radiant heat transfer and dimensioning of heating and cooling systems. With this software, an accurate building model was created in which thermal zones were modelled with all building, occupancy, equipment and HVAC information. Based on the building plans, the building construction model was created, shown in Fig. 43.

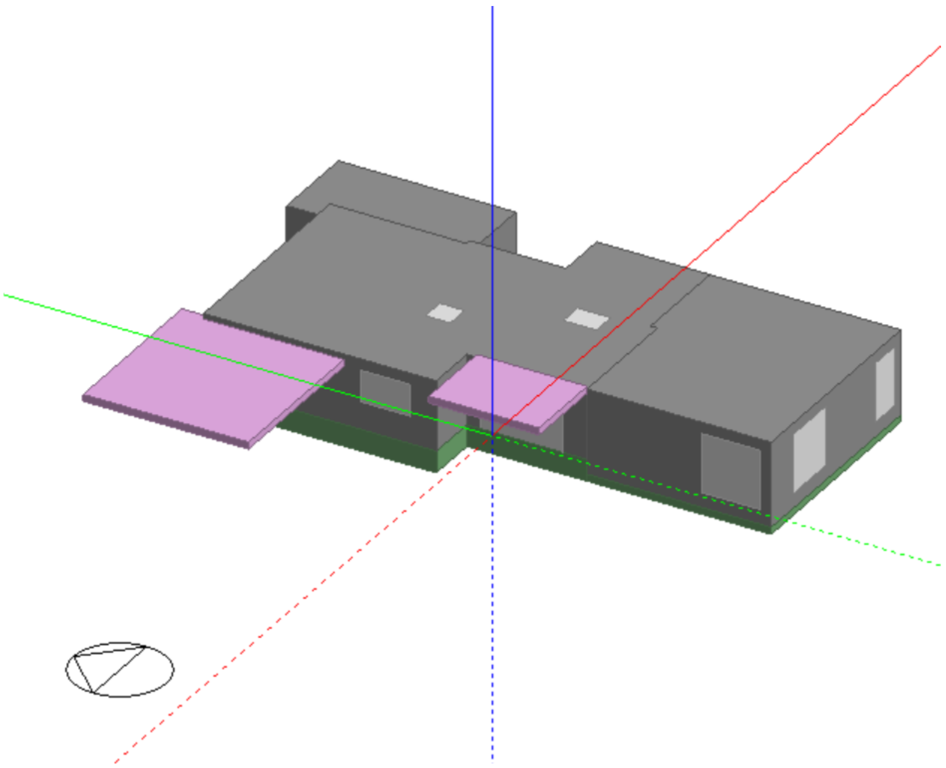

Figure 43 - House simulation model realised with Design Builder

The simulated building has a lower part consisting of a bathroom, bedroom, dressing room and living room, and an upper part containing the second bathroom, three rooms, the living room and kitchen, which form a single room, and the storage room. The technical room and the storage room, both unheated spaces, are also located in this area.

The house does not have a basement room so the floors in each area are in contact with the ground. The model also contains two carports.

For this work, each room in the house is considered a zone, with a total of 11 thermal zones. Every surface of the house, exterior and interior walls, roofs, floors and subfloors, have been created based on the actual construction of the building. The same applies to openings: there is a specific section for the glazing of the house.

The Design Builder programme allows you to choose the materials used for the construction of the building through its material libraries. The type of lighting and its specifications, such as radiant and visible fraction, were created to match that of the actual building, but illuminance and light output were not considered in the energy calculation for residential buildings.

5.1 Model calibration

Model calibration is an iterative process that, through the evaluation of a series of simulations with different inputs, aims to reduce discrepancies between simulated and actual building energy behaviour. The following figure illustrates the calibration method of the whole building energy model, in particular, ASHRAE Guideline 14/2002 was followed to calibrate the building model [19].

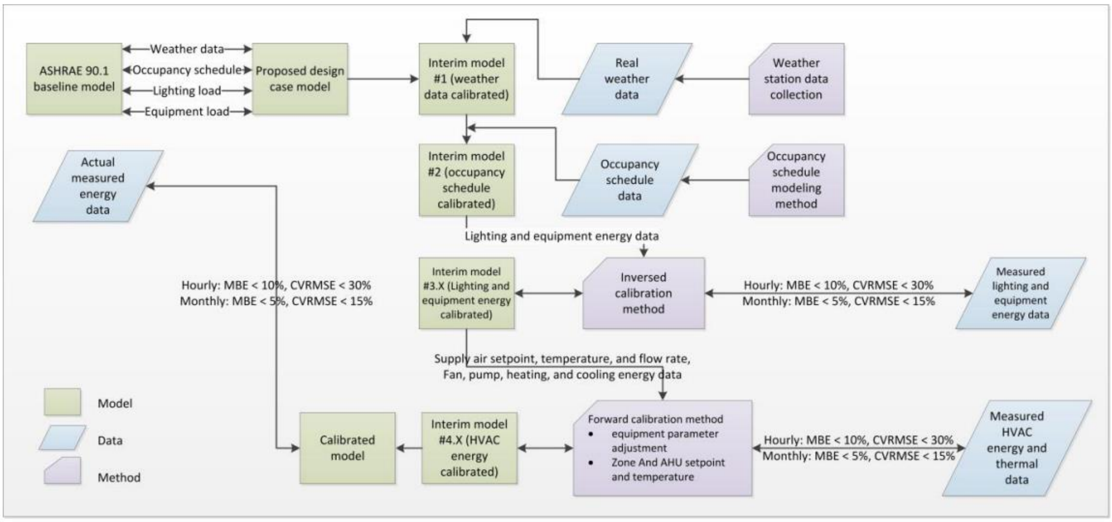

Figure 44 - Whole building energy model calibration method [20]

The calibration protocols use certain validation indices to quantify the calibration of the model. Defining Mi and Si as the respective measured and simulated data in instance i, and Ni as the number of values used in the calculation. The instance i represents the hours and ranges from 1 to the end of the period examined.

Mean Bias Error – MBE

$$MBE = \frac{\sum_{i=1}^{Ni}(S_i - M_i)}{\sum_{i=1}^{Ni}(M_i)}$$

The MBE predicts a general discrepancy between predicted and actual values. This index can give a misleading indication due to the compensation of the sign error.

Coefficient of the variation of the Root Mean Square Error - CVRMSE

$$CVRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{Ni}(S_i - M_i)^2}{N_i}}}{\frac{1}{N_i}\sum_{i=1}^{Ni} M_i}$$

The RMSE takes the absolute value and squares it, which means that larger deviations gain more weight than smaller ones, but at the same time, it loses information on the direction of the error, i.e. whether the result is overall over or under predicted. Building on this, the CVRMSE goes a step further, normalising this metric by the mean value of the dependent variable.

The objective of this model calibration is to create a dynamic model that achieves the indoor temperature within error limits. This parameter is of considerable importance in this analysis, since one of the goals of the PRELUDE project is to sacrifice the building's indoor climate by monitoring user acceptance in order to optimise energy performance. A good simulation by the internal temperature model, therefore, would allow the model to be able to verify the trend of the internal temperature based on the changes made to the setpoint of the house, thus being able to predict the actual possibility of the changes being realised.

To this end, several models have been created to obtain the most accurate representation of the house's interior temperature and the indoor comfort. The variable that is used to validate the energy model is the indoor temperature.

The calibration acceptance criterion for each calibration step is MBE < 0.05 and CVRMSE < 0.15 for calibration of monthly data, and MBE < 0.10 and CVRMSE < 0.30 for calibration of hourly data, respectively. For this analysis, the error was calculated on an hourly basis.

Iterative manual calibration, used in this analysis, consists of adjusting inputs and parameters based on an error until the programme output matches the known data.

5.1.1 Model simulation 1 – Standard

A basic model was created that follows the European standard EN 16798-1-2019. It refers to indoor environmental parameters for the design and assessment of the energy performance of buildings, with reference to indoor air quality, thermal environment, lighting and acoustics [17].

First, file was created with the available meteorological data monitored during the period of interest. In particular, data on the external dry bulb temperature and relative air humidity during the period from January to May 2022.

Then, taking Annex C of the European standard, which specifies the inputs to be included in the energy calculation, as a reference, the standard dwelling model was created. In this case, the table of inputs referring to detached houses was chosen.

Starting from the activity model, an occupancy rate of 0.0235 pers/m^2 was defined, which corresponds to a value of 42.5 m^2/pers.

Internal gains are divided into occupants with a value of 2.8 W/m^2 and appliances with a value of 2.4 W/m^2.

Setpoint conditions, the same for each zone, have also been defined and are shown in the table below. The parameter T,op represents the operating temperature of the model.

Table 18 - Operative temperature used in the first model

Min T,op	20 °C
Max T,op	26 °C
Min T,op in unoccupied hours	16 °C
Max T,op in unoccupied hours	32 °C

The relative humidity was set to a minimum value of 25% and a maximum value of 60%.

The standards consider a domestic hot water consumption of 100 l/m^2y, which means a value of 0.274 l/m^2y.

This first model has a simplified HVAC system, which means that energy use is calculated based on space loads and the COP value of the system, operational control is provided by setpoints and schedules, and auxiliaries and domestic hot water are also modelled according to schedules.

In this standard case, the ventilation rate was set at 0.5 l/m^2s. In addition, the operating time of the HVAC system is 24 hours. AHU heat recovery and natural ventilation have not been considered for the time being.

EN 16798-1-2019 also gives the times of use for calculating energy by occupants, lighting and appliances, divided into weekdays and weekends.

Table 19 - Time use for calculating energy by the EN 16798-1-2019

	Weekdays			**Weekends**		
h	**Occupants**	**Appliances**	**Lighting**	**Occupants**	**Appliances**	**Lighting**
1	1	0.5	0	1	0.5	0
2	1	0.5	0	1	0.5	0
3	1	0.5	0	1	0.5	0
4	1	0.5	0	1	0.5	0
5	1	0.5	0	1	0.5	0
6	1	0.5	0	1	0.5	0
7	0.5	0.5	0.15	0.8	0.5	0.15
8	0.5	0.7	0.15	0.8	0.7	0.15
9	0.5	0.7	0.15	0.8	0.7	0.15
10	0.1	0.5	0.15	0.8	0.5	0.15
11	0.1	0.5	0.05	0.8	0.5	0.15
12	0.1	0.6	0.05	0.8	0.6	0.05
13	0.1	0.6	0.05	0.8	0.6	0.05
14	0.2	0.6	0.05	0.8	0.6	0.05

15	0.2	0.6	0.05	0.8	0.6	0.05
16	0.2	0.5	0.05	0.8	0.5	0.05
17	0.5	0.5	0.2	0.8	0.5	0.2
18	0.5	0.7	0.2	0.8	0.7	0.2
19	0.5	0.7	0.2	0.8	0.7	0.2
20	0.8	0.8	0.2	0.8	0.8	0.2
21	0.8	0.8	0.2	0.8	0.8	0.2
22	0.8	0.8	0.2	0.8	0.8	0.2
23	1	0.6	0.15	1	0.6	0.15
24	1	0.6	0.15	1	0.6	0.15

This basic model was simulated with the current climate file running from 1 January 2022 to the end of May.

In the table below, there are the results in terms of Mean Bias Error and Coefficient of Variation of Root Mean Square Error for the indoor temperature of each room.

Table 20 - MBE and CVRMSE of the operative temperature for the first model

Room type	**MBE of T,op (-)**	**CVRMSE of T,op (-)**
Room1	-0.13	0.15
Room2	-0.14	0.15
Room3	-0.14	0.16
Bedroom	-0.12	0.13
Livingroom	-0.13	0.15
Kitchen	-0.16	0.17
Utility	-0.17	0.18
Lavatory2	-0.18	0.18
Lavatory1 (lower part)	-0.15	0.16
Total	**-0.15**	**0.16**

It can be seen that the internal temperature reached in each room by the simulation is lower than the real one, and this is well demonstrated by the MBE.

Especially during the months of January and February, the model, being based on an ideal HVAC system, tends to remain constant on the setpoint temperature, losing the temperature fluctuations present in the real building.

The following graph shows the real and simulated indoor temperatures during the month of March, which is a good example of the building model's ability to often follow the peaks of the real temperature trend.

It can be seen from the Figure 45 that the model manages to simulate the peaks present in the real trend, but the simulated temperature remains considerably lower than the real one.

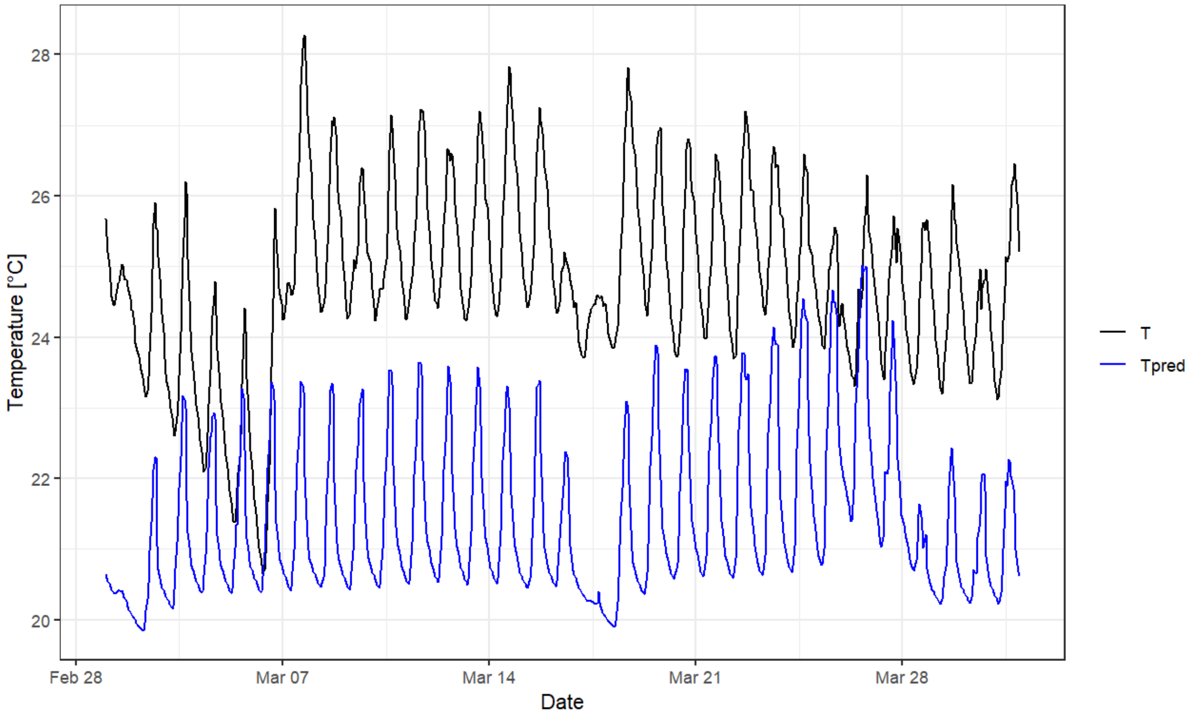

Figure 45 - Comparison of measured and simulated living room temperature of March based on simulation model 1

The scatter plot between the measured and predicted internal temperature also underline the differences obtained, as a strong linear correlation between the two values cannot be seen. An example for the living room indoor temperature is shown in the figure below.

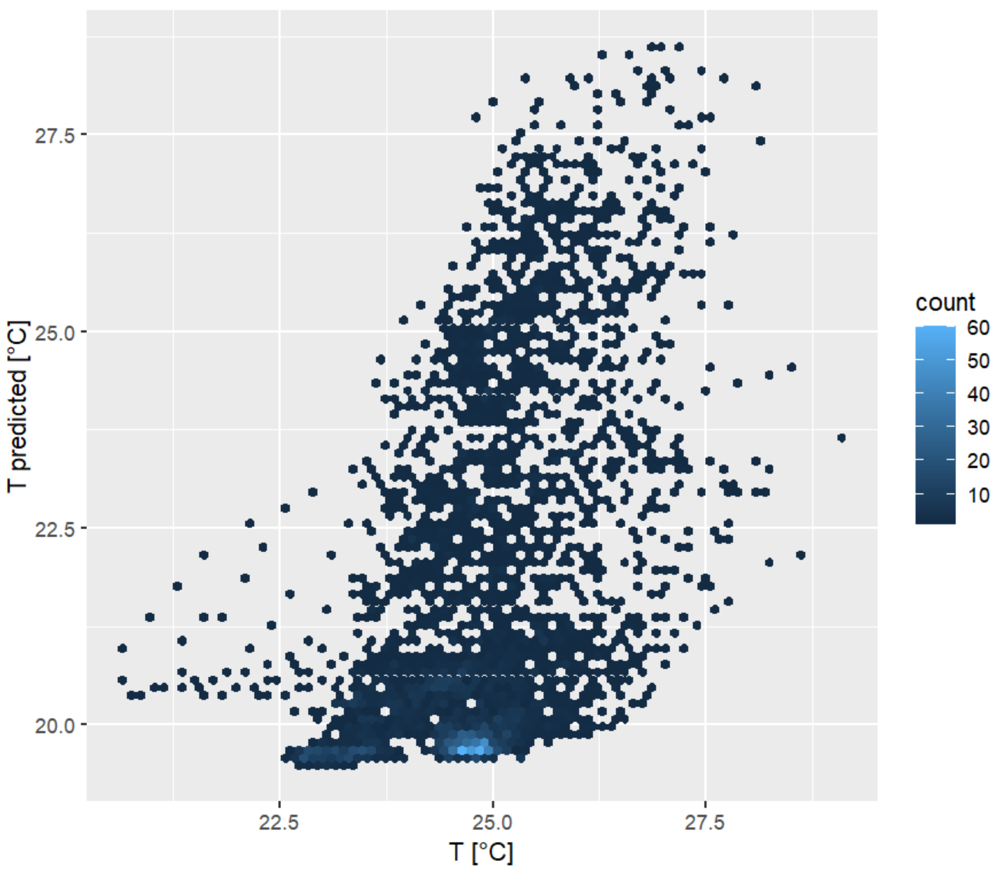

Figure 46 - Comparison of measured and simulated living room temperature based on simulation model 1

5.1.2 Model simulation 2 - Occupancy

This second model includes an occupancy module with the weekly routine of the occupants.

For each room, a schedule was created specifying the presence or absence of the occupants for each hour. this was possible because the inhabitants of the house specified their routines in a normal week, as is shown in the table below.

Starting from their weekly routines under recruitment to recreate the hourly occupancy of each room. For example, for the master bedroom, an occupancy of unity was assumed from 11pm to 6am, and 0 throughout the day, as shown below, as the occupants are both workers, so it was assumed they spend the remainder of the day, when at home, in other spaces.

In the first model, therefore, there was a single occupancy schedule for the entire building, whereas in this second simulation, each space has an occupancy profile. In particular, 7/12 schedules were created in which each day of the week and each month of the year can have a unique daily variation defined by the profiles. Below is an example of the daily occupancy fraction of the master bedroom on Monday.

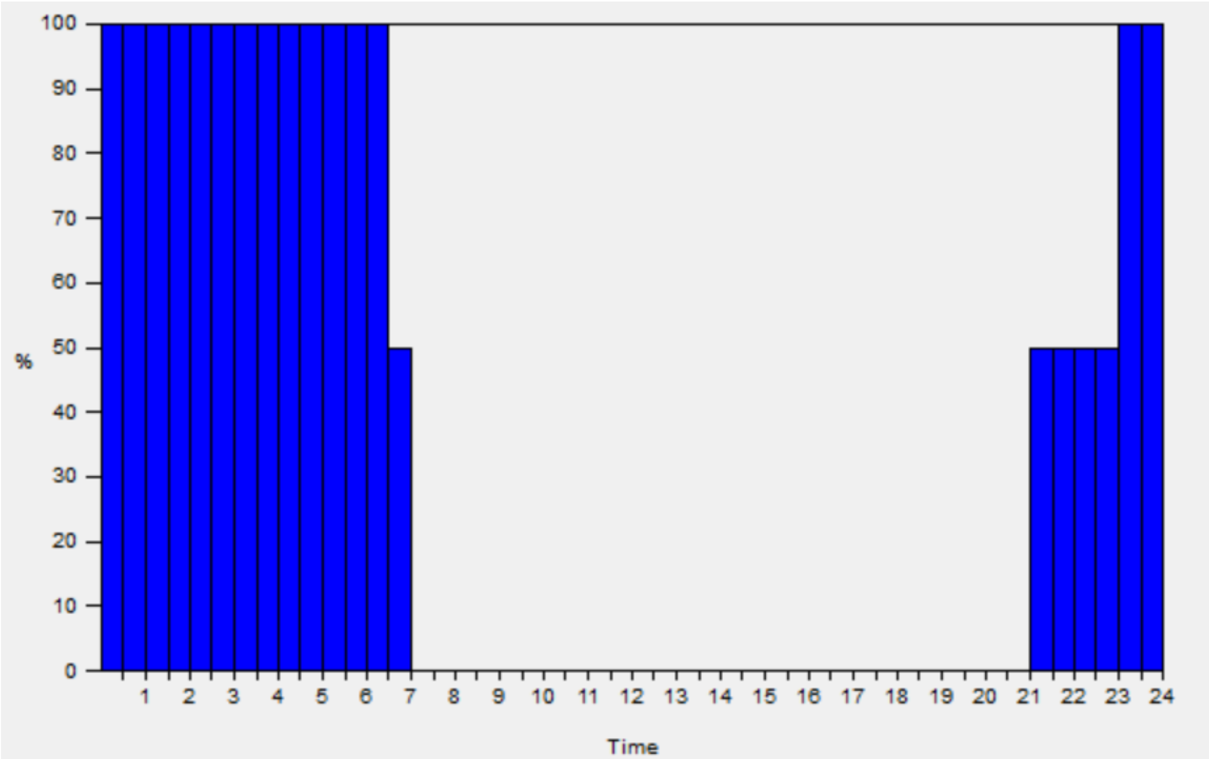

Figure 47 - Master bedroom occupancy schedule on Mondays

From the table below, it can be seen that changing the occupation plan does not lead to differences in terms of MBE and CVRMSE; on the contrary, the results are worse than for the first model. Especially for the Mean Bias Error whose values, on average, increased slightly. This is because with the new schedules there are fewer occupancy hours in each room than in model 1, so the internal temperature is slightly lower.

It is evident, however, that occupancy, in this case, has very little influence on the internal temperature of the building. In fact, it is good to remember that the family consists of 3 members, and on such a building, their occupancy profile changes the internal conditions very little.

Table 21 - MBE and CVRMSE of the operative temperature for the second model

Room type	MBE of T,op [-]	CVRMSE of T,op [-]
Room1	-0.14	0.15
Room2	-0.14	0.15
Room3	-0.15	0.16
Bedroom	-0.13	0.14
Livingroom	-0.13	0.15
Kitchen	-0.16	0.17
Utility	-0.18	0.18
Lavatory2	-0.18	0.18

Lavatory1 (lower part)	-0.17	0.17
Total	**-0.15**	**0.16**

5.1.3 Model simulation 3 - Setpoint

Starting with model 2, in this one the set point of each room was modified by taking as a reference the lowest indoor temperature measured in the coldest month of the period. As the following graph shows, the lowest temperatures were recorded in January, particularly in the first two weeks, because although temperatures as low as -5 degrees were recorded in March, they were higher on average.

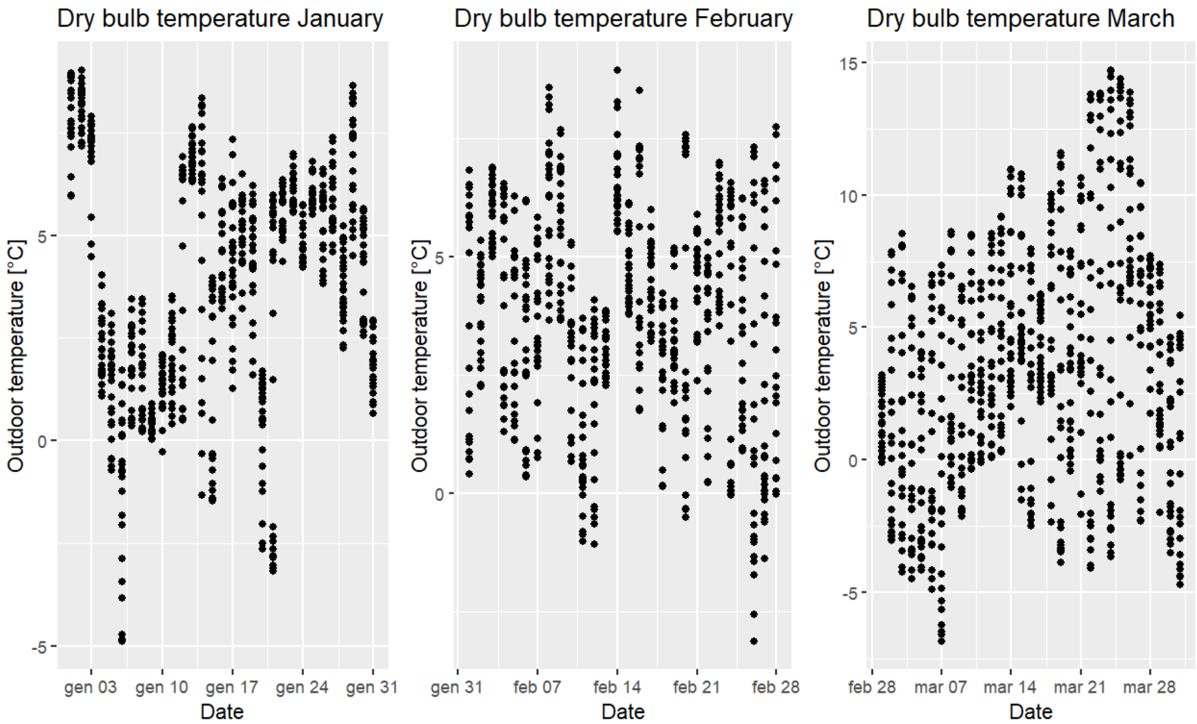

Figure 48 - Outdoor temperature during January, February and March 2022

Then a boxplot was created with the first two weeks of January in order to have a visual summary of this data and to find the closest actual setpoint temperature. Below is an example of the process performed, corresponding to the living room, a boxplot was created for each day in order to achieve greater accuracy on the internal temperature values.

Outliers were first eliminated where present and then the setpoint value corresponding to the first quartile of the boxplot was chosen. Lower values were considered as values caused by the opening of the windows.

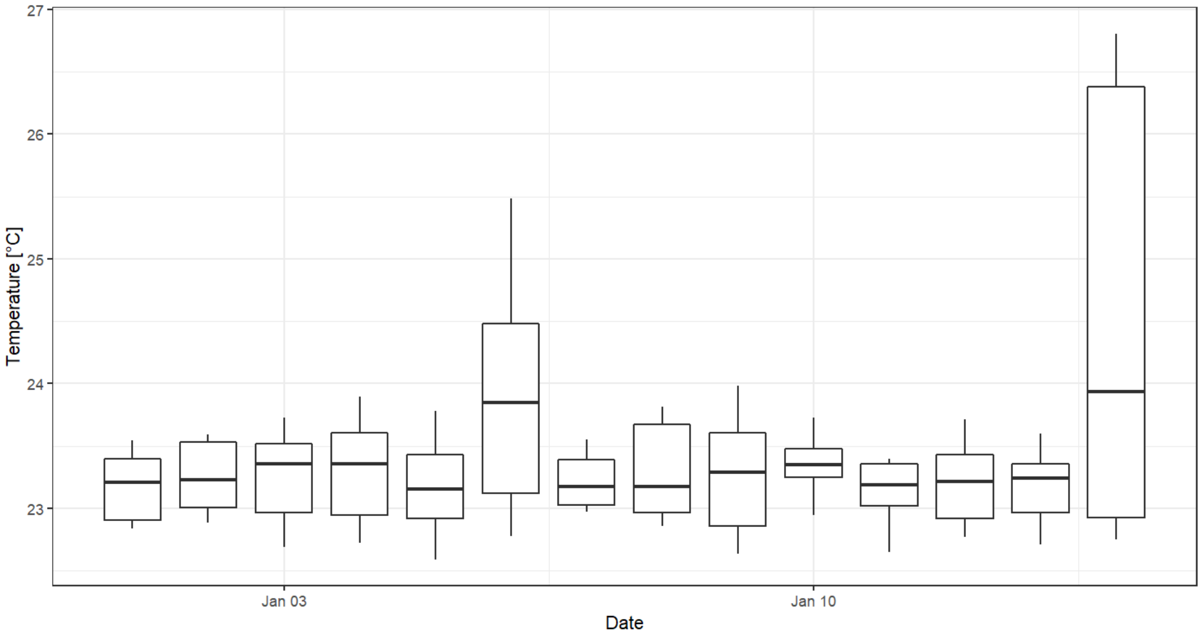

Figure 49- Boxplot for each day of the indoor temperature of the living room during the first two weeks of January

The following table shows the final temperature setpoints adopted in the model based on this analysis. As can be seen from the table, there is a big difference from the initial model which considered a single setpoint temperature for the entire building of 20°C.

Table 22 - Setpoint temperature used in the third model for each room

Room type	Setpoint temperature [°C]
Bedroom	22.5
Livingroom	22.9
Kitchen	24.0
Room1	22.7
Room2	22.8
Room3	22.9
Bathroom1	23.2
Bathroom2	23.9
Utility	22.5

It can be seen that this third model differs considerably from the first, even though the simulated temperature does not reach all the peaks of the real one, it can be seen that the modification of the model setpoint enabled satisfactory results to be obtained. The adjustment of the setpoint temperature has a great influence on the results, since in this building, as can be seen from the measured internal temperature values, each room has its own internal comfort, which often differs substantially.

The line graph below shows the comparison of the simulated and measured internal temperature trends during the month of March.

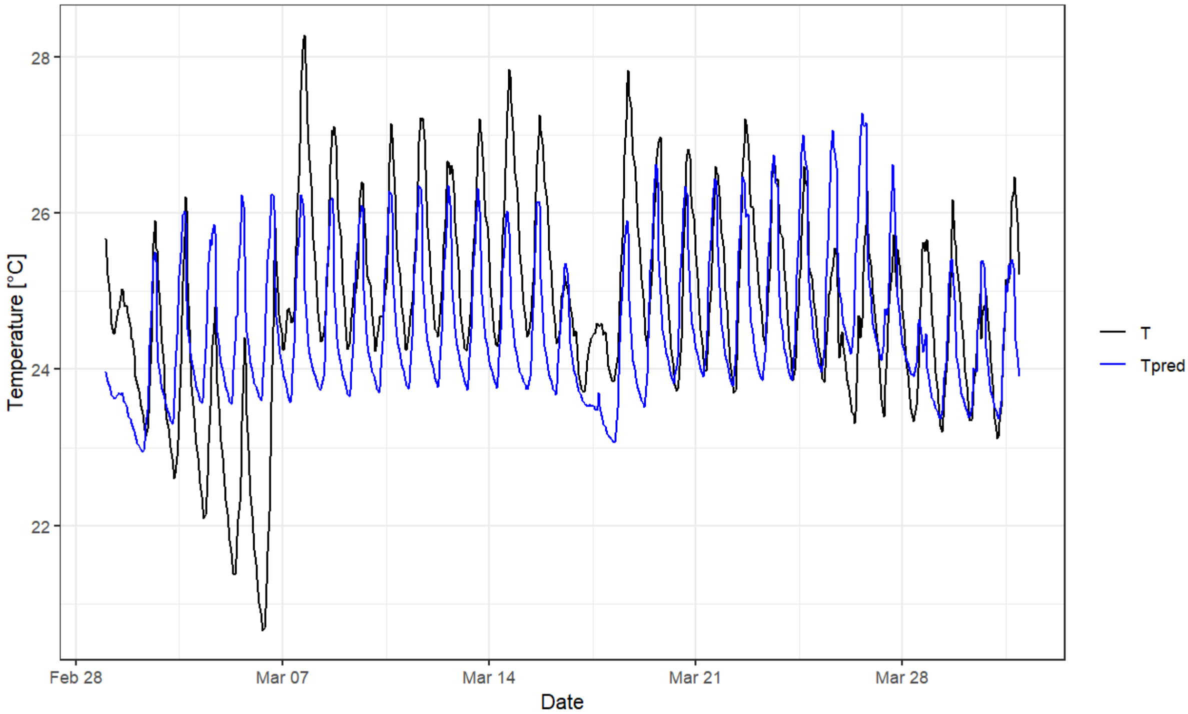

Figure 50 - Comparison of measured and simulated living room temperature of March based on simulation model 3

During the first week of March, there was a noticeable drop in the actual indoor temperature, probably due to a failure in temperature sensor detection or an actual malfunction of the HVAC system.

Furthermore, from the second half of January until the end of February, it can be seen that the simulated internal temperature, despite the setpoint adjustment, remains significantly lower than the actual temperature.

One explanation for this trend could be that the family was on holiday during the first two weeks of January and therefore lowered the setpoints in the house, which means that the model during this month and a half could not effectively represent the actual indoor temperature. The graph below shows the variation of the indoor conditions in the house during the month of January.

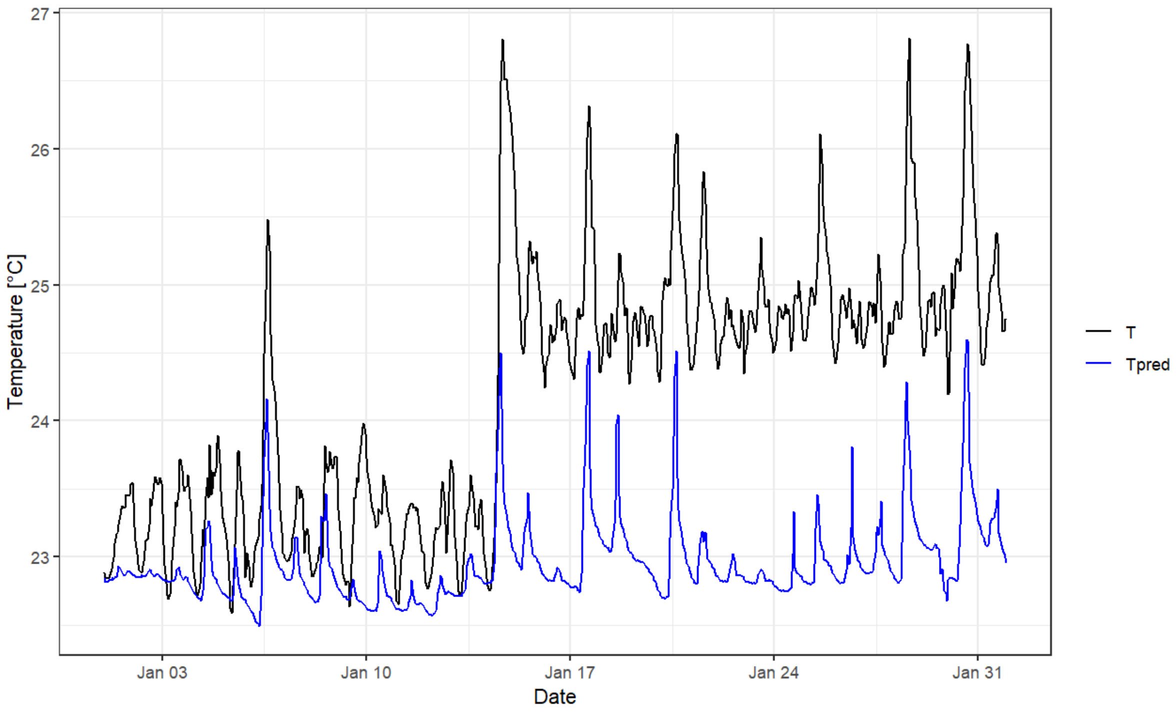

Figure 51 – Comparison of measured and simulated living room temperature of January based on simulation model 3

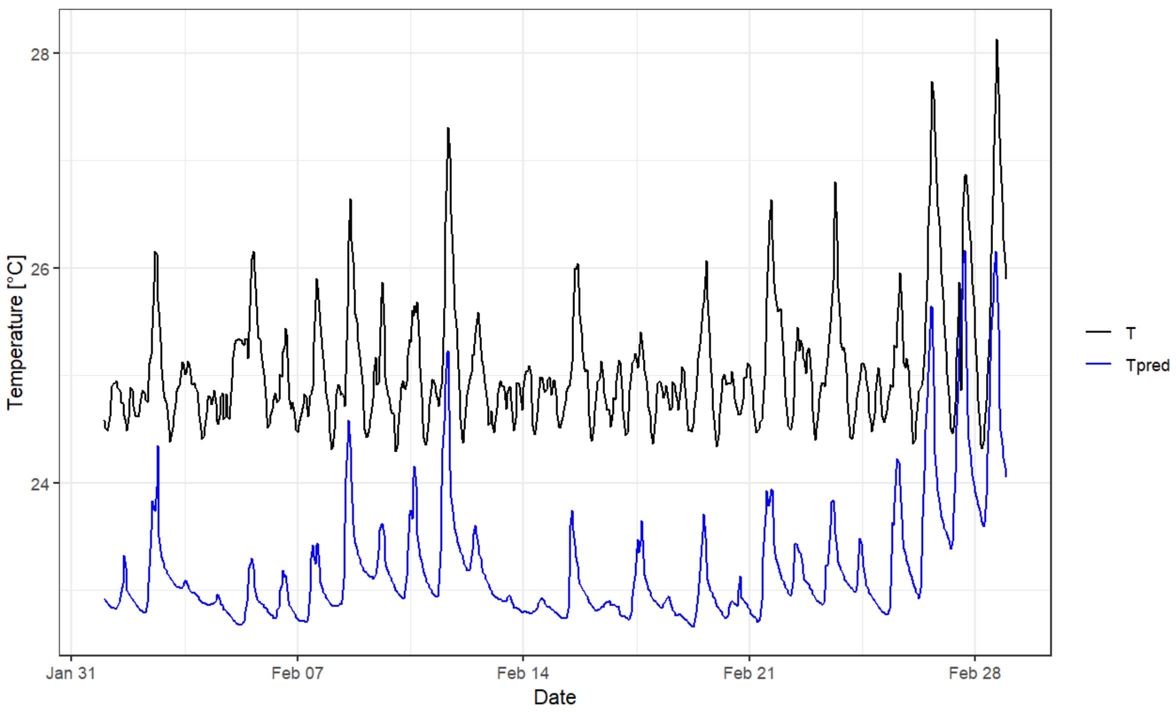

Figure 52 - Comparison of measured and simulated living room temperature of February based on simulation model 3

The following graph summarises the comparison between the real and simulated indoor temperature trends in the second week of each month considered.

The second week of each month was chosen in order to have a better representation of real and simulated temperature trends. In fact, considering this period, one can see both the model's efficiency in following the real temperature trend, especially in March, April and May, and its inability to simulate the internal temperature in February in particular.

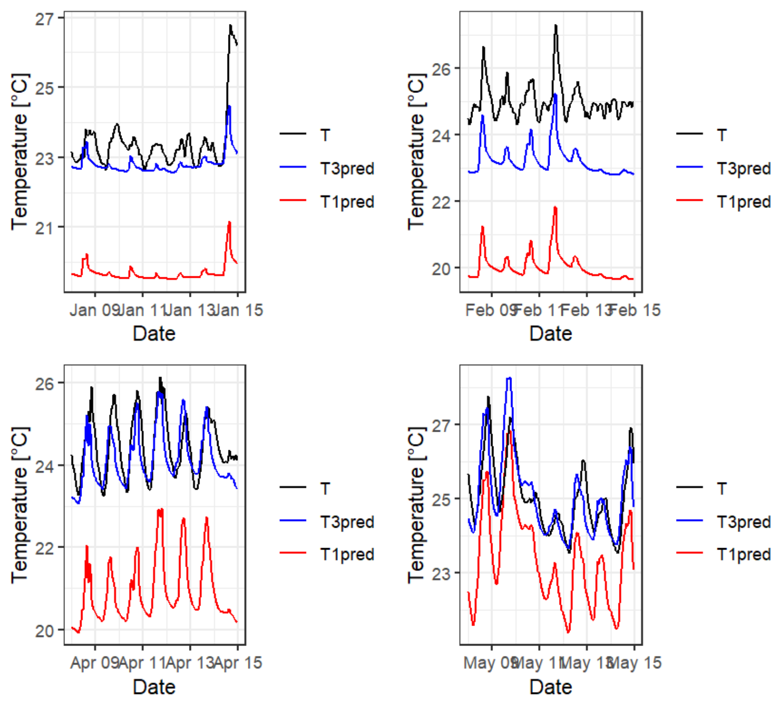

Figure 53 - Comparison of real and simulated living room indoor temperatures in the first (T1pred) and in the third (T3pred) model during the second week of each month considered in the analysis

The next scatter plot, compared to the previous one, also shows a greater correlation between the two temperature values. the points on the graph are much closer together and more compact.

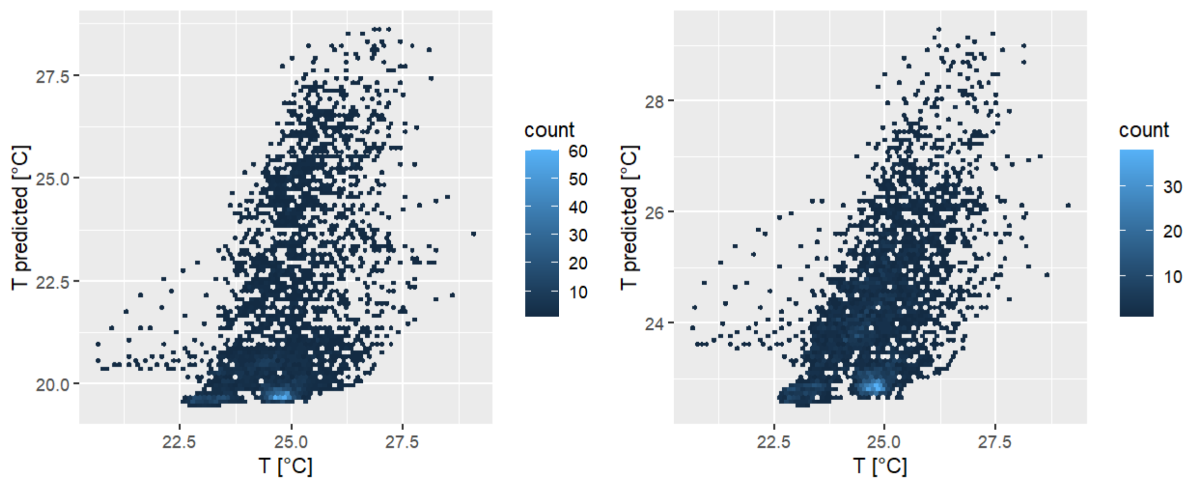

Figure 54 - Comparison of measured and simulated living room temperature based on simulation model 1 on the left and model 3 on the right

As can be seen below, changing the setpoint significantly reduced the MBE and CVRMSE with respect to the internal temperature. The values are now within the previously defined limits. The model therefore achieves its goal in terms of representing the internal temperature of the house.

Table 23 - MBE and CVRMSE of the operative temperature for the third model

Room type	**MBE of T,op [-]**	**CVRMSE of T,op [-]**
Room1	-0.04	0.06
Room2	-0.04	0.05
Room3	-0.05	0.06
Bedroom	-0.04	0.06
Livingroom	-0.02	0.05
Kitchen	-0.04	0.06
Utility	-0.08	0.09
Lavatory2	-0.06	0.06
Lavatory1 (lower part)	-0.05	0.06
Total	**-0.05**	**0.06**

5.1.4 Model simulation 4 - HVAC

In this last model, the HVAC system was represented in detail and no longer simplified. This option controls how the temperature and humidity setpoints of the zones are defined, as well as data on ventilation requirements and hot water consumption. Three circuits were therefore designed: Air Circuit, Water Circuit and the District Heating Circuit.

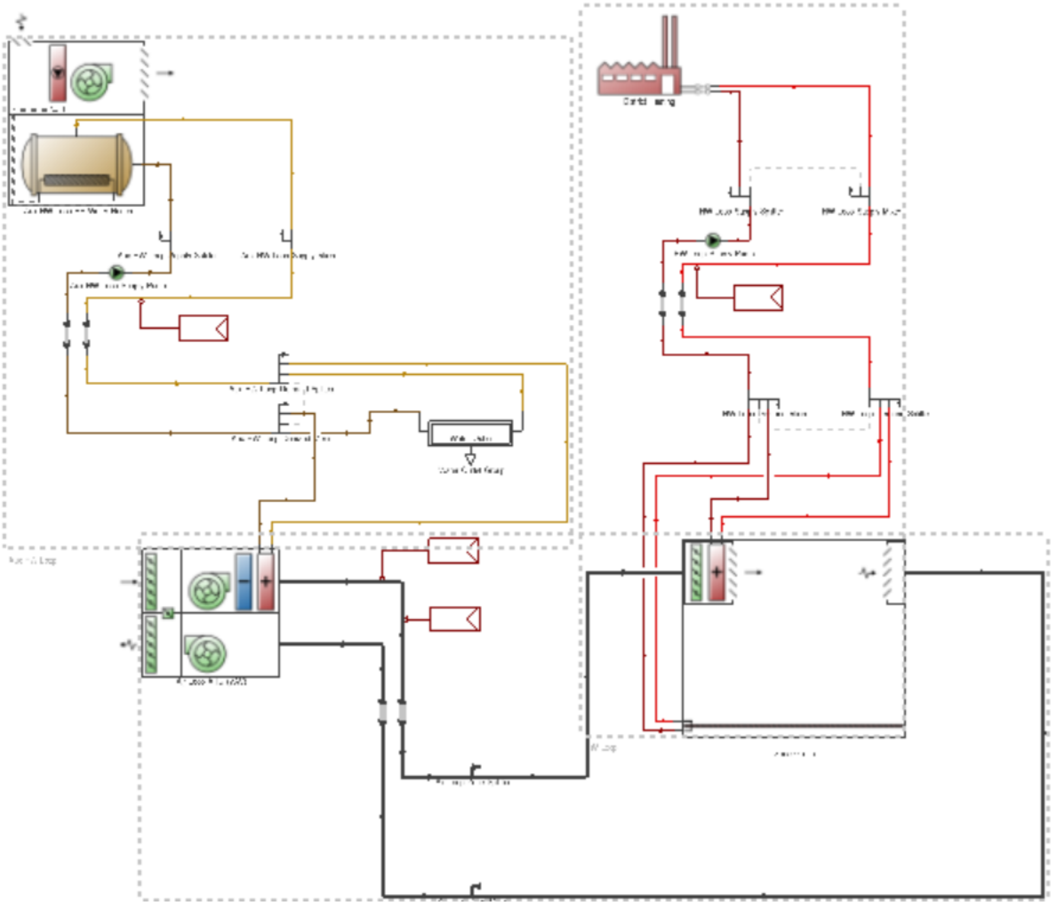

Figure 55 - HVAC model in Design Builder

This model was created to evaluate the differences in the simulation of the indoor temperature with a defined HVAC system in detail and also to evaluate how well the model was able to represent the consumption of electricity and heating.

The aim of the modelling in Design Builder, in fact, is to represent the internal temperature of the house as realistically as possible, as this will be the focus of the third phase of the PRELUDE project, in which energy reduction is prioritised and the indoor climate is sacrificed, while user acceptance is monitored.

At the same time, it is useful to consider how the model is also able to simulate energy consumption, despite the fact that the house has a HVAC system that is very complicated to represent and sometimes, as described above, prone to failure.

The air changes per hour were changed, as the average measured value of the volumetric flow of supply air for the six months analysed is approximately 136 m^3/h, which corresponds to 0.346 ac/h.

In addition, the total amount of domestic hot water was also changed. The actual amount of domestic hot water for the selected months is 15.9 m^3/h, which means a value of 0.552 l/m^2 day.

These are the results in terms of MBE and CVRMSE of the internal temperature of the fourth simulation.

Table 24 - MBE and CVRMSE of the operative temperature for the fourth model

Room type	**MBE of T,op** **[-]**	**CVRMSE of T,op** **[-]**
Room1	0.06	0.10
Room2	0.04	0.08
Room3	0.05	0.09
Bedroom	0.07	0.11
Livingroom	0.07	0.11
Kitchen	0.05	0.08
Utility	0.00	0.05
Lavatory2	0.02	0.05
Lavatory1 (lower part)	0.04	0.08
Total	**0.04**	**0.08**

It is evident how, in this fourth model, the simulated indoor temperature is higher than the real one, unlike in the other three models. Both MBE and CVRMSE for temperature maintain values within limits.

Comparing the line graphs of the third and fourth simulations, the model that manages to simulate the behaviour of the indoor temperature better over the five months is the third one.

The simulation with the detailed HVAC system does, indeed, seem to simulate the building's winter behaviour better, especially in February, but in the warmer months it fails to replicate the peaks that occur in the real indoor temperature.

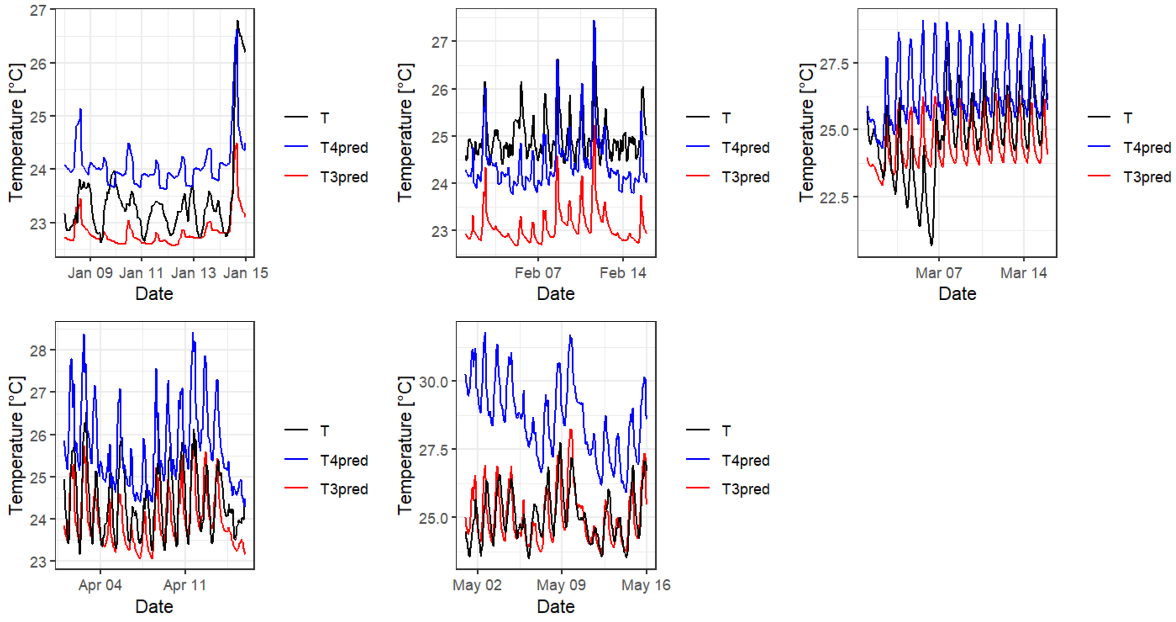

Figure 56 - Comparison of real and simulated living room indoor temperatures in the third (T3pred) and in the fourth (T4pred) model during the second week of each month considered in the analysis

Analysing the simulation of energy consumption for heating, it can be seen that the model fails in its representation, significantly underestimating it. MBE and CVRMSE, in fact, are well above the imposed limits, as shown in the table below.

Table 25 - Summary table of the results of the fourth model in terms of electricity consumption

	Total heating consumption [kWh]	Heating errors [-]	
Simulated	1786	MBE	CVRMSE
Measured	4785	-0.63	1.70

With regard to the simulation of the electricity consumption of the house, from the analysis of the MBE and CVRMSE, shown in the Table 26, it can be seen that the model is not fully efficient and is, in fact, not within the imposed limits.

Table 26 - Summary table of the results of the fourth model in terms of heating consumption

	Total electricity consumption [kWh]	Electricity errors [-]	
Simulated	2367.266	MBE	CVRMSE
Measured	1342.413	0.76	1.25

Graphing the trend of real and simulated electricity, one can see that the model manages to replicate the order of magnitude of electricity consumption, but not the peaks that occur. On the contrary, sometimes, as in the graph of the second week of January, the model predicts inverse peaks to the real ones.

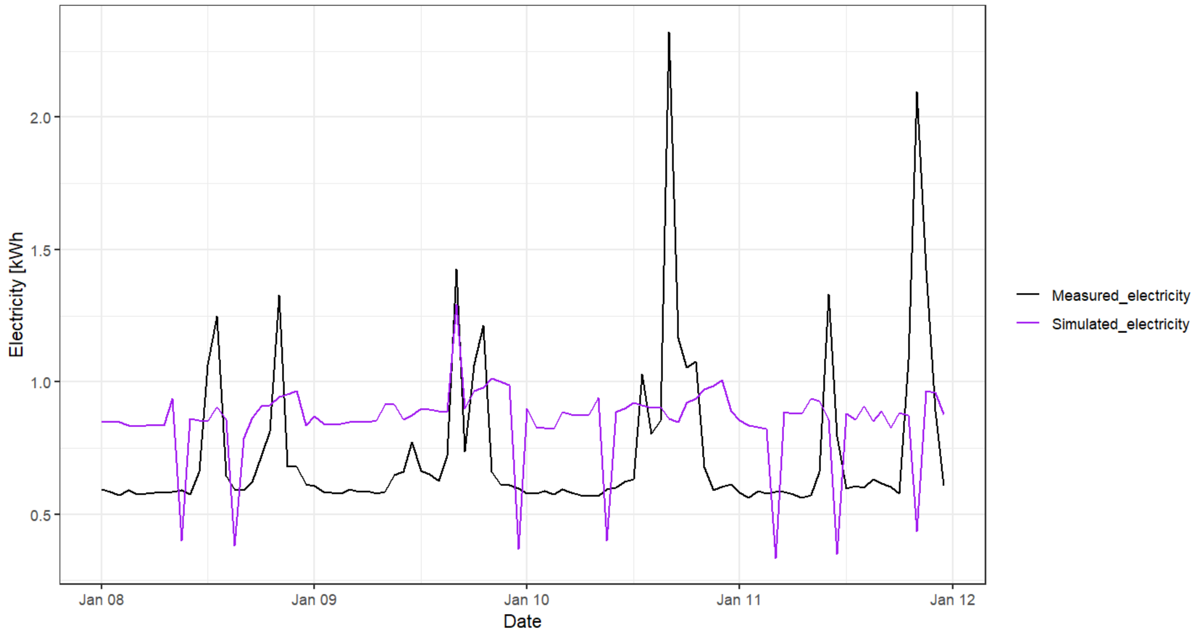

Figure 57 - Comparison of the simulated and measured electricity consumption during the second week of January

One of the main problems in the simulation of electricity consumption is the complexity of the building system. As shown in the Figure 4 and 5, the heat pump for hot water supply connected to the AHU of the house was represented, but this can be difficult to implement from the model itself.

Another test performed was to eliminate the domestic hot water consumption produced by the heat pump, to see if considering only the AHU without the heat pump contribution would give a more realistic representation.

As could be expected, electricity consumption decreased and so did the errors of the MBE and CVRMSE, but the electricity trend is less realistic. In fact, graphing the same trend presented in the Figure 57, one can see the presence of many more consumption peaks that are not related to the actual trend.

	Total electricity consumption [kWh]	Electricity errors [-]	
Simulated	1987.377	MBE	CVRMSE
Measured	1342.413	0.48	1.10

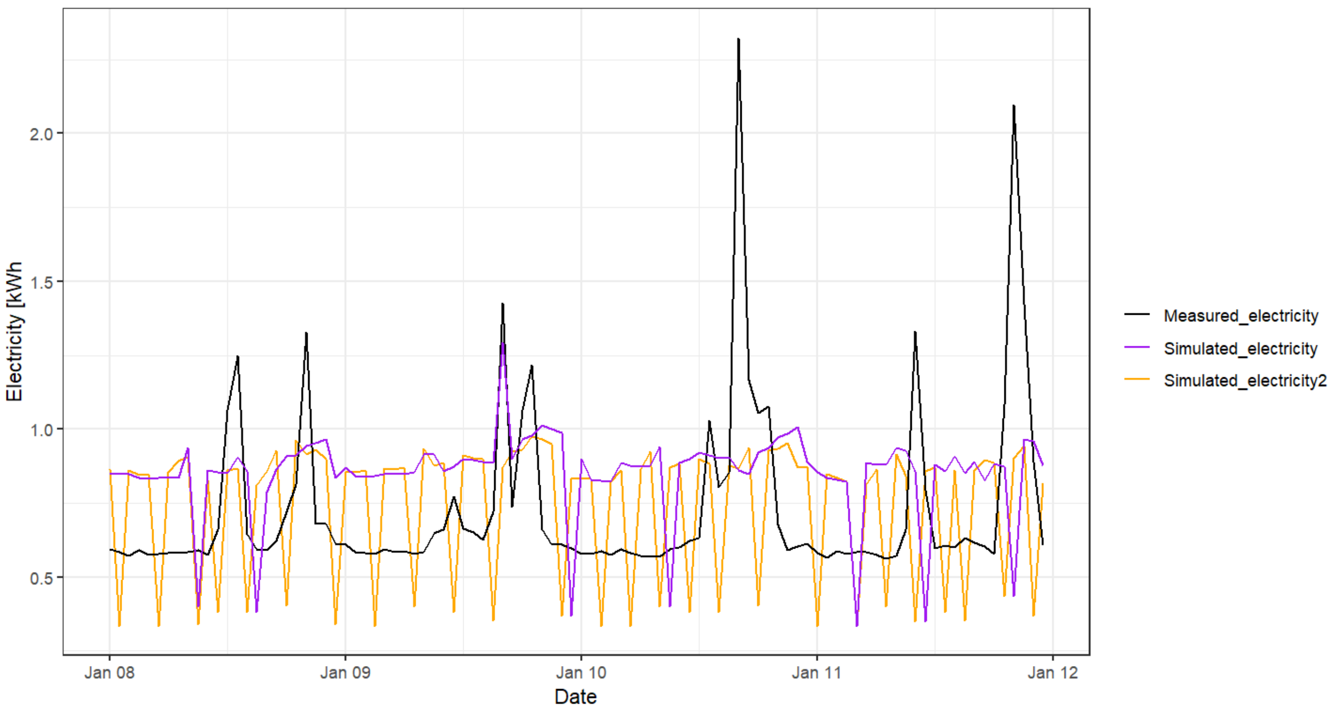

Figure 58 - Comparison of the simulated without DHW and measured electricity consumption during the second week of January

6. Conclusions

The role of zero-energy buildings has been recognised as crucial for the transition to post-carbon scenarios and there is an increasing orientation of the building sector towards near-zero energy consumption leading to a growth in the construction of NZEB buildings or the renovation of old buildings for this purpose.

However, the rising percentage of these types of buildings has led to increased investigation of their behaviour and the conclusion that often, even if the building is designed for low energy demand, it can be inefficient during actual use and the causes of the gap between actual and predicted energy performance can be of various kinds.

The study focuses on using real data to assess this possible gap between the two performances. Evaluations conducted on an NZEB building in Denmark identified system failures and occupant behaviour as the main reason for the discrepancy between estimated and actual energy consumption.

Denmark is a leading state in terms of energy-efficient buildings, and the increasing tightening of Danish building regulations to at least class A2015 means that the number of such buildings is set to increase. Therefore, the study of their energy behaviour is essential to analyse the causes of the performance gap and to create models that can be adapted and generalised to a large scale of buildings.

Once the difference between actual consumption and the performance defined by Be18 has been demonstrated, the study analysed the energy consumption and internal conditions of the case study over a 4-year period with two different families as occupants of the house.

The results of the analysis showed an increase in consumption due to faults in the HVAC system, such as air supply temperature sensors, and the behaviour of the inhabitants of the house, such as setting certain setpoint temperatures to achieve a desired level of indoor comfort.

A dynamic model of the building, then, was constructed to obtain a realistic reproduction of the building and to evaluate the effect of varying set point conditions, in particular the internal temperature, to obtain a reduction in energy demand.

In order to gain a good insight into the performance gap of NZEB buildings, in fact, it is necessary to collect in-depth data on them, monitor and replicate them in order to achieve a significant impact on the realisation of near-zero energy buildings that function as intended.

The application to a real case and the availability of measured energy use data made it possible to verify the inefficiency of building performance and the main factors responsible for the gap. Therefore, the difference in complexity of the implementation process of such monitoring between the Danish and Italian realities should not be underestimated.

Appendix A – Construction

Ground deck

Material	Thickness [m]	Thermal conductivity, λ [W/(m K)]	Thermal resistance, R [(m² K)/W]
Concrete	0.040	1.900	0.042*
EPS	0.320	0.031	10.323
$R_{surface}$ soil			1.500
Total thickness	0.440		
		R, [(m² K)/W]	11.865
		U-value, [W/(m² K)]	**0.0843**

*Having a floor with underfloor heating, the layers above the underfloor heating pipes are neglected, including the internal resistance. The concrete layer is then divided into two: 0.04 m below the floor heating pipes and 0.08 m above the floor heating pipes.

Exterior wall

Material	Thickness [m]	Thermal conductivity, λ [W/(m K)]	Thermal resistance, R [(m² K)/W]
$R_{surface}$ in			0.130
Aerated Concrete	0.125	0.170	0.735
Mineral wool	0.190	0.034	5.588
Bricks	0.108	0.730	0.148
$R_{surface}$ out			0.040
Total thickness	0.423		
		R, [(m² K/W)]	6.64
		U-value, [(W/m² K)]	**0.15**

Roof/ceiling

Material	Thickness [m]	Thermal conductivity, λ [W/(m K)]	Thermal resistance, R [(m² K)/W]
$R_{surface}$ in			0.100
Plasterboard or Acoustic board	0.013	0.250	0.052

Wood spread	0.025		0.160
Granulate mineral wool	0.430	0.041	10.488
Air gap	0.050	0.090	0.556
Wood board w/ roofing cardboard	0.018	0.050	0.360
$R_{surface}$ out			0.040
Total thickness	0.536		
		R, [(m^2 K/W)]	11.76
		U-value, [(W/m^2 K)]	**0.09**

Foundation

The stratigraphy of the foundation is composed of the construction of Skawblock, a foundation block with an aerated concrete shell and EPS between. The linear thermal transmittance is 0.13 W/(mK).

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