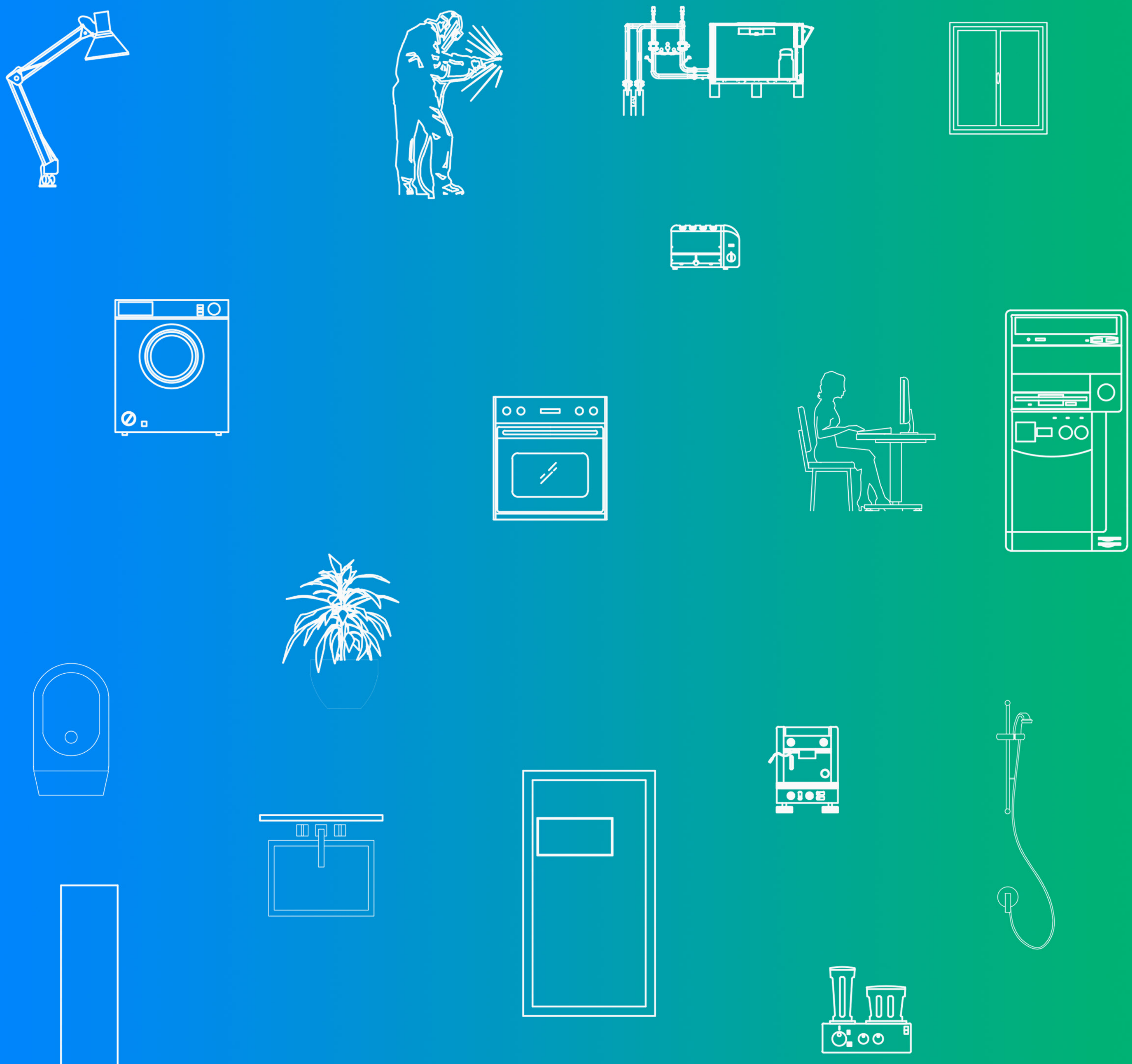

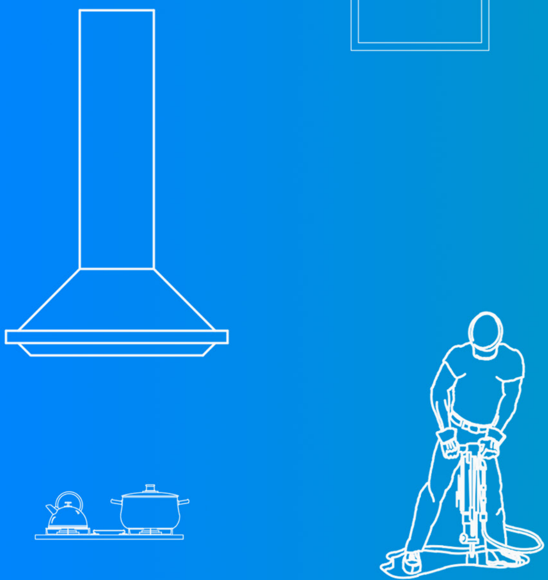

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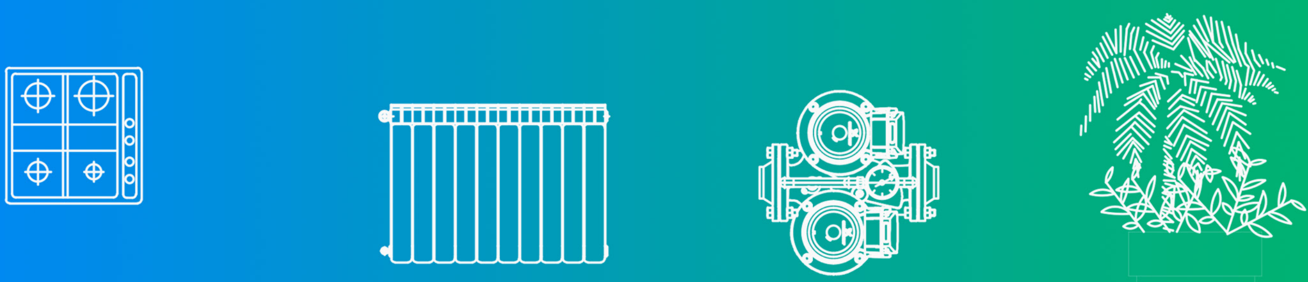

Investigating the effect of human behaviour on the energy performance of 3 typical Dutch residential dwellings using sensors and dynamic performance modelling

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To obtain the degree of

of

Master of Science in Civil Engineering - Track - Building Engineering - Specialization - Building Physics and Technology

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Contents

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Yash Dugar, Delft

Abstract

Buildings don't use energy: People do. Do highly efficient homes really save energy? Counter-intuitively, dwellings that use less energy have low energy efficiency, and those with higher energy consumption have higher efficiency. Moreover, even accurate building energy simulation for multiple buildings could not predict the actual energy consumption. This is termed as the 'energy performance gap'. The regulatory energy performance gap is found to deviate by +34% with an SD of 55% based on 62 case buildings. In certain cases, the energy performance gap due to occupant behaviour was 300%. This is attributed to factors such as- climate, indoor design criteria, building energy service systems, building envelope, building operation maintenance and occupant behaviour. Significant progress in all the stated aspects has been made, except the latter - occupant behaviour.

Occupant behavior is complex, stochastic and multi-disciplinary. Accounting for it is challenging. Typical human interventions like heating/cooling, opening/closing windows, use of sunshades, hot water used, number of electrical appliances, lighting and cooking (gas/electric) play an important role in predicting the actual energy usage. Over-simplification and negligence of these interventions during the design phase is responsible for the energy performance gap.

This study aims to study the impact of occupant behaviour on the energy consumption of three Dutch residential dwellings with an emphasis on data-informed decisions and predictions. Three candidates - senior couple, young couple and family were selected out of 13 interested candidates. Their houses were observed for 2 weeks from 7th - 21st of March 2019 with the help of sensors and meters. This study proposes a novel, flexible and inexpensive method of data collection with micro-controllers and sensors. The cost of one set-up being as low as € 14. With the help of actual data and the dynamic performance modelling tool - IES(VE) 2018, this study informs the readers about the energy distribution in low and highly energy efficient homes. Comparison of the actual energy consumption with energy standards like EPC and BENG has been made to study their reliability. It also discusses the possibility of sensors and actuators replacing sophisticated energy-siphoning HVAC systems. Lastly, the impact of the three households' behaviour on their energy consumption has been quantified.

Chapter 1

Introduction

Global temperature rise, shrinking ice sheets, glacial retreats, declining Arctic sea ice, extreme events, and ocean acidification are few of the phenomena that are part of the rapidly growing mound of evidence that points to the fact that climate change is causing irrevocable changes to Earth. According to the IPCC, this unprecedented trend of warming is due to human activity (with a probability of 95%) since the mid 20th century[1].

The residential and commercial building sectors consume up to 20% of the world's total energy [2]. In Europe between 1970 and 2014, the domestic sector consumed 24-27% of the total energy consumption [2]. In 2015, the European Environmental Agency (EEA) reported that buildings (services and households) used 40% of the total energy consumed that year[3]. Whereas in India and China, the building sector consumed 35% and 37% respectively of their total energy consumption [3]. Despite the technological advancements, energy consumption is not reducing at the rate that it should [4]. Furthermore, this ever-growing amount of energy consumed by the building sector coupled along with the exponential population growth makes this issue a pivotal one to address. This will inform and pave the way for the necessary regulations, strategies, and reductions in the global CO_2 emissions.

"Buildings don't use energy; People do" [5]. Do highly efficient homes really save energy? Counter-intuitively, dwellings that use less energy have low energy efficiency and those with higher efficiency have a higher energy consumption[5]. Moreover, accurate building energy simulation for five different buildings could not predict the actual energy consumption[6]. This is termed as the 'energy performance gap'. The regulatory energy performance gap is found to deviate by +34% with an SD of 55% based on 62 case buildings. In certain cases, the energy performance gap due to occupant behaviour was 300%. This is attributed to factors such as- climate, indoor design criteria, building energy service systems, building envelope, building operation maintenance and occupant behaviour. Significant progress in all the stated aspects has been made, except the latter - occupant behaviour.

Occupant behavior is complex, stochastic and multi-disciplinary, so taking it into account could be challenging. Typical human interventions like heating/cooling, opening/closing windows, use of sunshades, amount of hot water used, number of electrical appliances used, use of lighting, cooking (gas/electric) play an important role in predicting the actual energy usage. Accounting for the characteristics of these archetypes and their indoor environment preferences can bridge the energy performance gap.

Advancements in sensor technology have made it possible to adapt to the indoor environment by dynamically responding to the occupants' actions and preferences. Furthermore, this development could lead to accurate energy prediction, reduced energy waste, increased indoor climate control and therefore enhanced user experience.

At first, this study aimed at comparing the energy usage of three households with a similar topology. As the options of study candidates increased, three different house types on the basis of their insulation levels and HVAC systems were chosen. Instead of being a pure modelling study, this study based on real-time data and dynamic modelling. Real-time data provided credibility to the study and the data obtained from modelling aided in prediction and validating improvements. Initially the emphasis on sensor data processing but as the study progressed, the focus shifted more towards energy consumption and the dominant human interventions that influenced this. Comparison of actual use to energy standards like EPC and BENG has been made to study their validity. With the help of actual data and the dynamic performance modelling tool - IES(VE) 2018, this study also aims to study the energy distribution in low and highly energy efficient homes. Furthermore, it discusses the possibility of sensors and actuators replacing sophisticated HVAC systems. Recommendations for further improving the houses in terms of energy and health have been proposed. This study is a prelude to data-informed dynamic energy modelling & prediction and domotics.

1.1 Main research question

- By how much does occupant behaviour impact the energy consumption of typical Dutch residential dwellings?

1.2 Sub-research questions

- Are micro-controllers and sensors a reliable mean of data collection?
- How much can the energy performance gap be reduced to if real-time sensor data is fed into dynamic energy models?
- Are energy predictions by standards like EPC and BENG accurate when compared to the actual energy consumption?
- Can sensors and actuators replace sophisticated energy-siphoning HVAC systems in the future?

This study aims to discuss and answer the above questions.

Chapter 2

Literature Survey

The literature survey aimed at gaining information about the current trend and progress in the field of occupant behaviour and how it affects the energy consumption of residential dwellings. It helped gain perspective regarding the valuable parameters and factors that affect and drive a building's total energy consumption. The dominant factors being - Indoor design criteria, Indoor climate, Building energy & service systems, Envelope Operation & maintenance and Occupant behaviour [7]

Significant progress has been made in the first five fields, so much so that further optimisation for energy savings are challenging and not economically viable (law of diminishing returns [5]). The last field - occupant behaviour has been gaining attention in the past few decades - predominantly due to the impact it has on the building's energy consumption. A study conducted on 62 buildings reported that the effect of occupant behaviour resulted in a deviation of 10-80 % [8].

$$\text{Energy performance gap} = |\text{ Predicted energy consumption - Actual energy consumption }|$$

The energy performance gap due to the dynamic nature of occupant behaviour depends on a plethora of factors. Factors that make it a labyrinth of problems one needs to solve before getting a reasonable estimate of the actual energy consumption. The inability to do so has resulted in hauling the energy performance gap. The energy simulation tools used to predict a building's expected energy consumption generally accounts for the weather and building characteristics (physical and thermal properties) but lacks information regarding the occupants or their behaviour. Recent studies have shown that there is an alarming energy performance gap between the predicted and the actual energy consumption of buildings, in some cases up to 300% [6].

Given the complexity and the large number of ways an occupant can influence its surroundings, justifies the numerous research studies that study their actions. These studies researched the different typologies (commercial offices, residential -traditional & modern, and educational institutions), different interactions (plug loads, heating, electricity consumption, ventilation, air conditioning, window opening, lighting, window blinds, and HVAC systems) and their influential parameters (personal lifestyle, climate, socio-personal, economic, type of activity, design features, occupancy - arrival and departure, and regulations) to explain and quantify their impact[6].

The human energy consumption in dwellings is attributed to their needs and wishes. In the majority of the cases, these needs and wishes are responsible for the inaccuracies in predicting the energy use of a building, which then manifest themselves as a key component alongside with the building characteristics [5]. This has triggered a variety of approaches - theoretical, probabilistic, stochastic, dynamic modelling and data analysis being a few of them. Owing to the exponential population growth and ever-increasing standard of living, this issue becomes of paramount importance when compared to the past few decades. The first step in mitigating

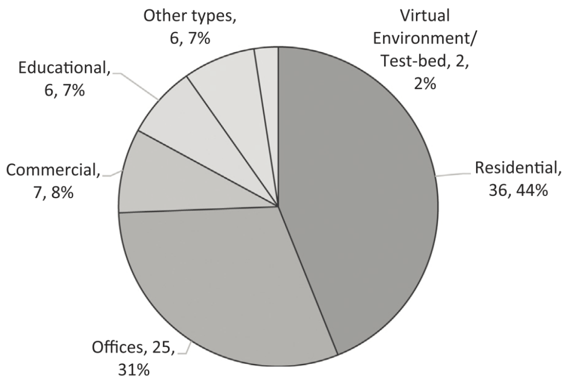
Table 2.1: Factors that drive occupant behaviour in a building [6]

Factors	Parameter
Climatic	Indoor/outdoor temperature Relative humidity Sunlight, wind, rain
Building type	Function
State of occupants	Arrival, departure and duration
Socio-personal	Psychological and Physiological Education and knowledge Lifestyle
Architecture	Spatial design features Building condition Environmental design
Economic	Income Socio-economic Energy price
Political	Regulations and policies

this problem would be to understand the complex relationship between human behaviour and the physical variables of the building they occupy. Then working from that point onwards to resolve where possible energy and emission savings could be made [5]. Following the law of diminishing returns, buildings that are already highly energy efficient are expensive to make more efficient because the majority of low-cost energy savings have already been adopted. For these homes, the most effective strategy for reducing energy and emissions will be to change the energy consuming behaviour of occupants. On the other hand, homes that consume less energy are less energy efficient when compared to the rest of the building stock and greatly benefit from improvements in energy efficiency measures such as improved loft & wall insulation, triple glazing, and improvements to the energy efficiency of the heating system.

Another approach to solving this problem would be to consider occupants' active and passive energy behaviours. Actions such as opening of windows, use of solar shading and blinds, adjusting HVAC set- points and hot water usage are either over-simplified or not fully considered in current energy analysis tools. Thus, this calls for energy modellers, researchers and designers to improve the calculation of the energy consumption of buildings by considering the energy behaviour of the occupants. Furthermore architecturally, the impact of interior design in terms of space layout, fixtures and fittings on the occupants' action scenarios, thermal perceptions, and consequently on their energy behaviour has been overlooked. This aspect required further investigation [6]. Five different studies reported by [9] show that even accurate building energy simulation could not predict the actual energy consumption of the building. Energy simulations take into account the metabolic rate of humans but what they don't take into account is their active energy usage - opening and closing of windows, use of lighting, solar shading, controlling the heating and cooling set-points, use of hot water and electrical appliances.

Occupant interacting components in building performance tools are typically represented in terms of static schedules and power or occupant densities [10], which means that these values do not change from design to design nor do they vary from individual to individual [11]. This implies that occupants are passive recipients of the indoor climate chosen for them but in reality, there is a dynamic interaction between the building and its occupants to restore comfort conditions. Occupants can adapt the indoor climate by interacting with their lights,



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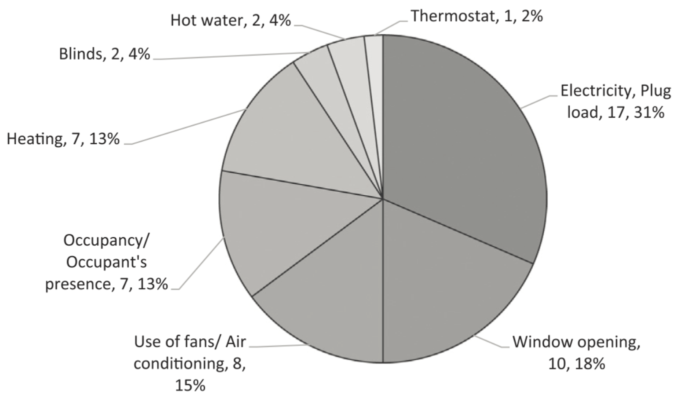
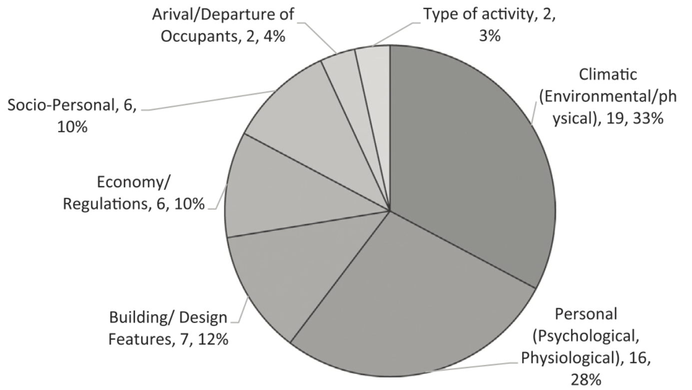
(a) Different building types used as case studies



(b) Different types of occupants interaction



(c) Influential parameters on occupants' energy behaviours

Figure 2.1: Themes of the different studies that researched the influence of occupant behaviour [6]

blinds, windows, thermostats ([12], [13], [14], [7], [15]) and can adapt to the indoor climate by changing their clothing or activity levels ([16], [17], [18]). These behaviors are classified as adaptive behaviors [19], as their primary intent is to restore comfort (thermal, visual, acoustic comfort, and indoor air quality).

On the other hand, there are non-adaptive behaviors such as plug-in equipment use and light switch-off behaviors immediately before departure from a space [19]. These behaviors are not undertaken to mitigate discomfort, but they still play a major role in a building's energy performance. The non-adaptive behaviors are mainly driven by contextual factors (non-physical factors affecting occupants' behaviors, habits, attitudes [20] rather than physical discomfort [21]. For example, office occupants' computer ([22], [19]) and light switch off behaviors at departure exhibit a close relationship with the duration of absence following the departure. Whereas on the other hand in well-insulated residential dwellings, the plug-in equipment use plays a dominant role. This can be attributed to the freedom the occupants have in terms of appliances and need to achieve a higher level of convenience.

Acknowledging limitations and answering the right questions is the key to meet future emission targets. The key is not only recognising the role of energy efficiency or human behaviour within the building stock, rather recognise that dwellings are heterogeneous and therefore a decarbonisation strategy that works well for one dwelling may not work for another. It is the complex interaction of variables (climatic parameters, economical parameters, regulations & policies, architecture & interior design of space and building types) occurring at the dwelling level that ultimately determine the optimal carbon mitigation solution. Regulations and policies, therefore, need to reflect the diversity within the building stock so that emission reductions can be realistically predicted and maximised across the building stock.

2.1 Conclusion

The key takeaways from the literature survey and have been implemented in this study are

Study approach

Occupant behaviour is a multi-disciplinary field ranging from engineering, architecture, information technologies to social sciences. This means the research in this field does not necessarily follow the same framework, therefore creating an issue of studies being inconsistent for external validation and drawing inferences. In response to this problem, a group of international multi-disciplinary researchers was brought together under the International Energy Agency's project on - Energy in Buildings and Communities Programme project - Annex 66 on "Definition and simulation of occupant behaviour in buildings". This project laid down protocols for carrying out research in this field. The methodology followed in this study was suggested by Annex 66 and D.Yan et al [23].

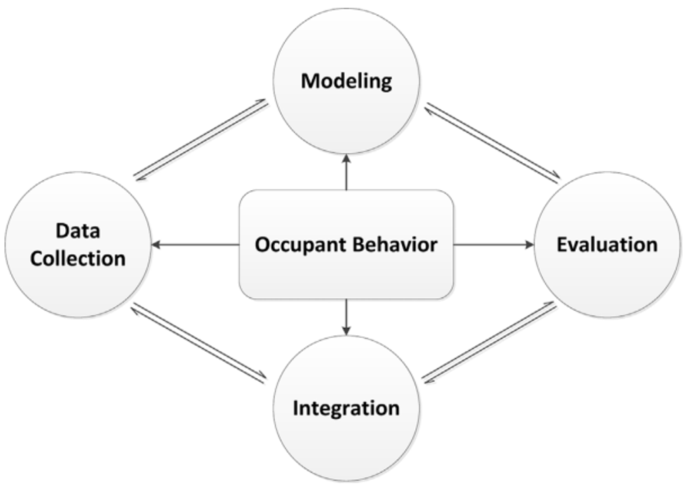


Figure 2.2: Methodology followed

Since occupant behaviour prediction is intricately complex because of the various factors involved. It is often good practice to depend on two or more methods to objectively pinpoint the cause, effect and the magnitude of certain actions. There are four ways to scientifically study occupant behaviour -

- In-situ
- Laboratory
- Survey
- Virtual reality

This study relies on two ways - in-situ and survey to objectively study the influence of occupant behaviour.

The reason for this was because laboratory and virtual reality are relatively expensive and time-cumbersome for the scope of this study. Moreover, since the environment of study is not the same as reality, it may psychologically alter the thought process of the study occupants and thereby not being an accurate representation of the reality.

Building type

Typical Dutch residential dwellings were chosen for the study. The reason for this is because the occupant behaviour is dominant in dwellings when compared to other building types such as offices, hospitals, and educational institutions. A total of three households were observed for a period of two weeks. The number of houses was decided to be three in order to break any even trends, cross-checking recurring patterns and results, and the number of sensor set-ups available. This approach is the first of its kind that takes place in the test-subjects' actual house. Whereas on the other hand these studies are usually conducted in laboratories or artificial environments because of the logistics involved.

Data collection using sensors

Numerous studies have researched the effect occupant behaviour has on energy consumption. Researchers have just started to understand its effect and are now trying to understand it. The prediction seems to be a future goal. The first step in understanding this is to collect data and draw conclusions from it. However, the data collection part is an expensive affair since it requires a large infrastructure and there are concerns related to privacy and ethical issues [24]. Following these concerns, there is a variety of applications for this data - such as developing models to support the design and improving controls and operations. A major area would be to predict occupancy and occupants' behaviour in building performance simulation. This will aid in efficient, comfortable spaces and avoid the uncertainty that is currently associated with occupant behaviour. Other applications include - post-construction building management system optimisation and to study unknown or counter-intuitive recurring patterns that could save energy. it was found that a few dominant factors played an important role in energy consumption as well as achieving a comfortable indoor environment in the house. These factors were the indoor operative temperature, relative humidity, CO_2 levels, outdoor temperature, interaction with windows. These parameters measured in a sufficient number of frequently occupied zones can represent the entire house's conditions.

Chapter 3

Method

The method followed to study the influence of occupant behaviour consisted of four steps - Data collection, Modelling, Integration and Evaluation. In the data collection phase, real-time data through various mediums like sensors, meters, energy bills, occupant interviews, drawings and specifications was collected. In the modelling phase, dynamic energy models of the three houses were made. These models help understand what implications certain improvements (increased insulation levels, efficient heating system) made to the total energy consumption of the house. During the integration phase, the real-time data is fed into (i.e., building characteristics, floor area, levels of insulation) the model and at the same time used to validate it (actual yearly electricity and gas consumption). In the evaluation phase, the houses are evaluated, necessary improvements for the three houses and design strategies for future homes are suggested.

3.1 Data collection

To make informed decisions and conclusions about the three households, a variety of data was collected. Table 3.1 shows the different kinds of data collected. Since quantifying the influence of occupant behaviour is not straight-forward, sensor data, meter readings and interviews help in quantifying and studying it. Documents and bills of the house helped studying the past trends of the household in terms of gas, electricity and water. Furthermore they also helped in validating the data collected during the two week observational period from 7th March - 21st March 2019.

3.1.1 Micro-controllers and sensors for data monitoring

As mentioned by various other researchers there is a need for cheap ways to collect data about occupant behaviour. But this becomes a difficult task because if the devices are too conspicuous, because then there a big chances that it might alter the way occupants naturally behave in their houses. Commercially available set-ups were too expensive for the scope of this study, so a novel method of data collection was defined. This called for bridging three fields - electronics, computer science and building physics.

For the electronics part of the data collection, it was decided that ESP32 by Espressif systems fit the criteria of this study best. This micro-controller has capabilities to receive the data from the sensors and transmit it wirelessly over the local Wi-Fi network. The relatively small size and economical price made it good option for large scale data collection.

The sensors as seen in the table 3.3 were chosen specifically to measure parameters that were influenced by the occupants and affected the energy consumption of the house.

Table 3.1: Data collected for this study during the observation period from 7th of March - 21st of March 2019

Method	Parameter
In-situ sensors	Indoor operative temperature
	Relative humidity
	Occupancy
	CO_2 levels
	Windows
	Radiators
	Hot water
Meter readings	High-power electrical appliances
	Gas meter
	Electricity meter
	Water meter
Interview	Occupancy schedule
	Appliance usage profile
	Lifestyle
Documents and bills	House construction details
	Architectural details
	Past monthly energy usage
	Energy certificates

3.1.2 Location and quantity of the sensor set-up

The location of the different sensors and subsequently their quantity was decided based on table 3.1 and figure 3.2. This was the initial methodology, but practical difficulties that occurred during the installation and observational period are discussed in Chapter 6 - Discussion. Furthermore the secondary reason to study these spaces in the house was partly experimental and partly due to the financial feasibility and the remoteness of the sensor set-up.

3.1.3 Server for remote sensor data collection

In order to remotely collect data from the sensors, the micro-controllers were programmed to deep-sleep (save energy), wake up send the data as soon as they receive it from the sensors to an online cloud file. This was executed using an IFTTT server. Unique files and servers were created for all the sensor nodes, this avoided dependency on a specific micro-controller or server for successful data collection. Since the data was being collected live and saved in a secure cloud file, this meant it could be accessed and viewed anywhere and anytime. Thus, allowing to check for errors or sensor malfunction.

Table 3.2: Specifications - ESP32

Features	Specification
CPU	Xtensa dual-core 32-bit LX6 microprocessor
Memory	520 KiB SRAM
Wi-Fi	802.11 b/g/n
Bluetooth	v4.2 BR/EDR and BLE
RF transmitter and receiver	2.4GHz
In-built sensors	temperature and hall sensor
Ultra low power mode	5μA (during deep sleep)
Clock	In-built clock with wake-up options
Operating voltage	2.3V - 3.6V
Price	3.61€

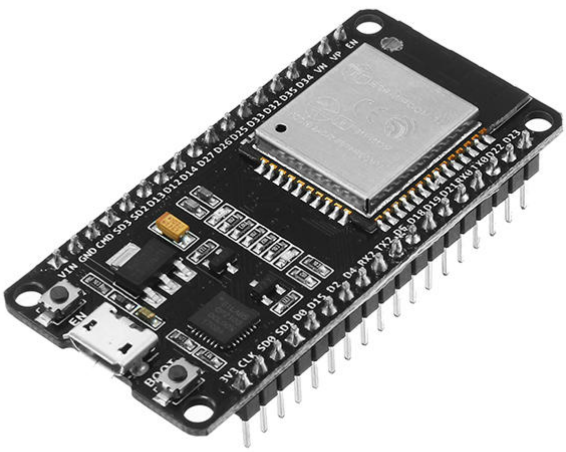


Figure 3.1: ESP32 micro-controller (Espressif systems)

3.1.4 Sensor calibration

In order to maintain the credibility of the data collected using the sensors, calibration becomes one of the important issues. All the sensors except the MQ135 (CO_2 sensor) and the PIR occupancy sensor required calibration. The MQ135 shows the levels of carbon dioxide in the air based on the electrical resistivity. It had to be set to a known voltage for a known level of CO_2. In this case, the sensor was calibrated to the atmospheric CO_2, which was assumed to be around 400 ppm. Every MQ135 sensor had to be calibrated.

Secondly, the PIR sensor had to be programmed to detect changes in the levels of Infrared radiation, since it works on the principle of detecting IR radiation from humans. The reason for choosing this sensor was because it is a relatively cheap option when compared to cameras. Furthermore, cameras for occupancy detection is a sensitive issue because of the risks and privacy laws involved in it. All the sensors were calibrated or tested with other reliable sensors

Table 3.3: List of sensors

Sensor	Type of Measurement	Function
DHT22	Operative temperature and Relative humidity	Indoor temperature and Relative humidity
Reed Switch	Open/Closed	State of window
MQ135	CO_2 level	Indoor CO_2 levels
DS18B20	Water-proof surface temperature	External temperature State of radiator Hot water usage
HC-SR501 PIR	Infra-red radiation	Presence/Absence of occupants

Table 3.4: Cost of one set-up

Item	Price €
Micro-controller - ESP32	3.61
Sensors	0.75-2.50
Breadboard	1.00
Battery - LiPo - 4500 mAh	4.90
Fire-safe bag for the set-up	2.03
Wires, resistors and electrical tape	1.00
Cost of one set-up	13.35 - 14.85

to cross-check the readings.

Sensors were installed to study the typical indoor operative temperatures and other aspects in the different rooms of the houses. They were installed in spaces which were frequently used and were representative of the houses' energy consumption. This data could then be useful in further assuming the temperature set-points while performing the energy simulations for the houses. In the senior couple's house, the sensors were placed in the kitchen, master bedroom, bathroom and the study room. In addition to this, a sensor for recording the external temperature was also placed.

3.1.5 House and appliance meter readings

Apart from studying the behavioural actions of the occupants like set-point temperature, windows open/closed, etc. Their appliances usage, electricity, gas and water was also interesting to study. So to monitor these, energy plug meters were installed on the commonly used appliances. The meter readings would provide actual usage and thereby allowing for a valid comparison between the houses.

3.1.6 Past energy usage

Apart from monitoring the houses for two weeks, an attempt to study their yearly energy consumption. This was done to further understand if there are certain unusual or recurring practices. This would help in suggesting long term measures which could result in substantial cost savings. Energy bills from the July 2017 till March 2019 were obtained for the senior couple and the family's case. In the young couple's case only data from January - April 2019 was obtained because of the fact that the house was recently constructed (2018 November). So in their case, information from occupants and interpolation from the available data aided in suggesting energy saving measures.

3.2 Study candidates

Study candidates are one of the most important aspects of this study. Candidates that represent the majority of the population would help inform other researchers and thereby increasing the chances of resolving or mitigating the existing problem. But attracting study candidates is rather a difficult task without a strong driving force. So in an attempt to attract potential candidates, a sensor demonstration was organised at ABT - Delft office. This demonstration was aimed at showcasing the sensor set-up to the audience and pin pointing how they can reduce or learn about their actions and save energy in their own houses. This was attended by 22 people and following the demo, a google form was circulated for the interested candidates. 13 out of the 22 people were interested in being a part of the study.

3.2.1 Questionnaire

The 13 candidates were of different backgrounds and had different lifestyles (Table 3.5). Winnowing down the candidates according to the scope of the study, house characteristics and information accessibility was necessary. The questionnaire sent to the interested candidates contained questions regarding their age, gender, house location, number of rooms, who they lived with, number of people over, year of construction of their house, if it had been renovated and if they had pets. These questions aided in selecting the candidates that would be a part of the study. Since the scope of the study was to study the common living and housing profiles in the Netherlands, candidates who lived in typical Dutch row houses which were constructed/renovated post 1990 and had a common lifestyle profile (couple or families). People who fulfilled these criteria were given preference. In the end 3 candidates were chosen. These candidates were (refer table 3.5) -

- No. 9 - Senior couple
- No. 5 - Young couple
- No. 3 - Family

The reason for selecting these candidates were the following -

- Information about the house and its characteristics.
- Scope and goal of the study.
- Co-operation.

3.2.2 Selected candidates

Out of the 13 interested people, 3 candidates were chosen for the study. To compare the different lifestyles, three different candidates namely - senior couple, young couple and family were chosen. The houses these three candidates live in are typical Dutch row houses because they constitute 4 out of the 7 million houses in the Netherlands.

Senior couple's house

This house is semi-detached row house situated in the South-Holland province. This house has a garage, garden and is surrounded by similar type of houses. This household has two permanent occupants and 3 temporary members which stay over during the week for a couple of days. The house does not have PV panels but can be equipped with. The occupants have an inclination towards sustainable and green energy with reducing the usage of gas to only space heating and hot water. This means an electric stove is used for cooking purposes. The ventilation system in this house is air supply through the window grilles and exhaust using

Senior/Young Couple's House

	Living Room	Bedroom 1	Bedroom 2	Kitchen	Toilet	Shower
Operative temperature and RH	✓	✓	✓	✓	✓	✓
Radiators	✓	✓	✓	✓	✗	✓
Windows	✓	✓	✓	✓	✓	✓
Occupancy	✓	✓	✓	✓	✗	✗
CO_2 level	✓	✓	✓	✗	✗	✗
Outdoor temperature	✓					
Hot water	✓					

(a) Senior/Young Couple's House

Family house

	Living Room	Bedroom 1	Bedroom 2	Bedroom 3	Kitchen	Toilet	Shower
Operative temperature and RH	✓	✓	✓	✓	✓	✓	✓
Radiators	✓	✓	✓	✓	✓	✗	✓
Windows	✓	✓	✓	✓	✓	✓	✓
Occupancy	✓	✓	✓	✓	✓	✗	✗
CO_2 level	✓	✓	✓	✓	✗	✗	✗
Outdoor temperature	✓						
Hot water	✓						

(b) Family's House

Figure 3.2: Location of the different sensors in the three different households

Figure 3.3: Demonstration at ABT - Delft office

Figure 3.4: The senior couple's house (2016); Occupants - 2 permanent and 3 temporary

Table 3.5: About the chosen candidates' and their house

Interested Candidate	Age	Gender	House Type	Year of Construction [1]	Type of Household	Number of People [2]
1	28	Male	Apartment	1960-C, 2018-R	Housemates	3-P, 0-T
2	27	Female	Studio	1800-C, 2010-R	Couple	2-P, 0-T
3	48	Male	2/1 Roof Row House	1934-C, 2000-R	Family	4-P, 1-T
4	27	Female	Studio	2017-R	Self	1-P, 1-T
5	28	Male	Corner Row House	2018-C	Couple	2-P, 0-T
6	25	Male	Apartment	1914-C	Self	1-P, 1-T
7	54	Male	Semi-detached Row House	1987-C	Family	5-P, 7-T
8	27	Female	Row House	1920-C, 2016-R	Housemates	3-P, 0-T
9	50	Male	Semi-attached Row House	2016-C	Couple	2-P, 3-P
10	29	Female	Row House	1925-C, circa 1990-R	Housemates	2-P, 2-T
11	25	Female	Corner Row House	circa 1930-C	Housemates	4-P, 1-T
12	33	Female	2/1 Roof Detached House	2017-C	Couple	2-P, 0-T
13	33	Male	Apartment	1946-C, 2018-R	Couple	2-P, 4-T

[1] C- Constructed, R- Renovated
[2] P- Permanent, T- Temporary

an exhaust fan system with dedicated ducts in the toilet, kitchen and the shower. The main thermostat is situated in the living room/ kitchen on the ground floor. It has a CO_2 sensor to regulate the air quality and exhaust the contaminants. Every room has a localised temperature knob with 1-5 levels offering personalised comfort for occupants. The floor heating pipelines are decentralised in different spaces thereby allowing the freedom to changing the temperature according to personal preference.

Young couple's house

The young couple's house is located in the South Holland province. This house has two permanent residents. It is situated in a new and developing location. With strict regulations to make new houses nZEB, this house sets a good example of it. This house complies with the high standards set by the building codes. Highly insulated, no gas connection, equipped with a modern HVAC system with a heat pump and PV on the roof, a major emphasis on sustainability, green energy and high levels of comfort. The HVAC main control system is in the living room/kitchen which offers temperature control and information about the heat pump usage. Monthly and yearly usage information about the floor heating and hot tap water. Apart from that it also shows the temperature the water is being heated to, operative temperature in the room & entire house and operation profile for the floor heating. Individual rooms have personalised floor heating knobs with 1-5 levels.

Figure 3.5: The young couple's house (2018); Occupants - 2 permanent

Family house

The family house is a two under one roof Dutch row house which was constructed in 1934 but renovated in 2000. This house is situated in Rotterdam - South Holland province. It accommodates 4 permanent members - 2 of them are parents and the other 2 are children. There is a temporary member of the house which stays over a few days over the week. In comparison to other houses, this house does not have a dedicated ventilation system and has the conventional boiler with radiators for space heating. The house is surrounded by neighbouring houses on three side - down and both the adjacent sides. This subsequently contributes to the neighbour effect and therefore affecting the heating demand and the indoor temperature of the house.

Table 3.7 shows the appliances in the three households. The reason for choosing these appliances was based on three reasons -

- Power.
- Frequency.

Figure 3.6: The family's house (constructed - 1934 and renovated - 2000); Occupants - 4 permanent and 2 temporary

- Duration.

The appliance power was known from the product specifications. The frequency and duration of the these appliances was known after consulting with the occupants.

3.2.3 Sensor installation

The same observational time period of two weeks was chosen for the three houses, from the 7th of March till the 21st of March 2019. Two reasons for this was to be able to compare the results from the three houses and have the same external temperature during the observational period. Because external temperature is one of the strongest driving force for energy consumption. The location of the three houses were less than 30 km from each other. Thereby allowing minimal deviations in the weather conditions.

The time period was chosen so that it would be representative of the major part of the year. The external temperature throughout the two weeks was between 6-10°C, which is roughly the yearly average in the Netherlands.

Figure 3.7: Placement of the sensor at the senior couple's house

Table 3.6: About the chosen candidates' and their house

Candidate	Senior Couple	Young Couple	Family
House type	semi-detached row house	corner row house	2/1 row house
Year of construction	2016	2018	1934; renovated in 2000
Number of people living [1]	2-P 3-T	2-P 0-T	4-P 1-T
Total floor area (m^2)	144	106	158
Ventilation	Natural supply and mechanical exhaust	Mechanical supply and exhaust	Natural supply and exhaust
Heating system	Floor heating with a gas boiler (CoP- 0.975)	Floor heating with electric heat pump (CoP- 2.40)	Radiators with gas based boiler (CoP- 0.94)
Cooling system	-	Night cooling	-
Hot water system	Gas circulation boiler (CoP- 0.95)	Electric heat pump (CoP- 1.90)	Gas circulation boiler (CoP- 0.94)
Cooking system	7400 W - Electric induction stove	7100 W - Electric induction stove	Gas stove
EPC	0.57	-0.02	$\sim$ 1.83
Sources of energy	Electricity and Gas	Electricity and PV	Electricity and Gas
R-value (m^2K/W) - Ground floor	5.00	5.00	0.09
R-value (m^2K/W) - External walls	4.23	5.00	0.41-1.19
U-value (W/m^2K) - Windows	1.20	0.70	2.3
R-value (m^2K/W) - Roof	5.17	6.00	1.19-2.5

3.3 Modelling

Dynamic energy modelling and simulation was preferred because it is an accurate representation of the actual situation when compared to static simulations, which do not account for the dynamic thermal mass changes. Dynamic energy simulation models allow you to input the different occupancy and operational profiles (space heating, hot water, lighting, set-point temperature). They also allow editing the material properties of construction elements such as roof, external walls, floors, partition walls, glazing and doors.

3.3.1 Why IES(VE) 2018?

IES(VE) is a commonly used dynamic energy simulation software. It offers modeling capabilities within the software but at the same allows dedicated import options from Autodesk Revit. At first it was decided to make use of Revit to detail the houses and then perform energy simulations on IES(VE). But up on discovering the modeling capabilities of IES(VE), modeling in Revit

Table 3.7: High-power appliance profile

Appliance	Senior Couple	Young Couple	Family
Washing machine	✓	✓	✓
Dryer	✓	✓	✓
Dishwasher	✓	✓	✓
TV	✓	✓	✓
Electric stove	✓	✓	×
Fridge	✓	✓	✓
Ventilator	✓	✓	×
Others	Deep freezer	-	2000 W electric hot water boiler (kitchen)
	2000 W electric radiator (garage)		
	600 W electric radiator (bathroom)		

seemed unnecessary. IES(VE) offers high levels of details when assigning materials and their properties. Furthermore its user-friendly graphical interface allowed easy cross-checking of the assigned data. This is an important aspect when it comes to correlating the model with the actual usage. Most of the errors occur either due to the inexperience of the energy modellers or improper assignment of the properties. The Vista tab in IES(VE) allows the modeller to visually see all the parameters they have assigned, thereby increasing the chances of rectifying errors.

3.3.2 Level of detail

Unlike other static energy energy modelling tools, IES(VE) 2018 takes into account the building properties, external conditions and occupants while dynamically solving the energy consumption of the house. It allows inserting occupant schedules, water usage schedules, appliance schedules (for heat gains) in various spaces while calculating. This plays an important role in accurate prediction as it represents the reality and not an over-simplified situation, which is usually the case with the other energy models. Furthermore, in order to speed up this process, schedules and profiles (daily, weekly and yearly) can be imported from the other commonly available and used softwares (Microsoft excel) and python scripts.

3.4 Integration

For this study, the sensor data which was collected in sheets on the cloud was imported using the import options in the schedule/profile menu bar. This option is rather tedious because it has to be manually imported. The type of data which was imported into IES(VE) from the sensors and interviews were the set-point temperature, window opening profile and occupancy profile in different rooms during the various different periods.

Figure 3.8: Placement of window/door sensor at the family house

Figure 3.9: Placement of the sensor at the senior couple's house

Figure 3.10: Plug meter installed at the young couple's house

Chapter 4

Measurement Results

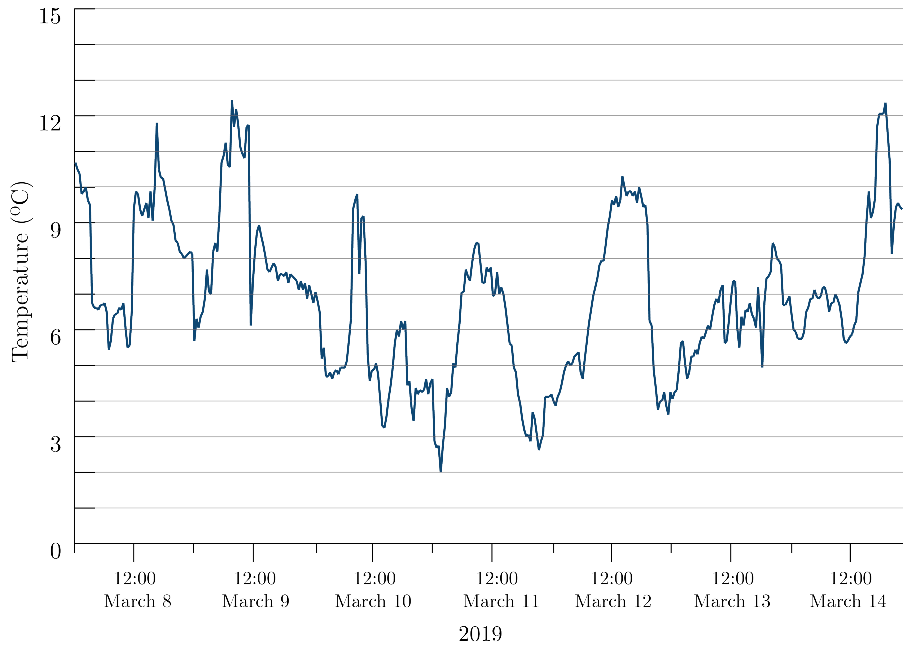
The intricate and complex nature of occupants makes prediction and modelling a difficult task. Real-time data can help make it a easier and accurate. This is the reason this study incorporates actual past and sensor data. Not only does this reduce the number of inaccurate assumptions but also establishes credibility to the study. Sensors in particular were used to study two aspects - 1. Study the already studied aspects (like window opening behaviour) of the occupant behaviour and to see if they hold strong in this case as well and 2. To study the collected sensor data and see if there are any anomalies or unexpected patterns that can justify and aid in answering the questions this study seeks.

4.1 Data from sensors

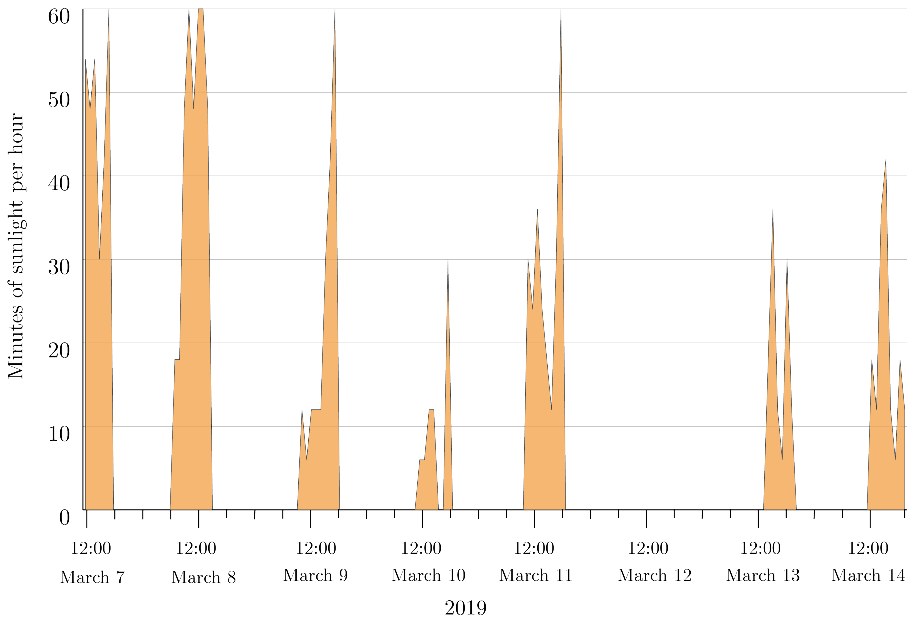
Measurement data from sensors give an insight into the actual situation in the household. A timely report of the conditions in the house help understand what the occupants prefer. Furthermore they give you insight into what the occupants do to achieve homeostasis.

In the senior couple's house ((refer fig.4.2), the temperature profile in the kitchen/living room varied significantly due to the increased cooking activity and the heat gain from it. The relative humidity profile in addition to the presence of humans again varied due to the cooking activity and increased moisture levels in the air. It is observed that only in rare occasions did the RH levels went above 55%, this could be due to the chimney, exhaust duct or the windows. RH levels could again be used to detect human presence in the space. The temperature in the master bedroom fluctuated much more when compared to other spaces. This could be because bedrooms are preferred cold during the nights and warm during the day. In addition to that, the bedroom is situated in south end so on sunny days and it is due to the radiation entering the space. In the bathroom, the temperature reached around 21°C. The relative humidity levels vary the most due to unstable moisture levels in the space. In the study room, the set-point temperature is the highest due to reduced human activity and low heat release. It can also be seen that the temperature drops substantially (around 16°C) on March 10th around 18:00, this is due to opening a window. This happened only once in 8 days. The steady drop in temperature suggests that the ventilation grilles on the window were open constantly. This was not the case initially between March 7th and 9th.

The young couple's house (refer fig.4.3), has higher levels of insulation and also a sophisticated HVAC system. This is evident from the sensor data. In the living room/ kitchen, the temperature set-point was 19°C and the set-back temperature was 18°C. The temperature profile is the most stable when compared to the other two houses. This is attributed to the higher thermal mass, insulation levels and regularly mechanical ventilated air (with heat recovery) in the space. The relative humidity levels are mostly between 40% and 60%. The fluctuation is higher and this is because the ventilation unit has a CO_2 sensor, which helps saving energy. The temperature in the master bedroom is again stable at 19°C. The RH levels clearly show



(a) External temperature outside the senior couple´s house

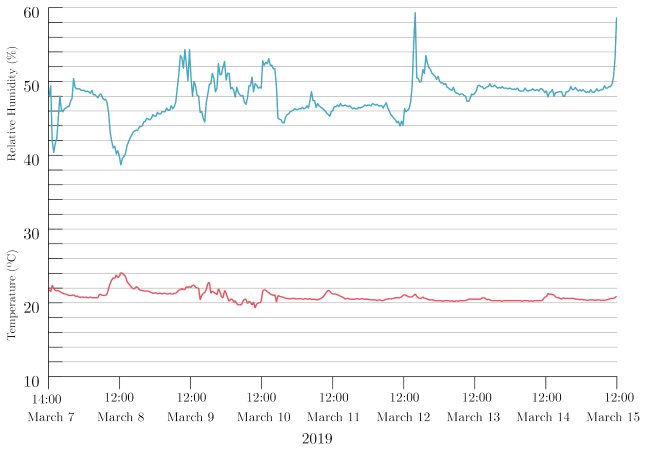


(b) Duration of sunlight (KNMI)

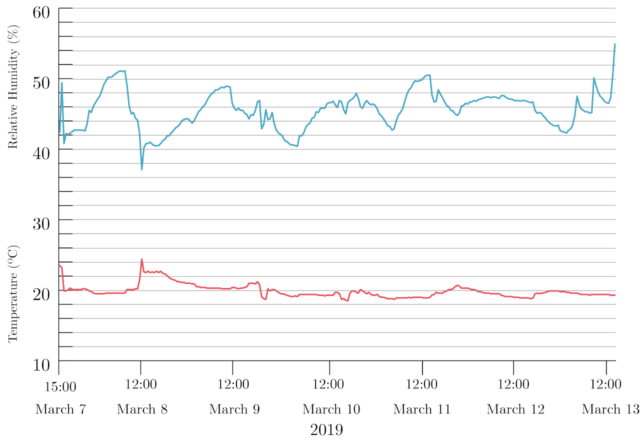
Figure 4.1: External temperature from the sensor outside the senior couple´s house and duration of sunlight (KNMI)

human presence over the night. These levels are again kept between 40% and 60%.

At the family house (refer fig.4.4), due to the low insulation levels, thermal mass and the frequent opening of the windows, the temperature is not very stable and fluctuates to great extend in the living room. The relative humidity levels do not follow a pattern like the young couple's house but they manage to remain under 60 %. Thereby suggesting that even though a dedicated ventilation system or grilles in the window are not present, the air quality inside is not bad. The temperature in the master bedroom fluctuated the most, due to the fact that occupants left their windows open for ventilation throughout the night. It fell down to 15°C on the morning of March 11th. Due to sensor malfunctioning, only 4 days of data was recorded.

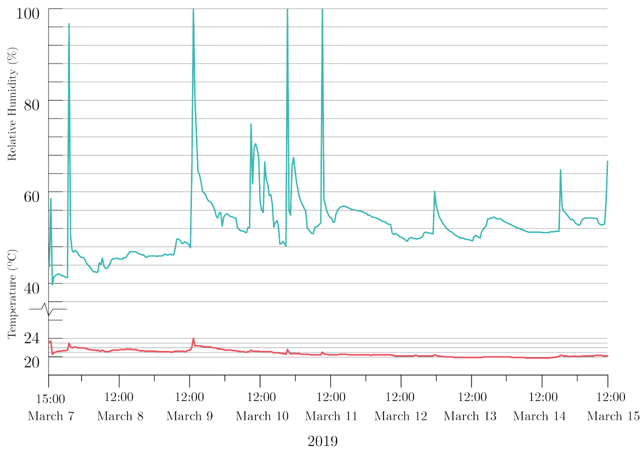


(a) Kitchen/living room



(b) Master bedroom

(c) Study room



(d) Bathroom

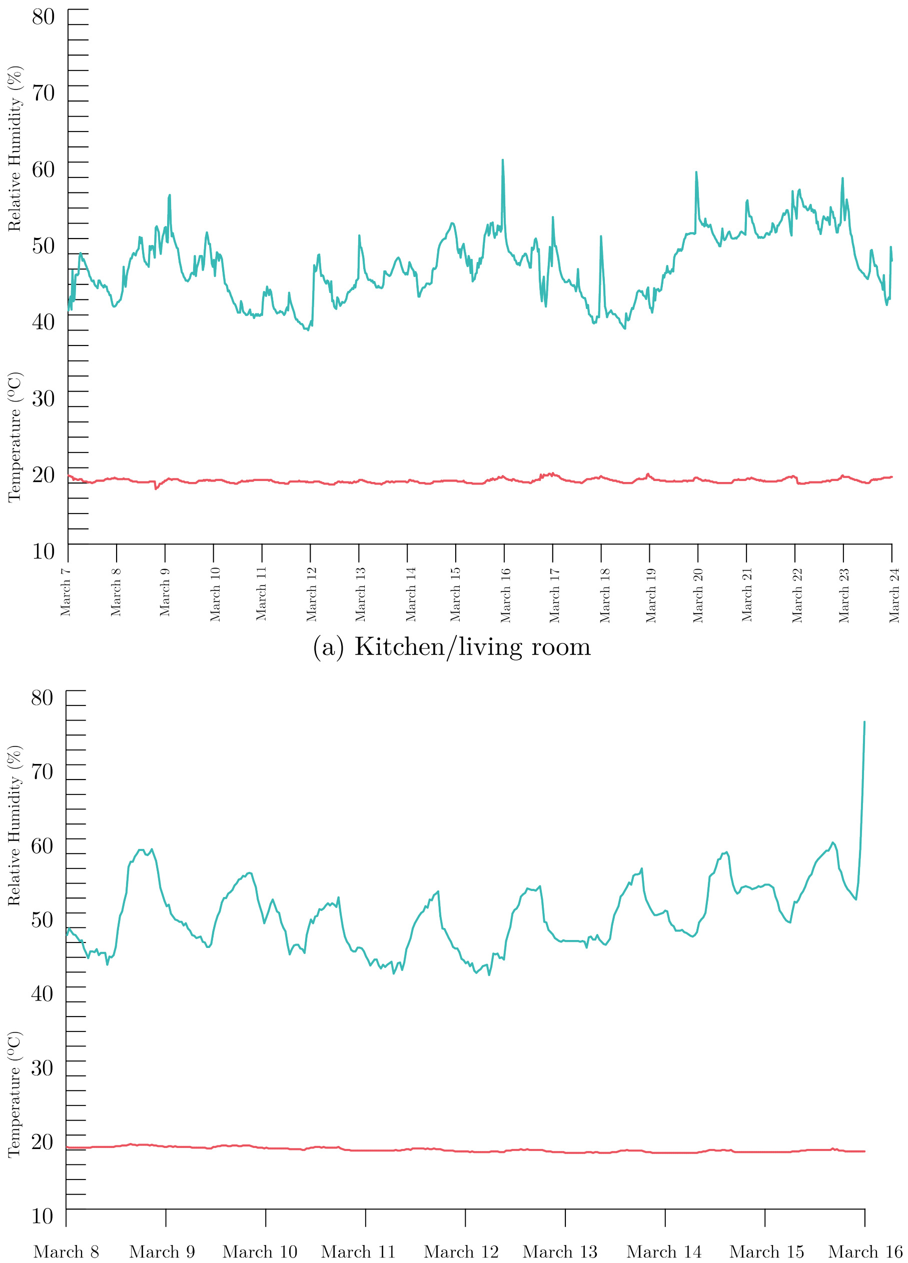
Figure 4.2: Sensor readings from the senior couple's house.

4.2 Plug meter readings

Since appliances consume a major part of the monthly electricity consumption, it is important to identify specific appliances that majorly contribute to this. Identifying these appliances could possibly help in lowering the household energy requirement or suggest alternative measures. During the observation period, 4 energy plug meters were installed in each house. The energy plug meters were installed on high power appliances that were frequently used. Apart from the energy consumed the plug meters also provided an idea of its run-time, lowest and highest power consumed and the current.

In the senior couple's house (fig. 4.5), the four appliances chosen were the coffee machine, entertainment unit (Television, internet modem, speakers and satellite modem), washing & dryer and ventilator (exhaust only). Apart from these appliances the household depended on an 7400 W electric induction stove - which could not be monitored using a plug meter because it was directly connected to the electrical line unlike other appliances which are connected using plugs. Additionally the house consisted of a deep freezer, refrigerator, 2000 W electric radiator for heating the garage and 600 W to heat the bathroom. These appliances were not monitored because of the lack of energy plug meters and also because they were thought to not consume more energy than the ones chosen.

In the young couple's house (fig. 4.6) , the number of household appliances were relatively fewer. This is because they recently moved into the house. In this house, the television, refrigera-



(a) Kitchen/living room

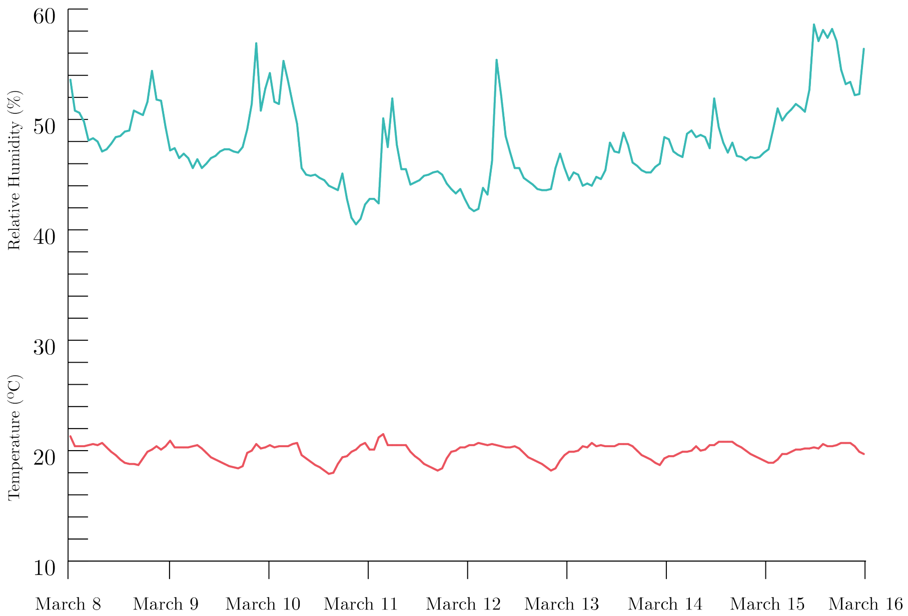
(b) Master bedroom

Figure 4.3: Sensor readings from the young couple's house

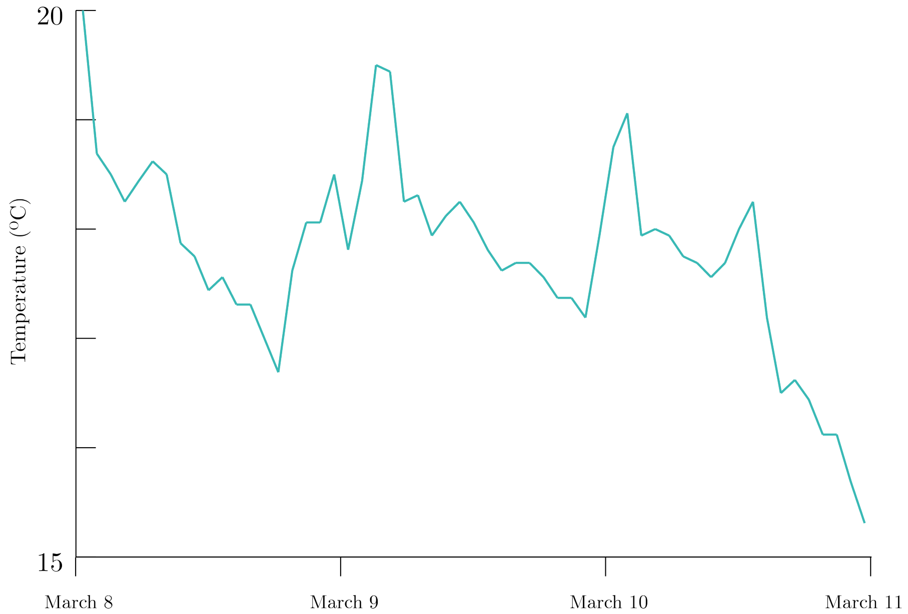
tor, washing machine and the heat-recovery ventilator were chosen. Apart from these appliances, others included - a 7100 W electric stove, coffee machine and the dishwasher. Since this house does not have a gas connection, a major part of the electricity was used for building-related purposes like heating, cooling, ventilation and hot water.

In the family house (fig. 4.7), the number of appliances were high due to the high number of occupants. But all these appliances relatively used less energy except the electric water heater in the kitchen. Apart from the heater, the other appliances relatively used the same amount of energy. In this house the highest percent of electricity use by appliances was accounted up to 40 %.

A few things that were observed from the energy plug meter were that the lesser the technical installations, the easier it was to account for the electricity. Upto 40% of the electricity used



(a) Kitchen/living room



(b) Master bedroom

Figure 4.4: Sensor readings from the family house

by appliances was accounted in the family house which is a traditional house with the fewest HVAC installations (only a circulation heating system with radiators for space heating and hot tap water) when compared to the young couple's house.

In the other two houses where an electric induction stove was used cooking had the highest input power (around 7100 W - young couple and 7400 W - senior couple). A simple calculation shows that during the observation period the electric gas stove could have consumed more than 50 % of the total electricity in both the houses.

If the family house's heating system was placed properly then the distance of the hot water pipeline would have been shorter from the circulation heater to the kitchen like other locations (bathroom, bedrooms and living space), therefore avoiding energy loss. Avoiding energy loss due to the poorly insulated pipeline from the circulation heater was the sole motivation to install

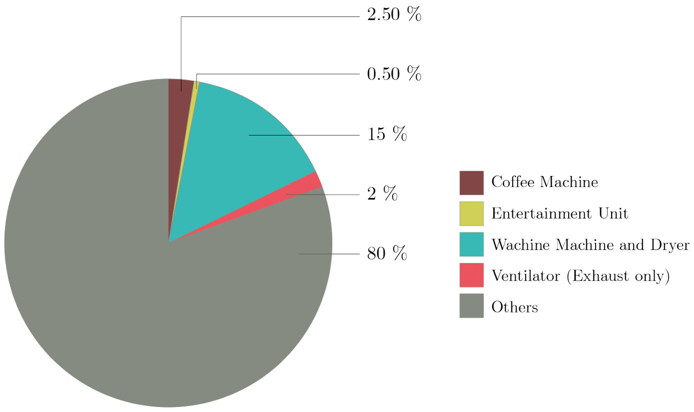


Figure 4.5: Energy consumed by appliances monitored by the energy plug meters in Senior Couple's house (Total electricity consumed = 112 kWh)

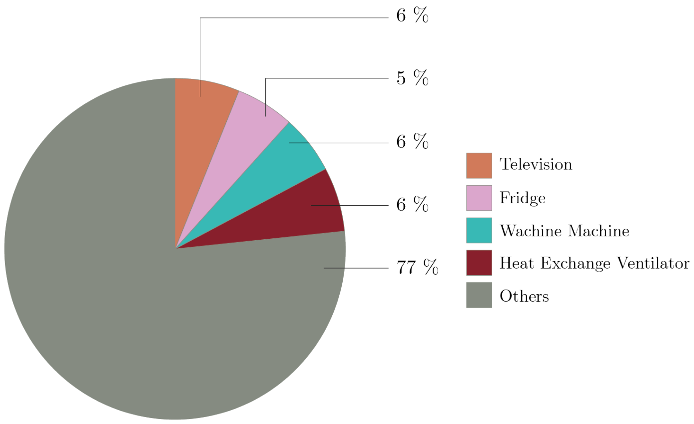


Figure 4.6: Energy consumed by appliances monitored by the energy plug meters in Young Couple's house (Total electricity consumed = 100 kWh)

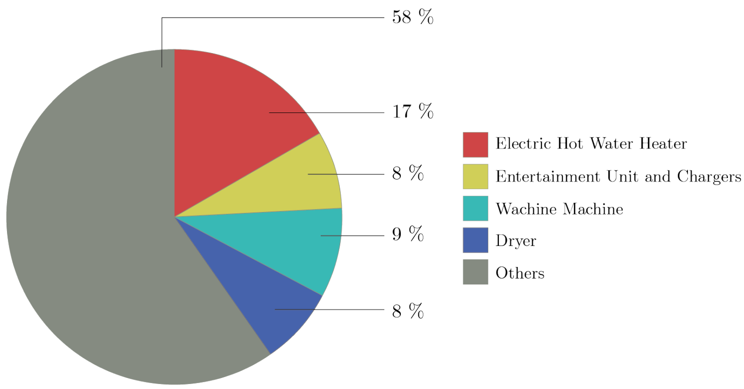


Figure 4.7: Energy consumed by appliances monitored by the energy plug meters in the Family's house (Total electricity consumed = 115 kWh)

the electric water heater in the kitchen. Since the electric hot water heater is relatively old, it consumed the same amount energy as the family's washing machine and the dryer during the two weeks of observational period.

Table 4.1: Appliance plug meter readings during the observation period (14 days)

House	Appliance	Run time	Power (W)	Energy (kWh)
Senior Couple	Coffee machine	00:09:54	0.9 & 2105	2.827
	Entertainment unit	02:03:05	0.5 & 14.7	0.638
	Washing machine and dryer	01:03:20	0.1 & 4378	16.71
	Ventilator(Exhaust only)	14:04:12	1.3 & 55.3	1.905
Young Couple	Television	04:01:42	0.1 & 179.6	6.327
	Fridge	05:16:55	0.3 & 233.7	5.474
	Washing machine	01:18:26	0.2 & 2401	5.695
	Ventilator(Heat Exchanger)	14:15:55	4.9 & 1717	5.889
Family	Electric hot water heater	00:09:45	0.1 & 2121	19.21
	Entertainment Unit	07:06:21	0.8 & 2039	6.521
	Washing machine	01:07:10	0.1 & 2155	9.772
	Dryer	00:08:42	0.1 & 2457	8.803

4.3 Meter readings during the observation period

All the three houses had smart meters for electricity. These meters are more advanced than their predecessors. These meters show peak and off-peak readings for electricity consumption and production (PV on the roof). The peak hours include 07:00-23:00 on weekdays and the off-peak hours include 23:00-07:00 on weekdays and weekends. Gas and water meters were conventional and did not differentiate between the usage timings. Meter readings were noted at the beginning and the end of the observation period for comparison between the different households.

In the three houses, electricity is used for different purposes (refer fig. 4.8). In the senior couple's house, the electricity is mostly used for only household related purposes except for the exhaust system. In the young couple's relatively modern house electricity is used for both household as well as building-related purposes. The electricity is used for mechanical ventilation, heating and cooling. This is possible due to the 31 PV panels present on the roof. These PV panels provide the house with electricity when needed, other times it supplies the excess energy to grid and vice-versa. This therefore prevents the need for a storage system. In the family house, there is a traditional set-up of radiators and a gas boiler, so in this case the electricity is solely used for household appliances.

The senior couple and the family houses are only ones which utilise gas (refer fig. 4.14). In the senior couple's house, gas is used for the floor heating and providing hot tap water by the boiler. Unlike the family house, gas is not used for cooking. But unlike the young couple's house, the senior couple's house does not have PV panels to support the high power electric stove.

The water usage (refer fig. 4.10) is relatively easy to predict as it has a direct correlation with the number of occupants in the house. The senior couple has children over every week, so that explains the slight peak than the young couple's house. In the family house, frequent use of washing appliances due to the number of people can in some ways account for the water consumption. A correlation between the water consumption and the number of occupants in the three households was found. Equation 4.1 gives that correlation. In the table 4.2 the

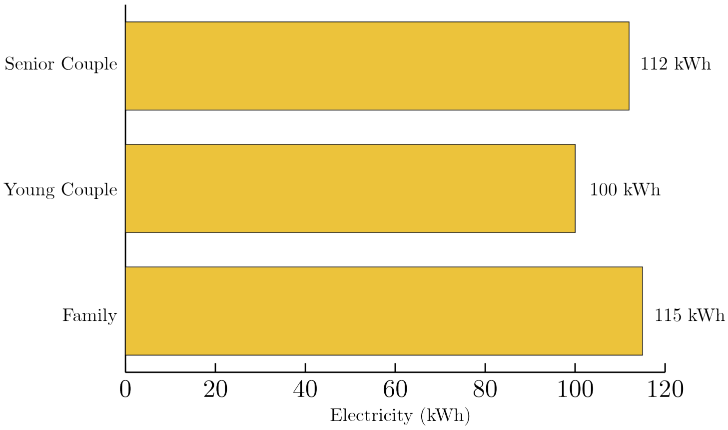


Figure 4.8: Electricity usage during the observation period (14 days)

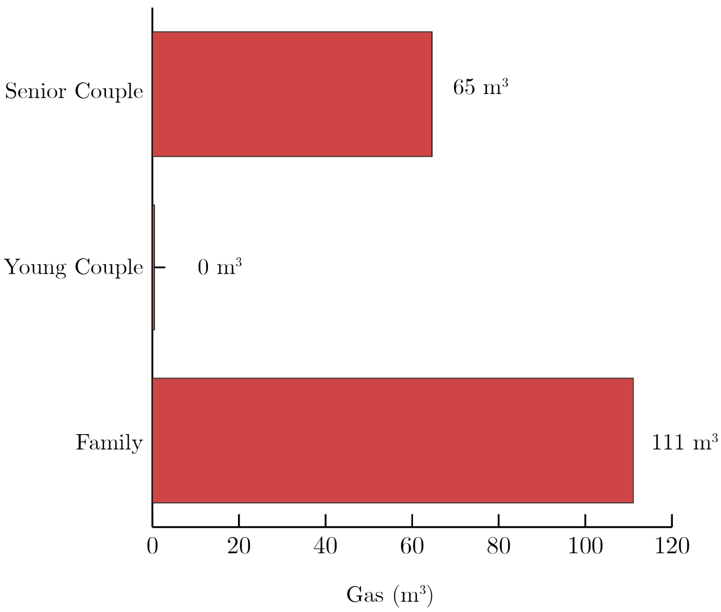


Figure 4.9: Gas usage during the observation period (14 days)

permanent occupants were considered with the weighted factor of 1 and weighed factor of temporary occupants was found by interpolating it with the number of days they spent in the house. Where 'N' is the number of occupants living in the house.

$$\textsc{Bi-weekly water consumption} = 1.032.N + 0.6905 \tag{4.1}$$

4.4 Past energy usage

Figure 4.11 shows the past energy usage (gas and electricity) of the senior couple's and family's house. It provides an informative perspective on how occupant behaviour affects the energy consumption of the two houses. Historical energy data prior to November 2018 was not available in the young couple's case since the house was recently constructed.

Fig. 4.11(a) shows the gas usage of the senior couple and the family household. It is of important to note that the senior couple's household uses gas for space heating and hot tap water, whereas the family household uses it for space heating, hot tap water and cooking.

Table 4.2: Water consumption correlation

	Senior Couple	**Young Couple**	**Family**
Number of occupants	2.625	2	4.5
Bi-weekly water consumption (m^3) (based on eq - 4.1)	3.40	2.75	5.33
Bi-weekly actual water consumption (m^3) (from meter)	3.49	2.70	5.31

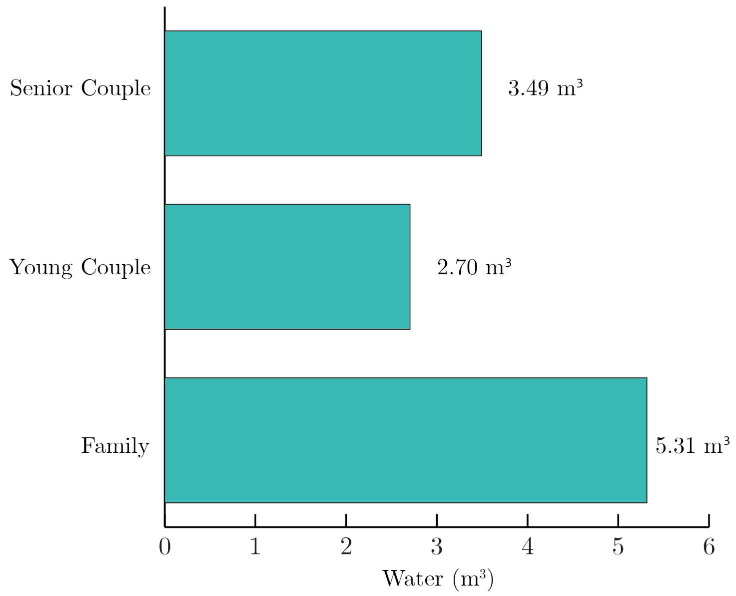
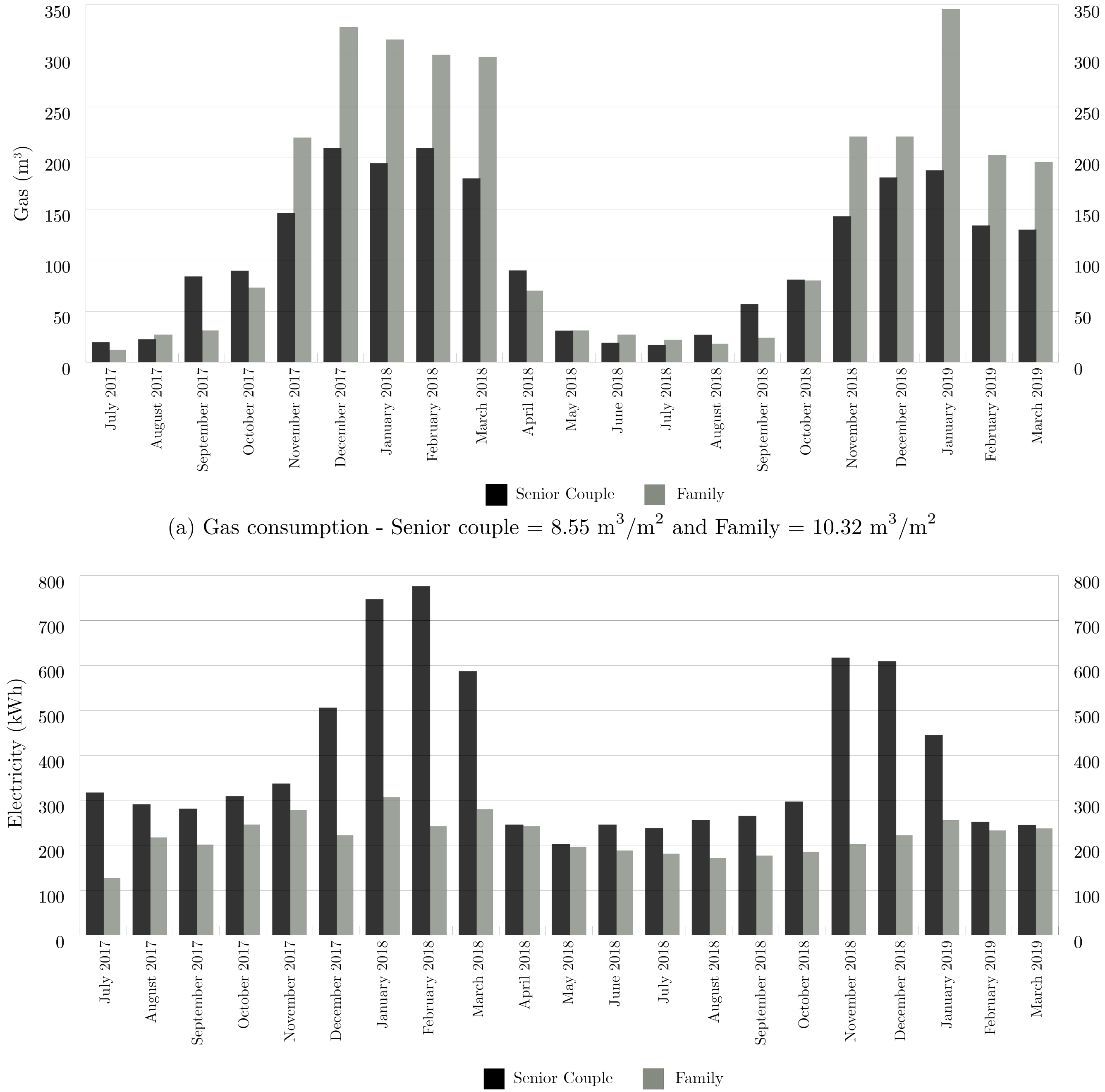


Figure 4.10: Water usage during the observation period (14 days)



(a) Gas consumption - Senior couple = 8.55 m^3/m^2 and Family = 10.32 m^3/m^2

(b) Electricity consumption - Senior couple = 35.33 kWh/m^2 and Family = 16.42 kWh/m^2

Figure 4.11: Past energy consumption of the senior couple and family's house from July 2017 - March 2019.

The monthly variation between the senior and the family house is mainly due to the different insulation levels of the two households. It can be seen that during the warm months of the year, the gas usage between the two households is almost same. It is because during these months, gas used for space heating is negligible. The hot water usage is also low when compared to other months due to the increased outdoor temperature and the higher supply temperature of the water. Furthermore, vacation could be also be of one of the contributing factors for the reduced consumption.

Fig. 4.11(b) shows the electricity usage of the senior couple and the family household. It is interesting to see that the influence of occupant behaviour is evident from this figure. This influence is clearly visible from senior couple's past electricity consumption - higher peaks in the colder months are due to the use of a 2000 W electric radiator in the non-insulated garage. Usually the electricity consumption unlike the gas consumption is stable throughout the year because in most of the cases, external temperature is not a driving factor for the electricity consumption (mostly household appliances).

4.5 Window experiment

In order to estimate how much of an effect open windows had on the energy consumption of a house, a small experiment was conducted at the young couple's house. Two windows in the living room & kitchen and one window in the master bedroom were opened for almost 3.5 hours on the first day (19th March) at around 17:20 till 20:45 and for 2 hours on the second day (20th March) from 17:30 till 19:30. The windows were opened in a bottom tilt fashion roughly at an angle of 20°. In order to see if this caused a temperature drop or not, the in-situ sensors were used. The figure 4.13 clearly distinguishes between.

1. The abrupt temperature drop due to opening the window
2. Steady step-by-step transmission loss to the surroundings

The step-by-step slope loss in temperature between 18:30 - 05:30 on the 18th of March and around 05:30 on 20th March are due to the transmission losses. Whereas, the abrupt drop in temperature both on the 19th as well the 20th are due to the open windows. The temperature drop is lower on 20th of March due to the higher external temperature when the windows were opened. The stable temperature range is due to the fact that the heating system has the option of set-point as well as set-back temperature. The set-point temperature was set to 19°C and the set-back temperature to 18°C.

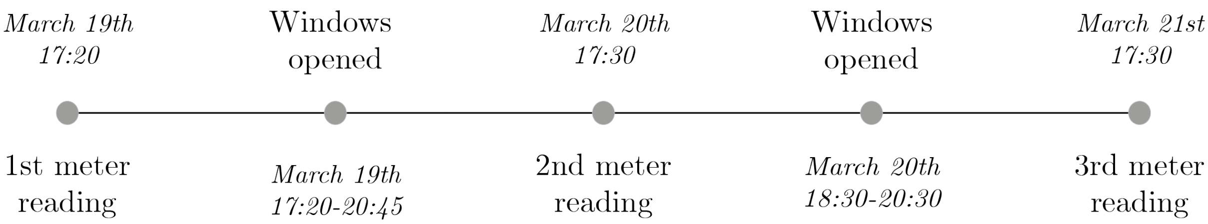


Figure 4.12: Window experiment at the nZEB house (the young couple) in the living room/k-itchen

To estimate the amount of air entering the spaces, the Dutch regulations were used.

$$A_{eff} = A.J(\Psi) \tag{4.2}$$

$$A_{netto} = A_{eff} \tag{4.3}$$

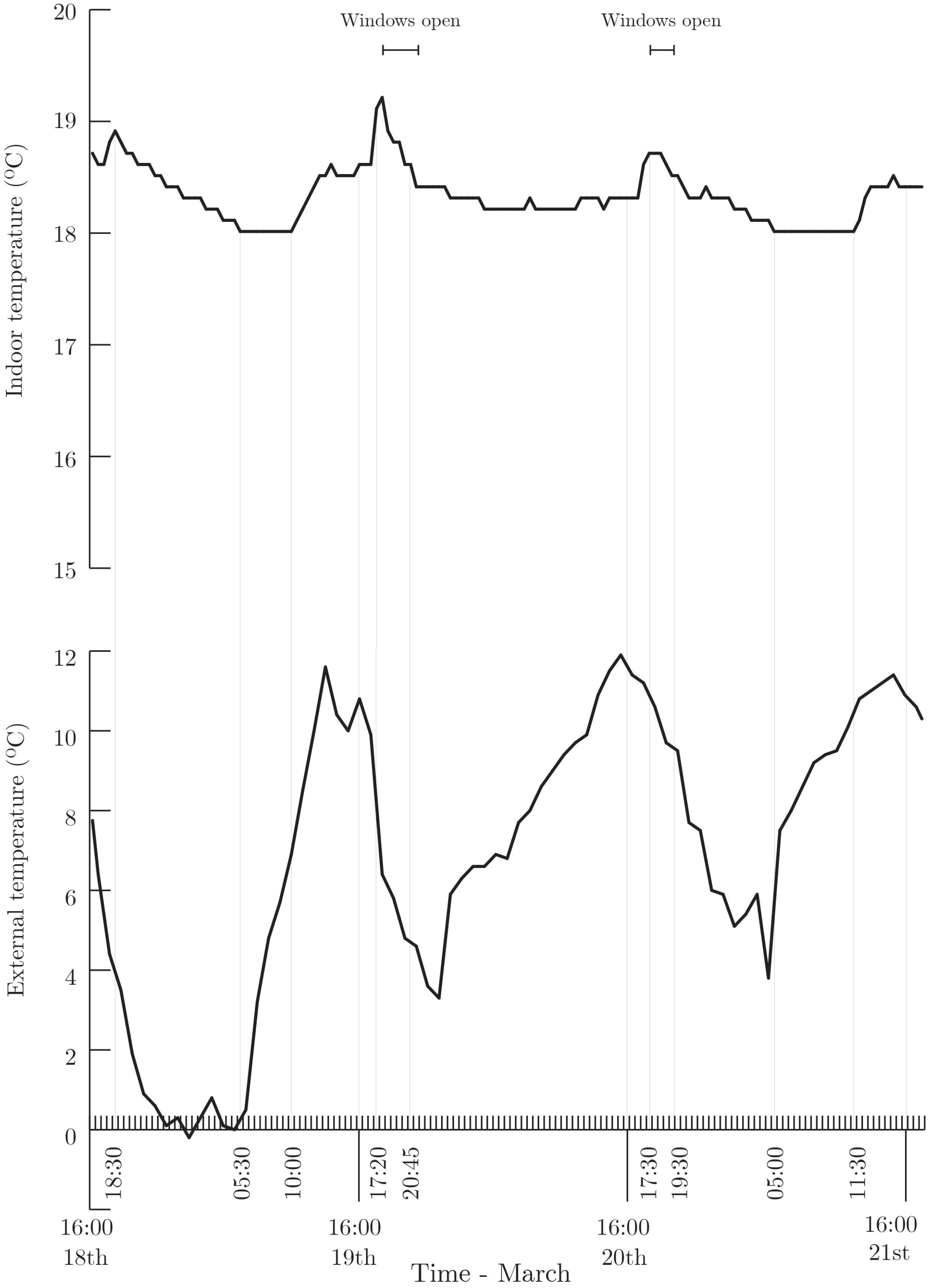


Figure 4.13: Window experiment in the kitchen+living room of the zero energy row house - the young couple

$$q_v = A_{netto}.v\ (m^3/s) \tag{4.4}$$

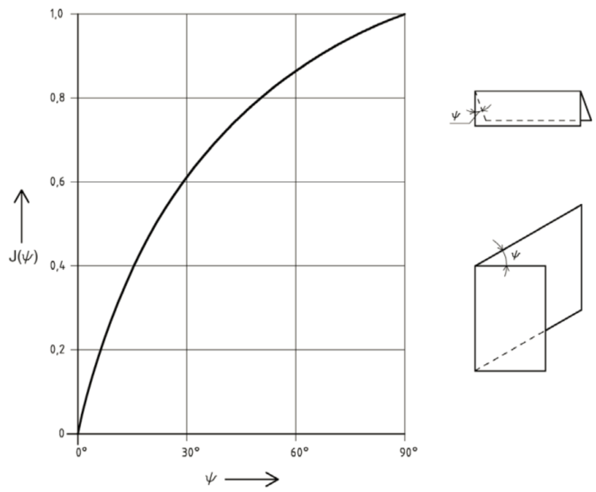


Figure 4.14: Reduction factor [25]

Table 4.3: Relevant values - Window experiment

	Living room + kitchen	**Master bedroom**
Number of windows	2	1
Dimension (m^2)	0.5 × 1.34	0.78 × 1.08
Window angle - tilt position	20°	20°
Reduction factor - J(Ψ)	0.45	0.45
$A_{eff}(m^2)$	0.3015	0.38
A_{netto}	0.603	0.38
Wind velocity (m/s)	0.1	0.1
$q_v(m^3/s)$	0.0602	0.0380
$q_v(m^3/hr)$	217	137
HR mechanical ventilation (m_3/hr)	50	50
$q_{v;correc}$	167	87

$$Secondary\ energy\ loss_{window;open;tilt} = \rho_{air}.c_{air}.V.(T_{in} - T_{out})\ (Joule/hour) \tag{4.5}$$

The energy loss shown in table 4.6 is the secondary energy produced by the heat pump (with a CoP - 2.40 - space heating).

From the fig. 4.5 the average energy consumed by the heat pump for space heating in the last 13 days was 5.9 kWh. But after the windows were opened, the value went up to 8 kWh. The heat-recovery ventilation unit increased its consumption from 0.40 kWh to 0.50 kWh. The relatively low increase in the energy consumption of the HR ventilator is due to its high efficiency. Day 1 the energy increased but on day 2 it did not. The reason the net energy loss on

Table 4.4: Variables used

Variable	Value
ρ_{air}	1.2 kg/m^3
c_{air}	1000 J/(kg.K)
T_{in}	19.2° C
T_{out}	6° C

Table 4.5: Meter readings corresponding to fig.4.12

		Space heating	HR ventilation	Total
	Daily average - energy consumed (kWh)	5.9	0.40	6.3
Day 1	Energy consumed (kWh)	8	0.50	8.5
Day 2	Energy consumed (kWh)	0.50	0.50	1
Day 1	Excess energy consumed due to the open windows (kWh)	2.1	0.10	2.2
Day 2	Excess energy consumed due to the open windows (kWh)	0	0.10	0.10

Table 4.6: Energy loss due to opening the window

		Living room + kitchen	Master bedroom	Total
Day 1	Energy loss$_{windows;open;tilt}$ (kWh)	1.93	0.92	2.85
Day 2	Energy loss$_{window;open;tilt}$ (kWh)	0.75	0.35	1.1

day 2 was low even though the window was open was because of the sunshine (refer fig.4.15) on the south facade, which is where the windows were located. The figure [cite figure] shows 12 minutes of sunshine at around 15:00. This was responsible for the negligible use of space heating to maintain the set-point temperature. Due to the high insulation levels, even low levels of sunlight reduced the demand for space heating to great extent, thereby rendering the effect of occupant behaviour nil.

On day 1, with the windows open for around 3 hours, there was a total loss of 2.85 kWh secondary energy. With a heat pump and a high efficiency this effect is negligible for just 3 hours. Although the energy loss could amplify with increased duration of windows being open. If this is a recurring pattern it could lead to a substantial increase in the monthly consumption.

$$\text{Net secondary energy loss}_{day-1;window;tilt} = 0.68 \text{ kWh/hour}$$

$$\text{Net secondary energy loss}_{day-2;window;tilt} = 0.05 \text{ kWh/hour}$$

The above two energy losses give us an estimate of how much energy is lost when a window is opened. This value is valid only in the following conditions -

- When the temperature difference between indoor and outdoor is 10°C.
- When the insulation levels are similar to the young couple's house (refer table 3.6).

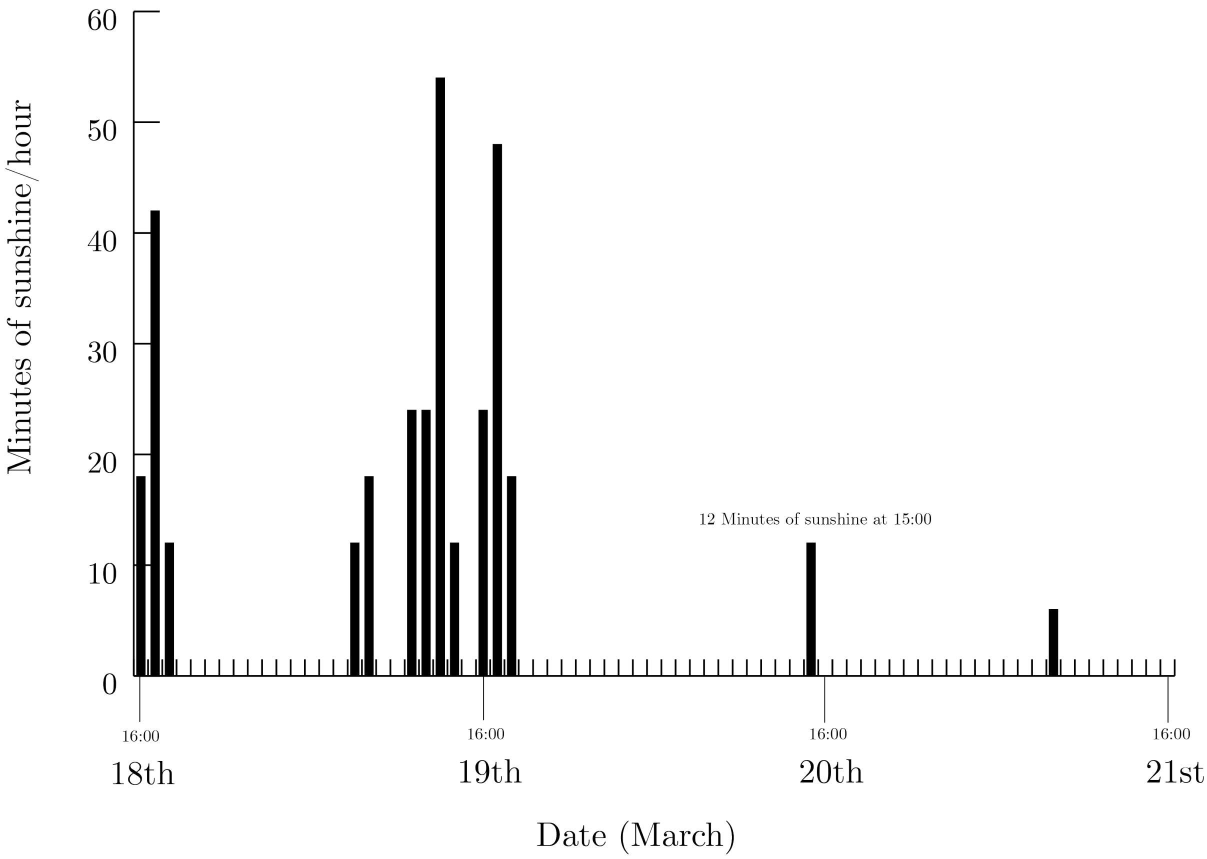


Figure 4.15: Minutes of sunlight per hour (KNMI)

- When the total opened window area (tilt position) is the same as in the young couple's case (refer table 4.3)
- In this situation, the heat pump for space heating has a CoP of 2.40 and there is mechanical ventilation supply and exhaust. In order to extrapolate these values, necessary corrections needs to be made.

4.6 Malfunctioning of the partial sensor set-up

Initially, the sensors along with the micro-controllers were tested. These testings were successful but problems were faced during the installation of the set-up. One of the issues was the micro-controllers and sensors worked well with constant power supply from USB cords or the plugs. But for data collection this was not possible because in order to collect correct and representative data the sensors and micro-controllers had to be placed in different locations. And the unavailability of a power source at every location the micro-controllers were placed, made using batteries the only option. Due to the lack of research into the battery capacity required for data collection, this caused some of sensors to switch off during the observation period. In addition to this, different sensors work on voltage differences to report data. The varying voltage supply of Li-Po batteries and the mistake of not placing resistors within the circuits led to false or no readings being recorded. In this situation the PIR and the MQ135 sensors did not work or report credible readings. So a decision was made to not install these at the houses. In-place of the PIR sensor, an estimate of occupancy was retrieved from the occupants. And in-place of the CO_2 sensors, an assumption was made, The assumption being that the CO_2 sensors of the HVAC system functioned properly and maintained the levels between 400-1200 ppm. In the case of the reed switch sensor, not all of them worked because the batteries were charged to different levels of voltage. If the voltage was too high, the reed switch did not detect the electrical change due to magnets.

4.7 Energy usage in the three households

The total energy usage (electricity and gas) in the three households have been compared for the observational period and the entire year. Actual energy consumption for the senior couple and the family has been considered. For the young couple´s house since this data was not available for the months April - October, an interpolation based on the predicted energy consumption (by the contractor) and the actual energy consumption (with data from November - April 2019) was been made. For the electricity and the hot water usage, a monthly average from November 2018 - April - 2019 was assumed for the rest of the months from April to October.

The energy consumption during the observational period as seen in the fig.4.17 in the young couple´s house consumes the least energy - 100 kWh. The senior couple´s and the family house consume 737 kWh and 1190 kWh respectively. This is due to the varying heating and electricity demand by the appliances. There are significant savings when the two houses are compared to the young couple´s house even after the sophisticated HVAC system. Although this could be due to the fact that the young couple has just moved into the house and is heavily influenced by the idea of energy savings.

The yearly energy (gas and electricity) consumption of the respective households are 17002 kWh, 4047 kWh and 18518 kWh (gas usage converted to kWh). The higher insulation levels, efficient heat pump and low appliance usage has resulted the young couple´s house to consume about 76% less than the senior couple and 78% less than the family house. Furthermore the annual PV energy production exceeds the energy usage, which means the house is net positive.

In the senior couple´s house there was a clearly discernible difference in the total electricity consumption during the cold months. Upon enquiry, it was found that the occupants used a 2000 W electric radiator in the non-insulated garage (which was used to store food). This action due to occupant behavior resulted in a massive increase of 33.5% in the yearly electricity consumption (refer fig. 4.18.

A cost comparison of the money paid for energy usage during the observation and yearly period is seen in fig. 4.19. In the case of the young couple´s case, the net energy consumption (net energy after subtracting the total consumption and production) was taken into account. That was found to be negative.

During the observational period, the senior couple´s, young couple´s and the family´s house paid 82 €, -30 € and 123 €. As observed, the young couple´s house actually earns 30 € during the observation period and around 395 € in the yearly scenario. Whereas the senior couple´s and the family´s houses paid approximately - 2289 € and 2031 €. It seen that the senior couple´s household paid 258 euros higher than the family house. This was predominantly due to the usage of the 2000 W electric radiator in the non-insulated garage. If the electric radiator in the garage would not have been used, then the senior couple would have saved approximately 420 €.

Out of the three houses, only the young couple´s house is equipped with PV panels. There are 31 panels on the roof which supply energy to the house. The energy mis-match is accomodated by supplying excessive energy to grid and vice-versa. During the observational period the PV panels produced around 110 kWh and the yearly estimation is around 5500 kWh (refer fig. 4.20).

4.8 Conclusion

As expected the three households had different levels of energy and water consumption. A large part of it was indeed contributed by the different households and their behaviour. Table4.7

shows the water, gas and electricity (produced and used) profiles for the three houses. These three houses exhibit different lifestyles and that clearly shows in their profile. This choice of lifestyle affects the number of appliances in the house. This is to seek convenience but in this process of seeking higher levels of convenience, the energy and water usage is greatly influenced. Additionally the varying levels of insulation clearly show in the energy used for space heating. The electricity demand in the family and senior couple's household indeed poses the question where can we draw the line when it comes to making assumptions about non-building related electricity usage. Another noticeable difference is seen in the water usage in the young and senior couple's houses. The excess usage in senior couple's household is also due to the temporary residents they have, thereby increasing the water used for dish washers, washing machine, showers, cooking and drinking purposes.

Table 4.7: Energy profile of the three houses during the observation period of two weeks (7th to 21st March - 2019)

Candidate	Senior Couple	Young Couple	Family
Water used (m^3)	3.491	2.704	5.315
Gas used (m^3)	64.61	0	111.06
Electricity used (kWh)	112	100	115
Electricity produced (kWh)	0	110	0
Energy consumed (kWh/m^2)	1.22	0.94	1.43
Remark	Net Negative	Net Positive	Net Negative

Table 4.7 shows that the non-building related electrical consumption varied substantially between the senior couple and the other two houses. BENG regulation predicts a rather conservative 14.8 kWh/m^2 for all types of houses. It does not take into account the number of people living (in addition to the total floor area) or the type of lifestyle they follow. The actual consumption shows a large variation. The young couple's house has less electrical appliances and thereby conforms to the BENG regulations. But this might change over time with increased standards of living.

Table 4.8: Comparison of non-building-related electricity consumption with BENG

Candidate	Senior Couple	Young Couple	Family
Total floor surface area (m^2)	144	106	158
Estimated yearly consumption - BENG (kWh)	2131	1569	2338
Actual yearly consumption (kWh)	5041	1477	2595
Estimated yearly consumption per m^2 - BENG	14.8 kWh/m^2	14.8 kWh/m^2	14.8 kWh/m^2
Actual yearly consumption per m^2	35 kWh/m^2	13.93 kWh/m^2	16.42 kWh/m^2

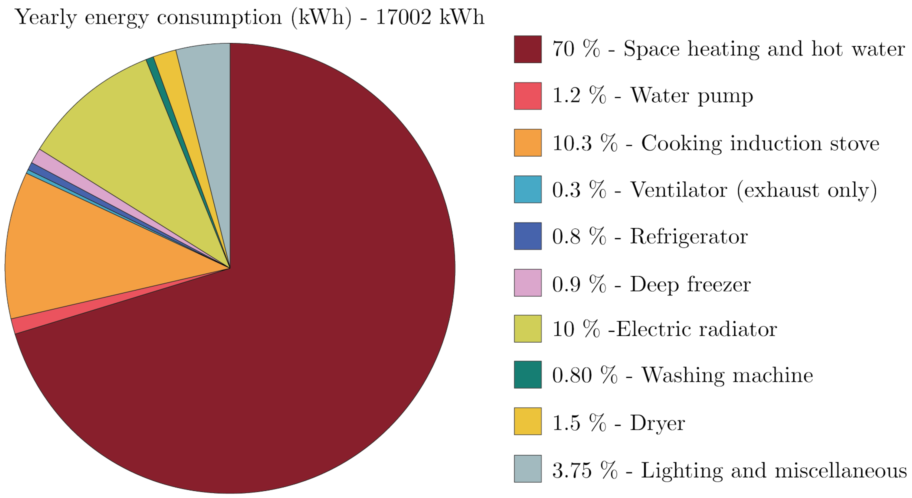
A comparison of the current actual usage and the usage predicted by EPC was made. EPC certficates were available for the senior couple and young couple's house but for the family house an energy estimation expected from the house type (two under one roof row house) was made. The actual usage was higher only in the case of the senior couple. The primary energy calculation included the energy needed for space heating, hot tap water, cooling/summer comfort, ventilation and auxiliary energy (pumps, fans and electricity for the cv). This calculation excluded lighting because measurements on the actual consumption were not carried out. Then the increase/decrease percentage of the actual usage to the predicted usage by EPC was made. In the case of the senior couple, the higher use of primary energy could be attributed to underestimating energy consumed by the pump to push the water for floor heating through the entire house. EPC assumes 41 kWh for operational energy of the floor heating, which was found to be far less than the actual scenario. A small hand calculation revealed that the pump would consume at least 110 kWh per year for pumping the water. Additionally the window grilles and the window opening behaviour was completely neglected for simplification and as seen from section 4.5, this could lead to large energy losses. Upon consulting with the residents, windows were occasionally opened for increased ventilation during cooking or sleeping.

In the young couple's case, due to the presence of 31 PV panels, there is on-site energy production. The panels produce up to 5500 kWh the entire year, which is less than their predicted usage. Furthermore, the low number of occupants, lower surface area, very high levels of insulation and glazing (triple glazing) reduce the energy loss drastically. Since the couple moved into the house in November 2018, data from November-March 2019 was available - which is useful because primary energy usage is expected to be the highest during these months. Interpolation from the predicted energy usage based on the current usage trend yielded the "actual" yearly consumption. Another aspect to be taken into account is the set-point temperature for heating was 2° C lower than what was assumed in the EPC, this is attributed to occupant's personal preference. Furthermore, use of a heat pump with almost an efficiency of 2.1, lowered the primary energy demand significantly.

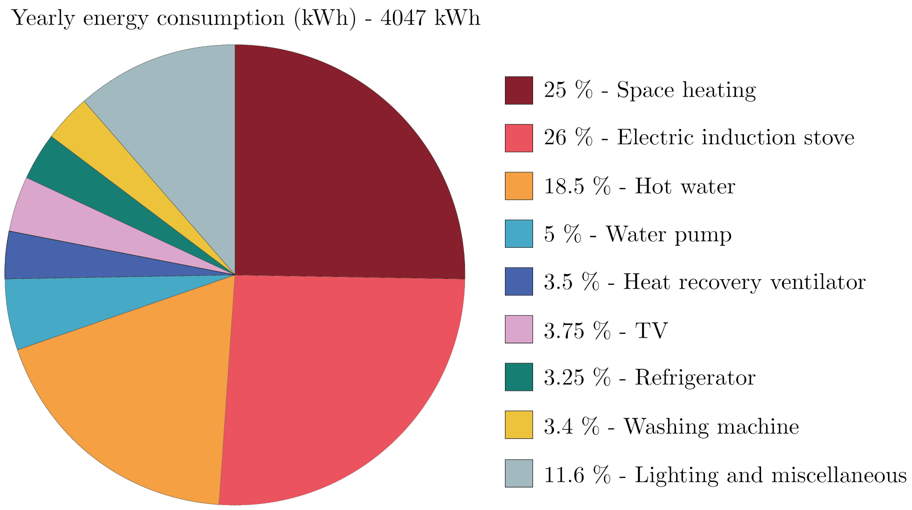
In the case of the family house, the house is surrounded by neighbouring houses by three sides (two adjacent sides and bottom side) therefore the neighbouring effect plays an important role. This effect is thought to be higher because the insulation levels between the neighbouring houses is very low. Analysing the data from the sensors shows the a temperature of around 19-20° C is preferred. Since the actual EPC certificate was not available, an assumption was made from the Dutch standards for this particular house type (two under one roof row house). The difference in primary energy between the family's and the senior couple's house is not high. A large part of this could be attributed to the neighbouring effect, in addition to the lower temperature set-point, lower energy used by the heating system and the pump to transmit the water throughout the house. A significant difference is seen in the energy used by the pump because the senior couple's house has floor heating - which requires higher pump energy due to the increased resistance and higher surface area when compared to the conventional radiators in the family house.

Table 4.9: Comparison of building's primary energy consumption (excluding production) - space heating, hot water, cooling, ventilation and auxiliary energy - pump and fans (**excluding lighting**) with EPC

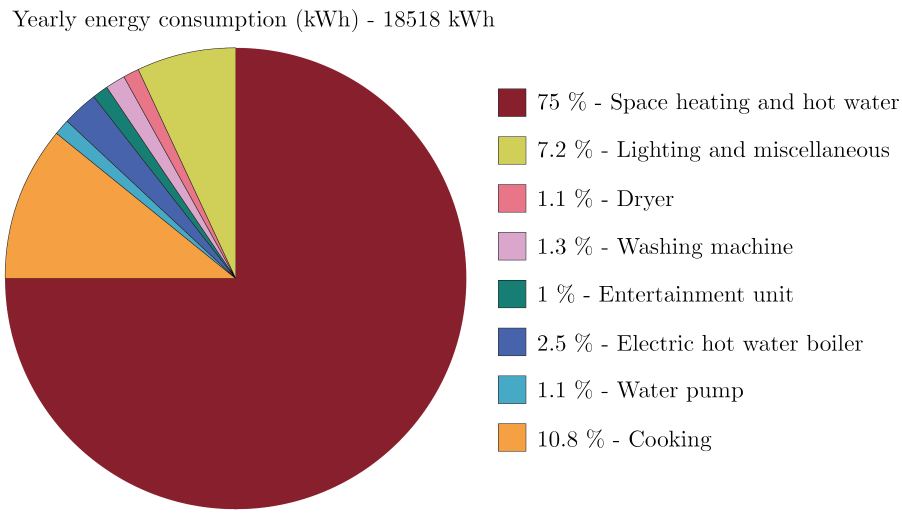
Candidate	**Senior Couple**	**Young Couple**	**Family**
Year	2016	2018	1934,2000
Occupants	2-P, 3-T	2-P, 0-T	4-P, 1-T
Total floor surface area (m^2)	144	106	158
EPC - Total yearly primary energy consumption (kWh)	9171	2179	15121
Actual yearly primary energy consumption (kWh)	12162	2120	14126
Difference percentage	+33 %	-3 %	-7 %



(a) Senior couple

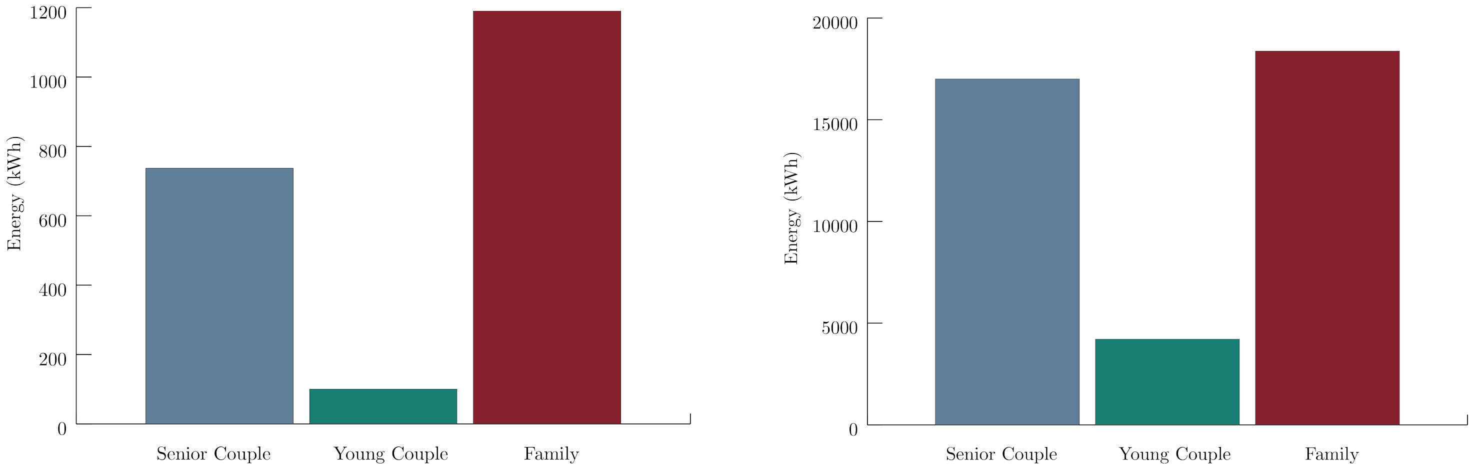


(b) Young couple



(c) Family

Figure 4.16: Total energy consumption (gas and electricity) breakdown at the three households



(a) Observational period

(b) Entire year

Figure 4.17: Total energy (gas and electricity) consumption in the three houses during the observation period and the entire year

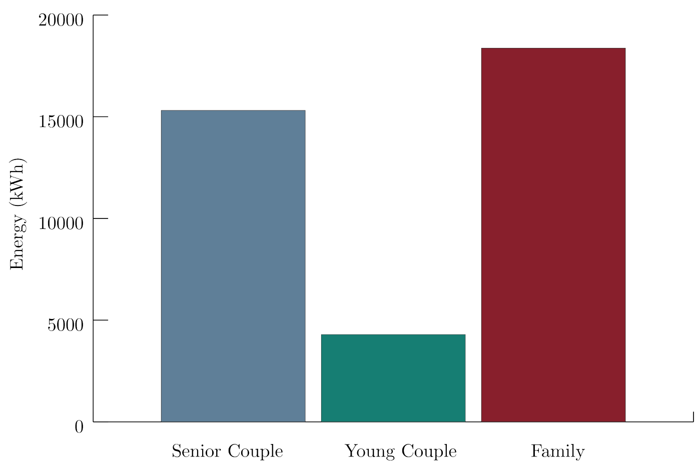


Figure 4.18: Yearly energy (gas and electricity) consumption in the absence of the 2000 W electric radiator in the garage of the senior couple

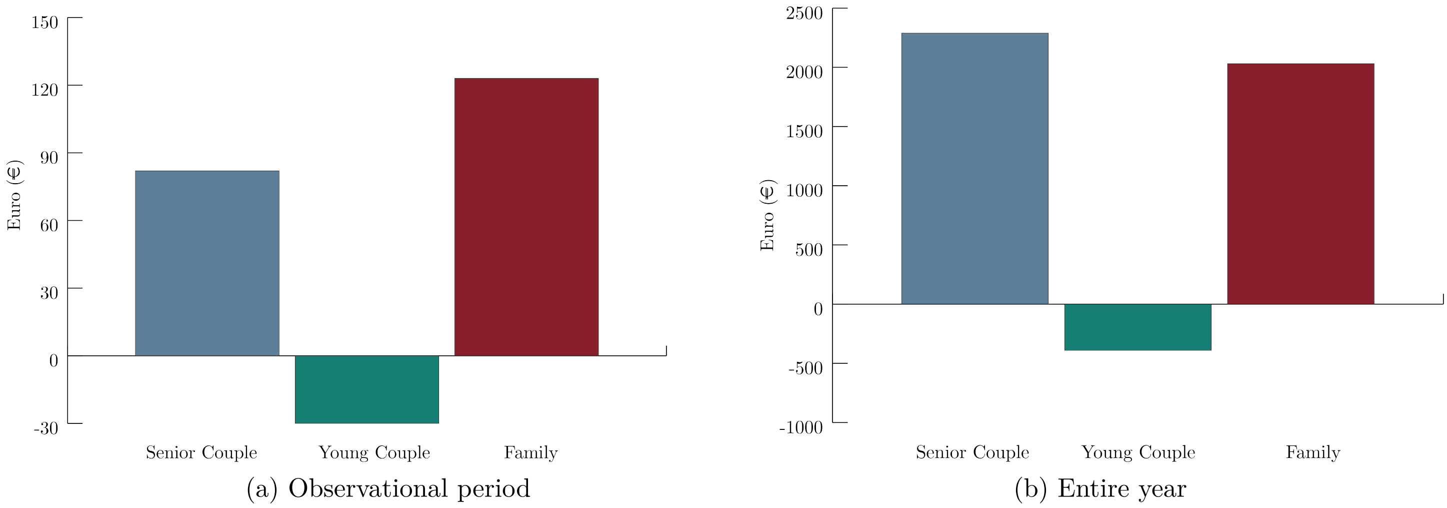


Figure 4.19: Total cost paid for energy (gas and electricity) usage during the observational period and the entire year

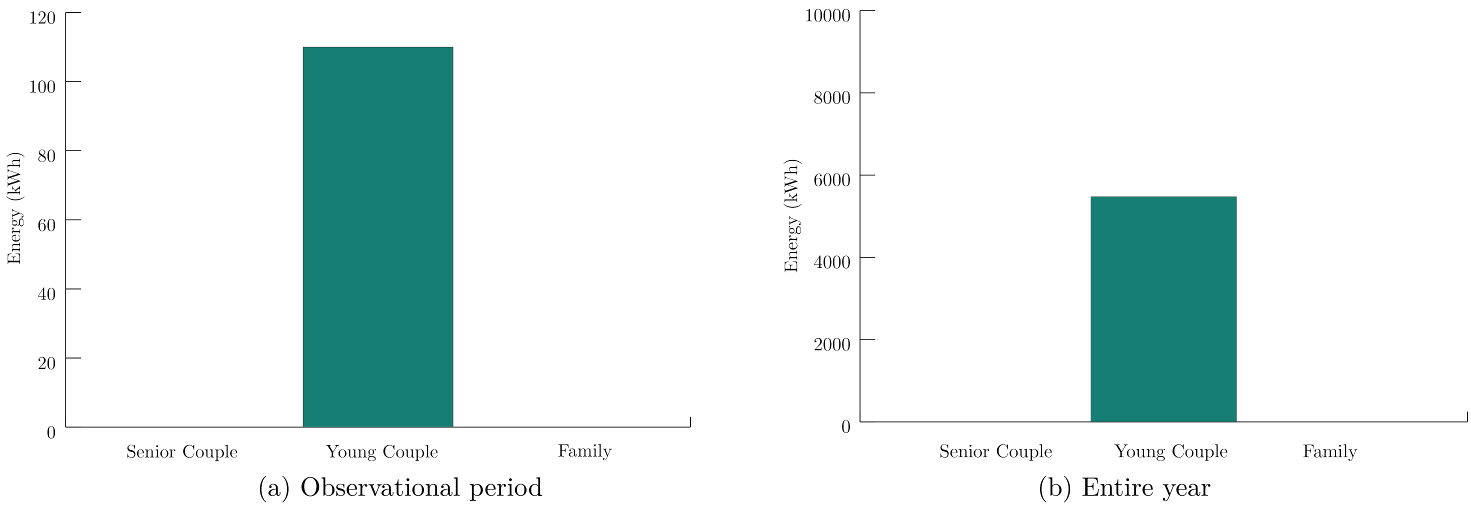


Figure 4.20: Total energy (electricity only) produced in the three houses during the observation period and the entire year

Chapter 5

Modelling Results

The three houses were modelled with IES(VE). The aim of this was to provide grounds for constructive suggestions, improvements on behaviour and house characteristics. Different cases were simulated for the three houses to analyse the accuracy of the simulation and actual energy usage, energy consumption after improving the insulation levels, indoor air temperature of the current and suggested scenarios and the yearly carbon dioxide emissions from each house.

5.1 Model validation

Prediction of a building's future energy needs using energy models are preferred because they are quick, inexpensive and allow for easy optimisation. But more often than not, if the energy modeller is inexperienced then these models are difficult to validate, which leads to an even larger problem of inaccurate results.

Since this study is based on already existing residential dwellings, the energy model was validated using actual monthly data (gas, electricity and water). Even with the real-time data, there are some common errors that can compromise the results of the energy model. These common errors which were paid attention to while modelling the three residential dwellings were

- Neighbour effect
- Daylight saving time
- Internal gains and ventilation rates

5.1.1 Neighbour effect

The neighbour effect takes place when two houses share partition walls. This occurs usually in the case of typical Dutch row houses. These partition walls are not insulated like an external wall but more often than not while modelling, it might be assumed that commonly shared walls have the same insulation levels as the external wall. This leads to either lower or higher estimation depending on the temperature difference between the two houses or higher if multiple walls are shared with the other houses.

In this study, the senior couple's and the young couple's house share one wall with their neighbours. In the family house's case, they share two walls and the floor with their neighbours. Proper attention has been given to this fact while modelling the three houses.

5.1.2 Daylight saving time

Since daylight saving time is adopted in the Netherlands, it is important to ensure that the imported data like weather and solar gains have been adjusted to the daylight saving time. Failing to do so can lead to inaccuracies that may compromise the model's credibility.

5.1.3 Internal gains and ventilation rates

Internal gains and ventilation rates have a great influence on the total energy consumption. So any over-simplification or erroneous assumptions can lead to large inaccuracies. While modelling it was made sure that appliances with a high heat gain (electric stove, dryer, refrigerator) were accounted for in their respective spaces.

5.1.4 Comparing actual data with the energy model results

In the senior couple's case the prediction of the energy used for space heating and hot tap water was robust and comparable during the relatively warm and cold months. The data varied more than other months during the spring months when the weather is not too cold or too warm. In these situation, the occupants may unpredictably decide to open the windows. These actions are difficult to predict and account for when setting up the energy model. This is the reason the energy performance gap is relatively high in those months.

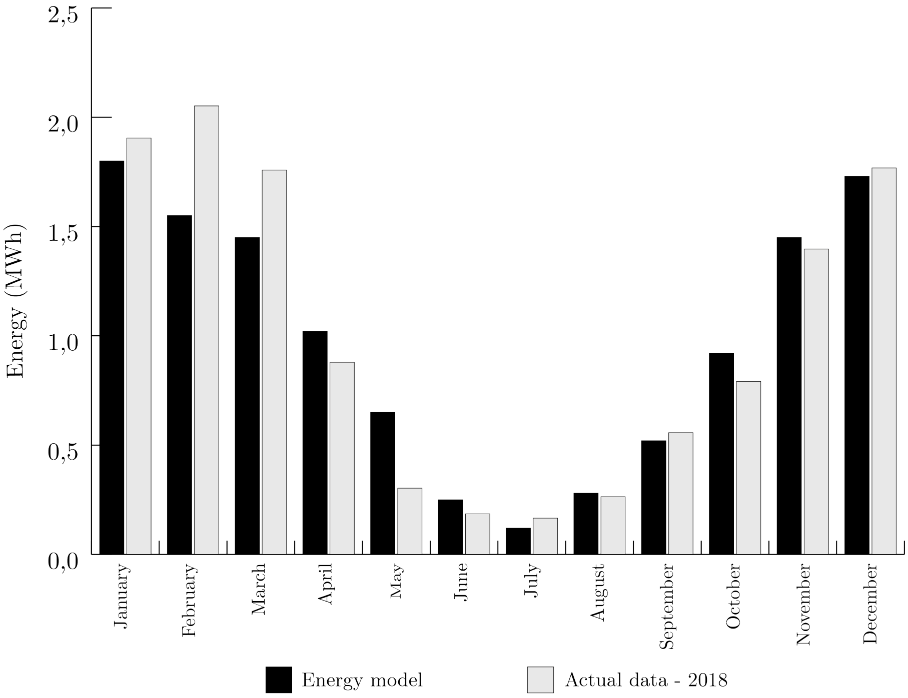


Figure 5.1: Model validation - senior couple's house - energy consumption (space heating and hot water) - Energy model vs Actual consumption

In the young couple's case, only data from the months of January to April 2019 was available since they had moved in only then. The energy performance gap in this situation is relatively low (the energy unit is kWh only in this case). The energy performance gap is low due to the fact that the windows were opened rarely (once or twice a month) and also because the house is equipped with mechanical ventilation (supply and exhaust with heat recovery). The occupants behaved as expected and assumed during the energy calculations. This was because the contractor had advised them to not open the windows otherwise it might consume more energy.

In the family's case, the energy consumption in the cold months is significant. This is due to the fact that the house is relatively old and has poor levels of insulation. Moreover windows are the only means of ventilating the space. It must also be noted that the energy consumption is influenced heavily due to the neighbour effect because it shares walls with three other houses. Even though this effect has been accounted for (by assuming lower insulation levels than the

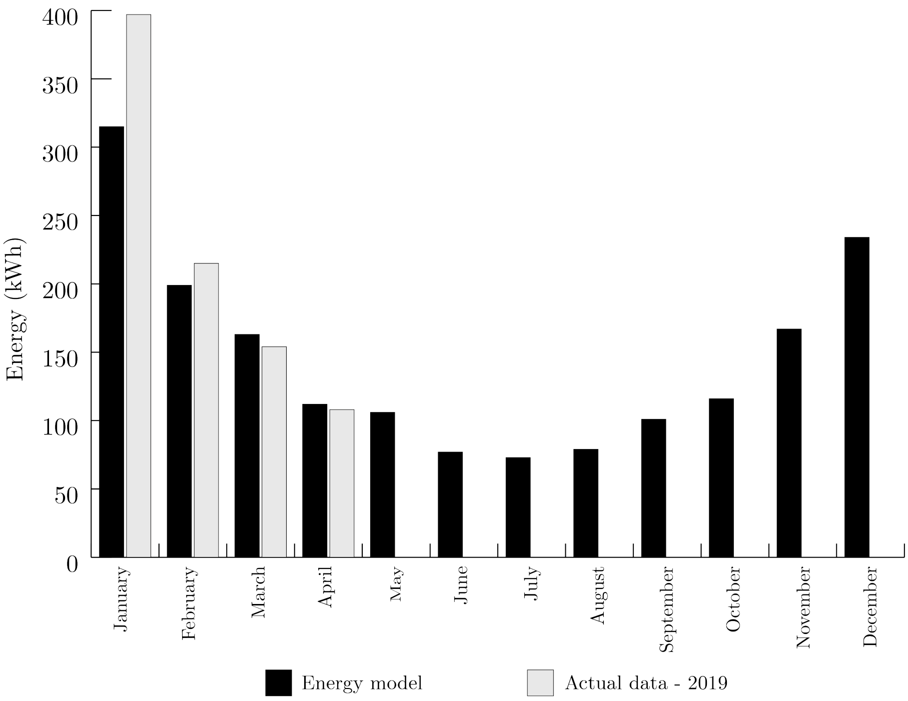


Figure 5.2: Model validation - young couple's house - energy consumption (space heating and hot water) - Energy model vs Actual consumption

external wall), it must be noted that it is out of this study's scope to research the temperatures in the other three houses and to see how exactly it impacted the family's house - whether it lost or gained heat.

5.2 Improvements

At the senior couple's house, the first improvement suggested is higher levels of insulation. The results are shown in the fig.**??**. As it is observed the energy consumption does decrease by 11 %, when the insulation levels are increased. But a major part of the energy consumption is due to the heating system which has a CoP of roughly 0.95 and the pump which transmits the water through the entire house for floor heating. In order to analyse the effects of increased insulation levels on the indoor temperature, an indoor air temperature profile was generated in the frequently used rooms.

Table 5.1: Current and improved insulation levels at the senior couple's house

Insulation	**Currently**	**Improved**
R-value (m^2K/W) - Ground floor	5.00	5.00
R-value (m^2K/W) - External walls	4.23	5.00
U-value (W/m^2K) - Windows	1.20	0.70
R-value (m^2K/W) - Roof	5.17	6.00

The temperature profile currently and after the improvement is shown in fig.5.5. It less temperature variations when approaching the warmer months of year. Furthermore, it decreases the indoor air temperature after improving the insulation levels, this is due to the fact that the cooling energy is preserved better.

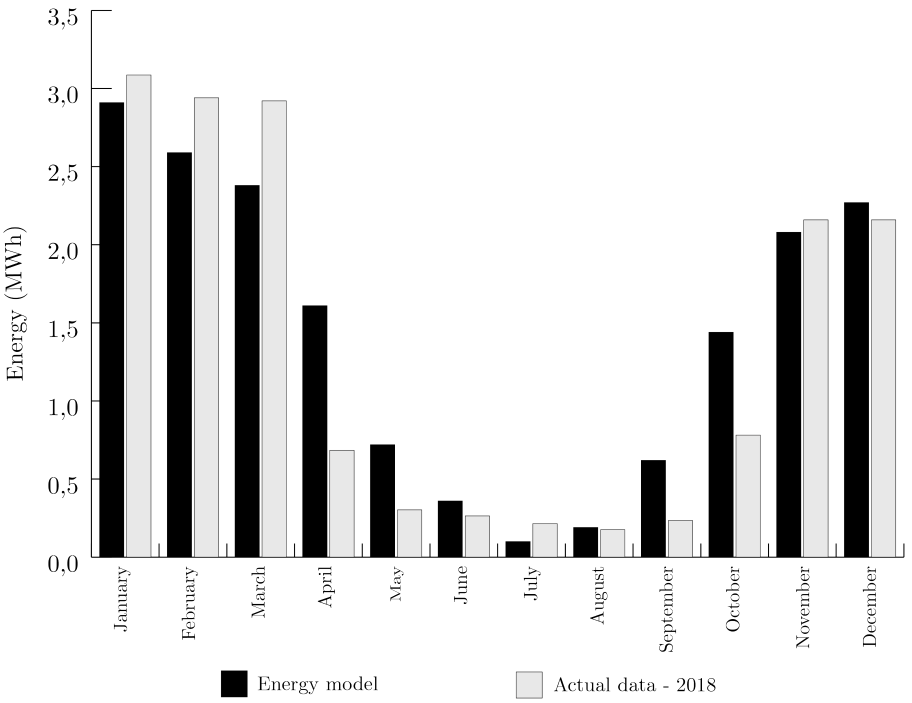


Figure 5.3: Model validation - family's house - energy consumption (space heating and hot water) - Energy model vs Actual consumption

In the master bedroom the difference is negligible as seen from the fig.5.6. In comparison with the living room this case is different because the master bedroom is present in the south end of the house, thereby gaining the extra heat during summer.

The study room which usually has the highest indoor air temperature as observed from the sensor data experiences negligible difference due to increased insulation levels as seen from fig.5.7.

For the family house, the insulation levels were found to be poor. In this case, since this house type is a two under one roof row house, the neighbouring effect is significant. Table 5.2 shows the modelled insulation values for the proposed improvement.

Table 5.2: Current and improved insulation levels at the family's house

Insulation	**Currently**	**Improved**
R-value (m^2K/W) - Ground floor	0.09	5.00
R-value (m^2K/W) - External walls	0.41-1.19	4.23
U-value (W/m^2K) - Windows	2.3	1.20
R-value (m^2K/W) - Roof	1.80	5.17

From the fig. 5.8, it can seen that higher levels of insulation caused a significant reduction of around 55% in the gas usage for space heating.

The indoor air temperature remains steady after improving the insulation levels, although due to the neighbouring effect being dominant in the living room, the temperatures rise slightly higher in summer than in the current case.

The same happens in the kitchen/dining area and this is even more due to the fact that it is south facing facade.

In the master bedroom the temperature stable throughout the day when compared to the

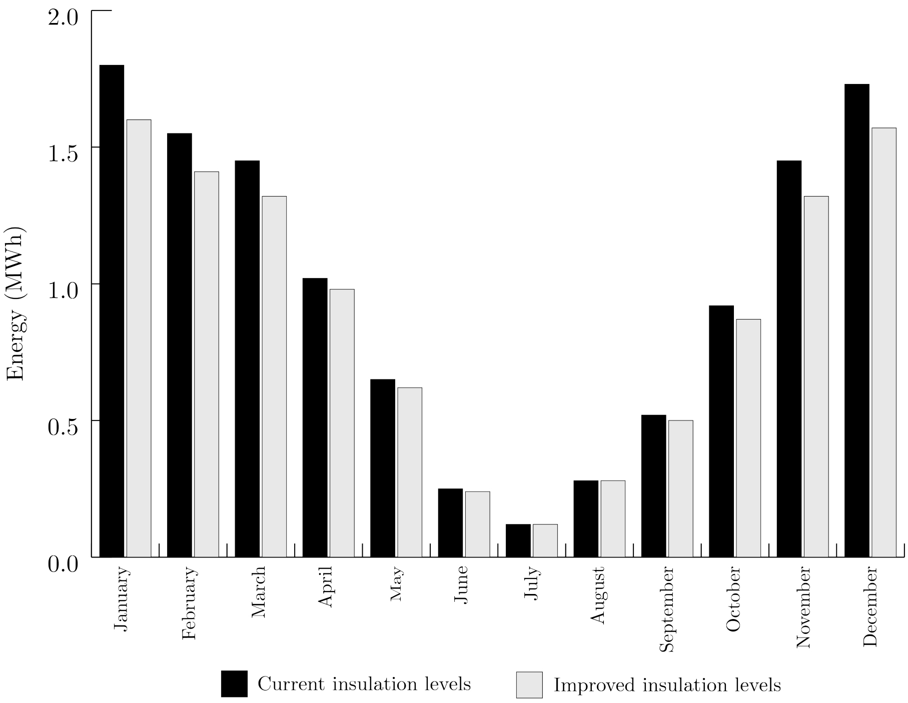


Figure 5.4: Comparison of the yearly energy consumption with the current and improved levels of insulation at the senior couple's house

current situation. But it does not overheat in summers because the neighbour effect is less dominant one floor higher.

In the young couple's case, the current house was analysed for the indoor conditions in summer since no data regarding that was available. The total electricity used is substantially low because of the high insulation levels and an efficient heat pump. Furthermore with 31 PV panels on the roof, the house fulfils the nZEB criteria.

The fig. 5.12 shows the differentiation between the energy used for space heating and for hot water. Both of the parameters have an equal consumption rate during the colder months but in summers the hot water usage dominates. It can also be seen that up to 5 months, the space heating consumes very less energy. But this leads to the question if there is over-heating in summers or not?

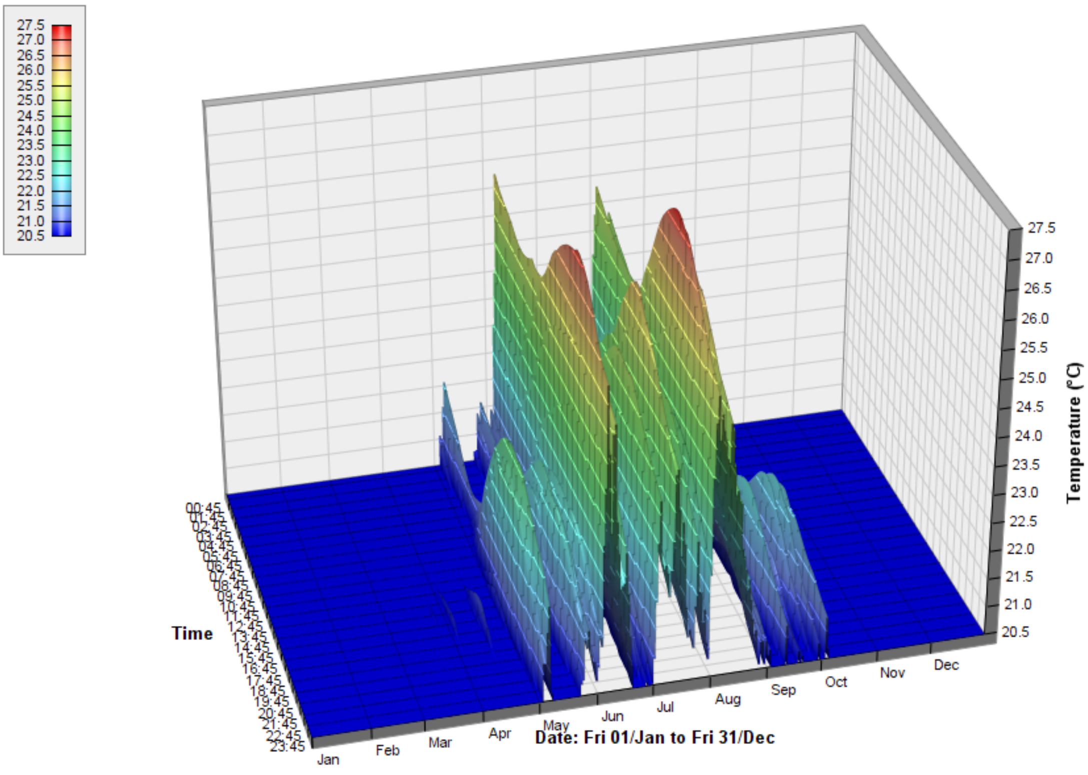
From the fig. 5.13 it can be seen that indoor air temperatures reach up to 33° C in the commonly used spaces. This is not comfortable. If night cooling is done then the temperatures might be a few degrees lower.

It is out of the scope of this study to look at the net carbon dioxide emissions of the houses due to their chosen energy source. The family house has significantly higher emissions due to natural gas. With higher insulation levels and using natural gas for only hot water and space heating, the senior couple's house emits 40% less. The young couple's house has low carbon dioxide emissions, considering it gets all of its electricity from a power plant, which is not the reality. If this house can sustain just on the energy produced by its PV panels, then it will emit negative amounts of carbon dioxide.

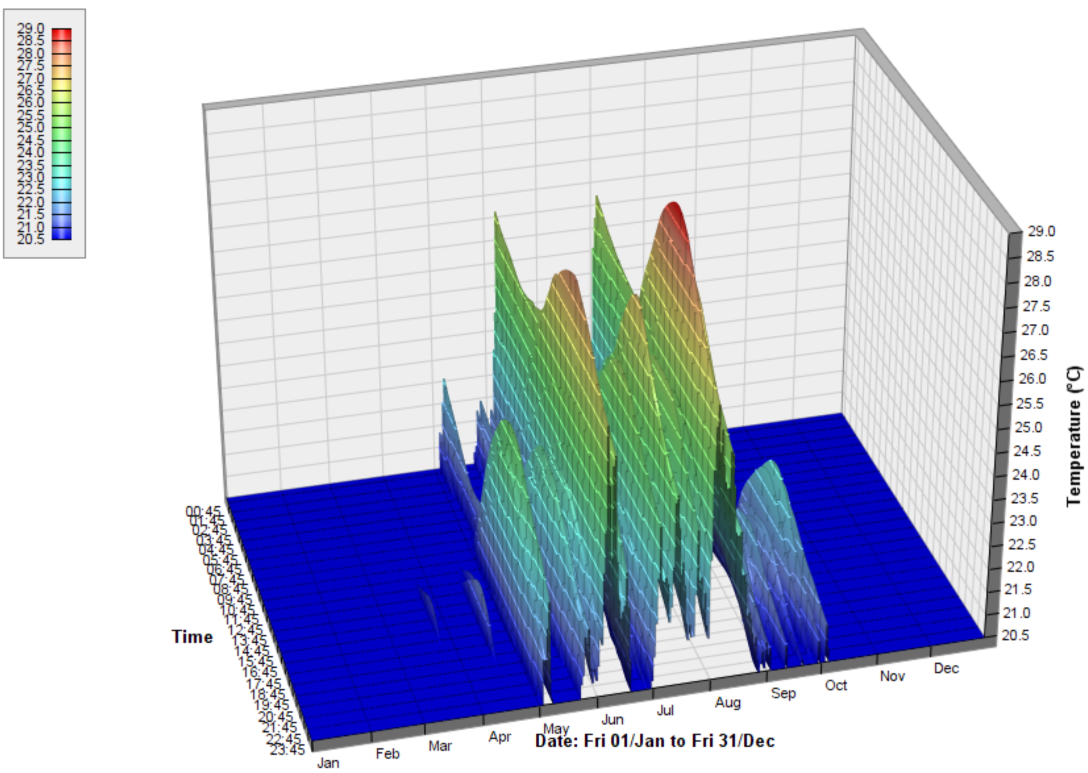
5.3 Conclusion

Based on the results, a close correlation to the reality was found but there are aspects such as hot water consumption which still remain a question mark. This is a parameter which can not be based on assumptions because even a small deviation could lead to significant differences between the predicted and the actual energy usage. Therefore, further research should be carried into patterns of hot water usage. Another valuable aspect could be feeding in occupancy and other schedules which represent the reality. Assuming a constant temperature and closed windows throughout the year is what leads to the energy performance gap.

In the poorly insulated family house it is seen that the monthly actual and predicted energy model consumption deviates to a much larger magnitude than the other two houses. This is mainly due to the heating system chosen. Small changes made by occupants in hot water usage or changing the set-point temperature cause big changes in energy consumption and therefore it is difficult to validate all the months to a high accuracy. Also because occupant choices are subjective and not always predictable.

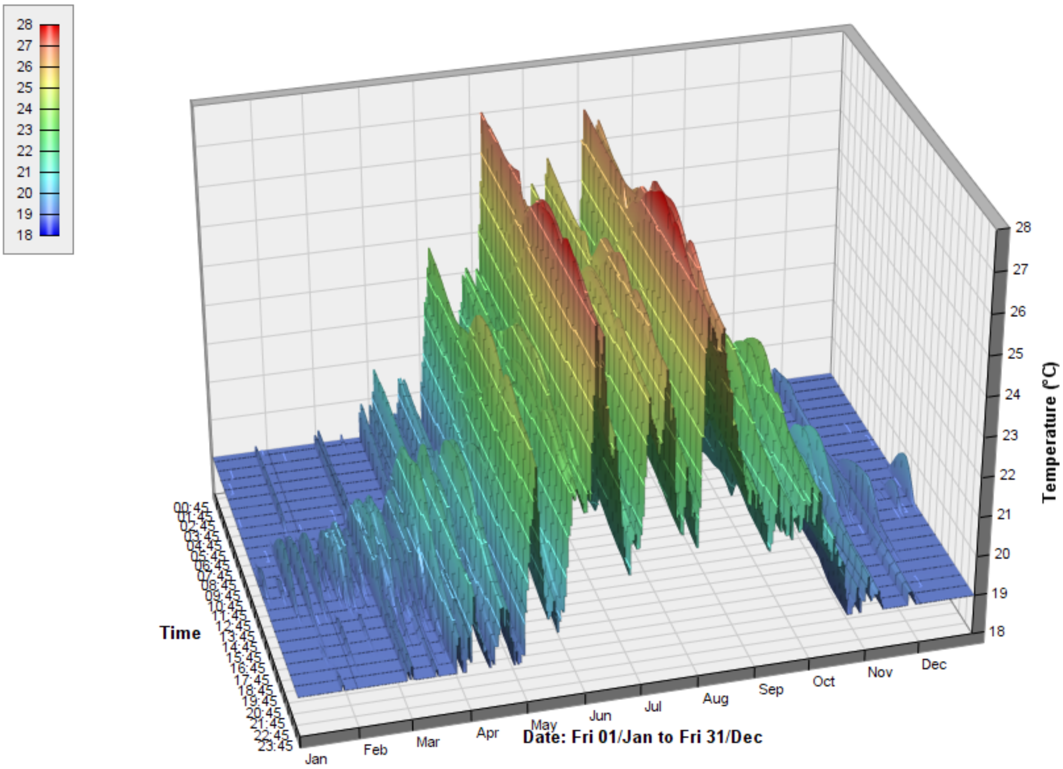


(a) Current insulation level

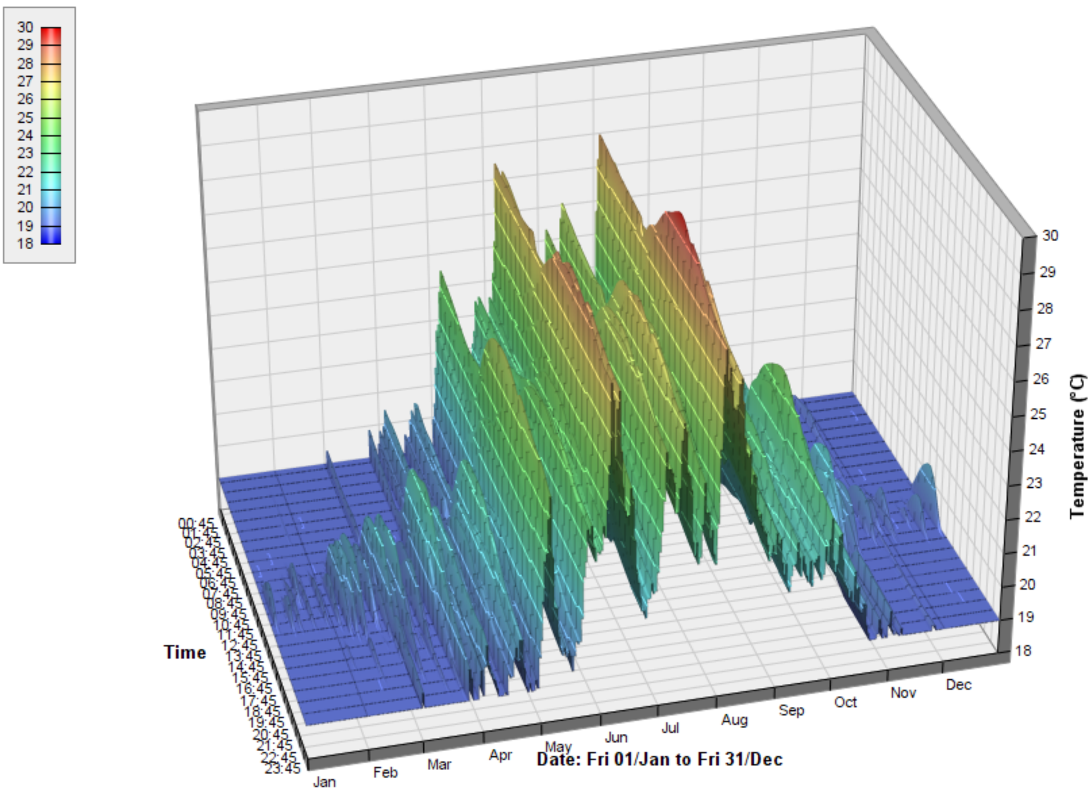


(b) Improved insulation level

Figure 5.5: Indoor air temperature in the living room of the senior couple

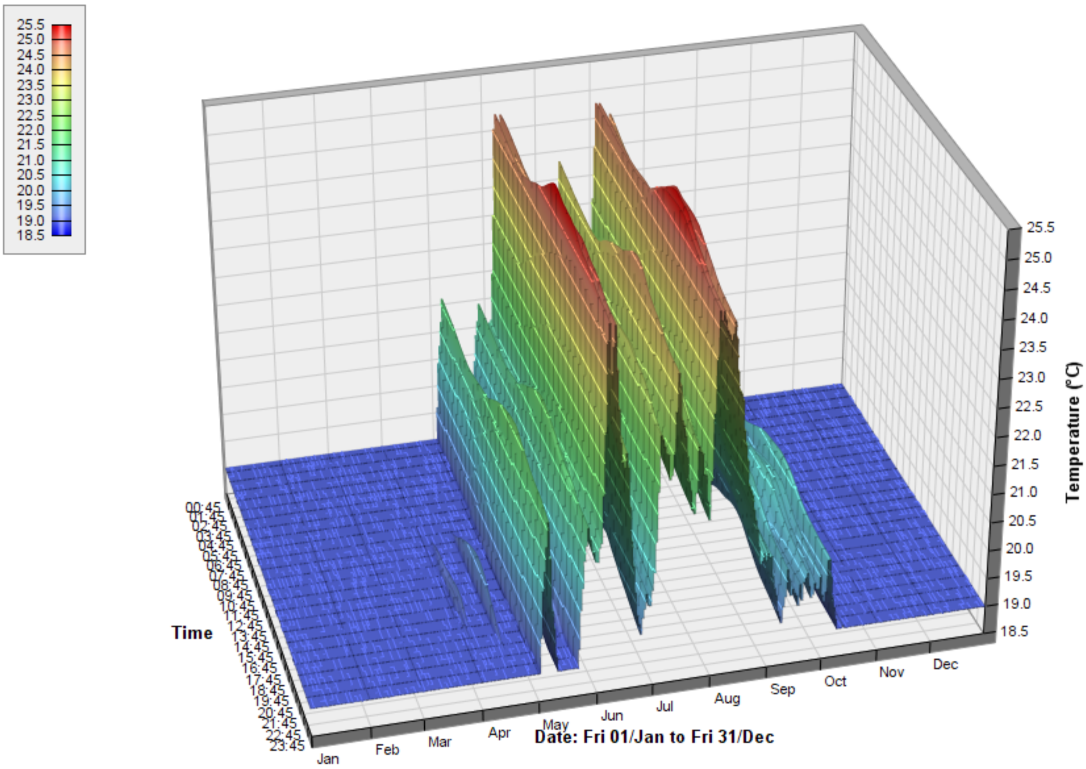


(a) Current insulation level

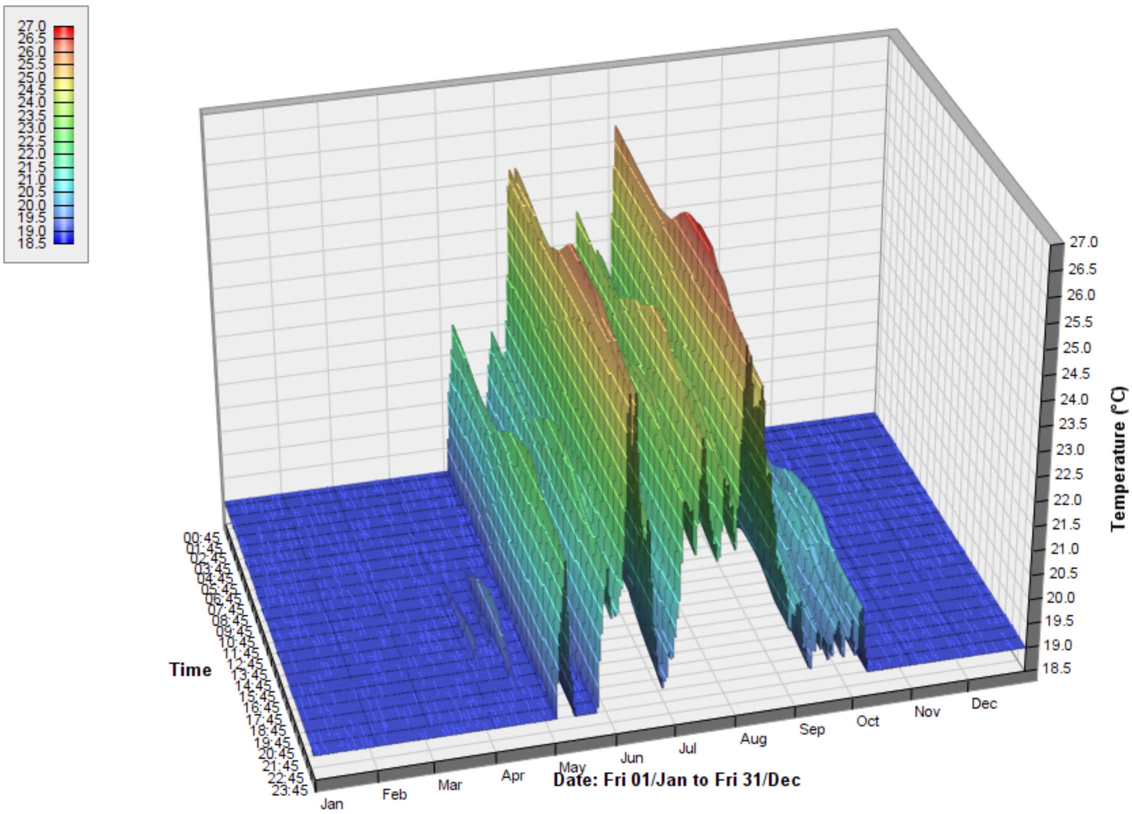


(b) Improved insulation level

Figure 5.6: Indoor air temperature in the master bedroom of the senior couple



(a) Current insulation level



(b) Improved insulation level

Figure 5.7: Indoor air temperature in the study room of the senior couple

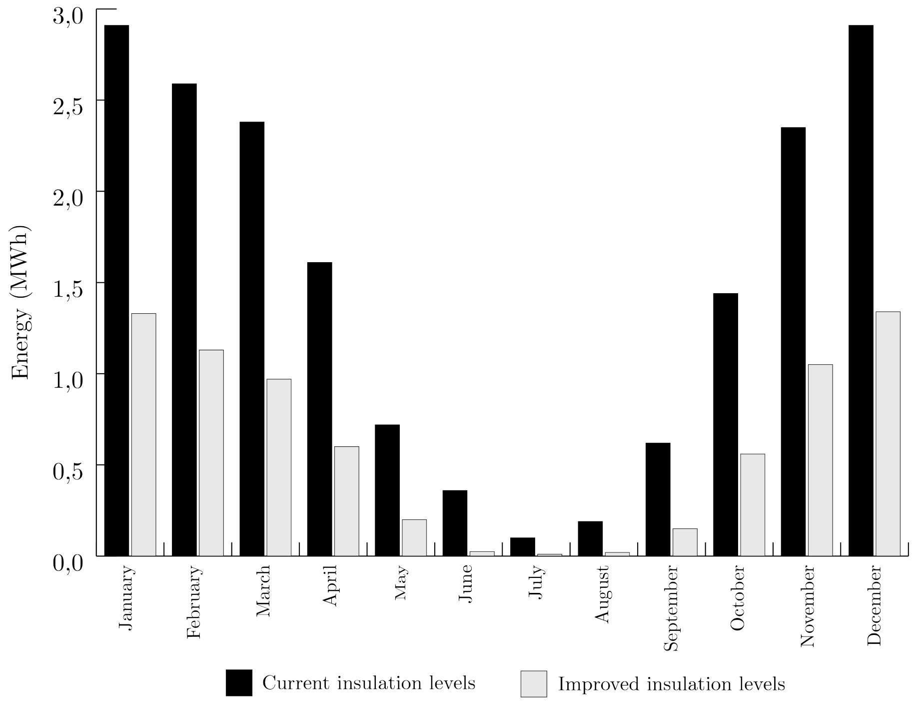
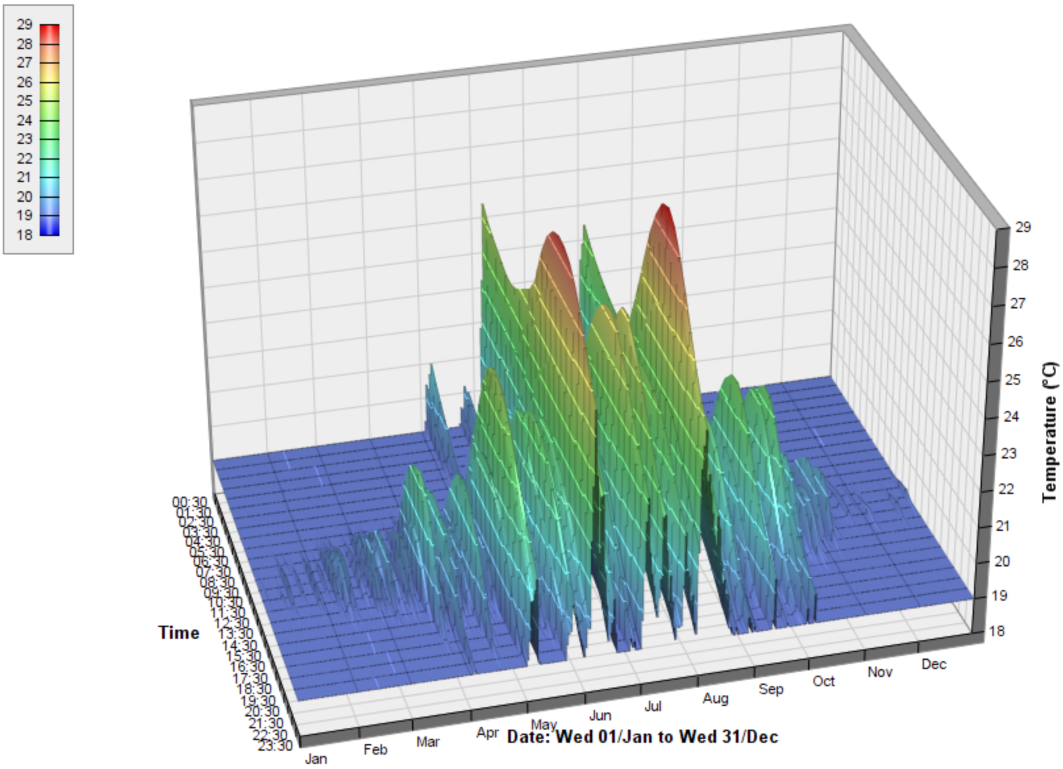
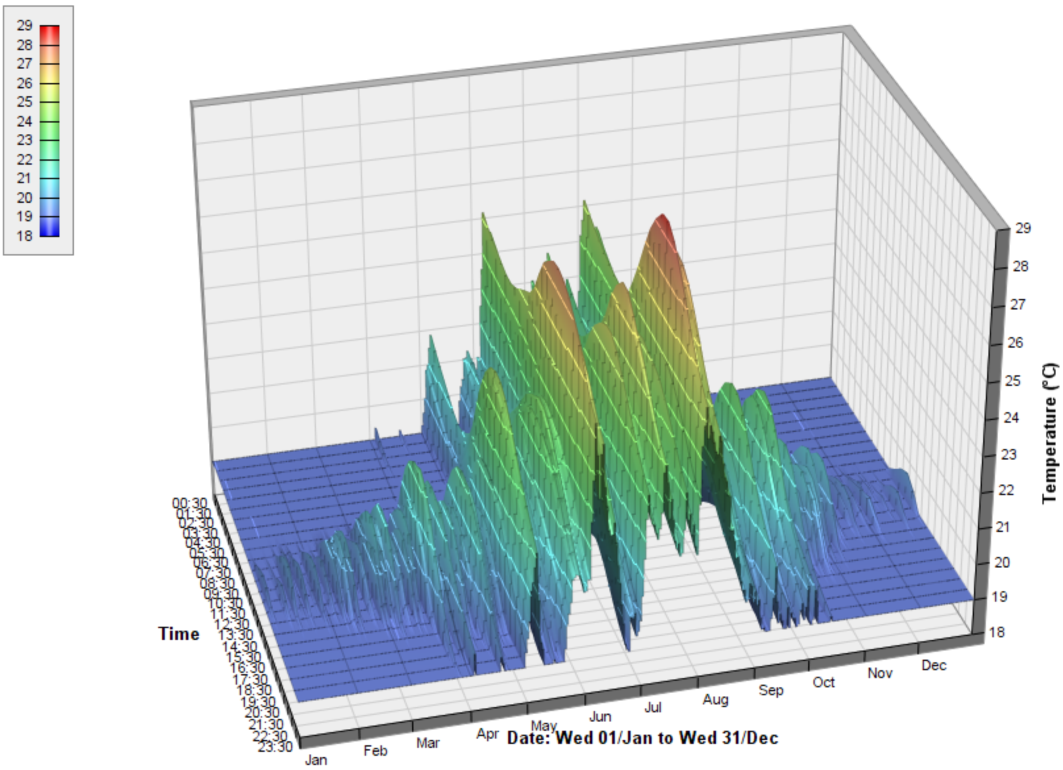


Figure 5.8: Comparison of the yearly energy consumption with the current and improved levels of insulation at the Family's house

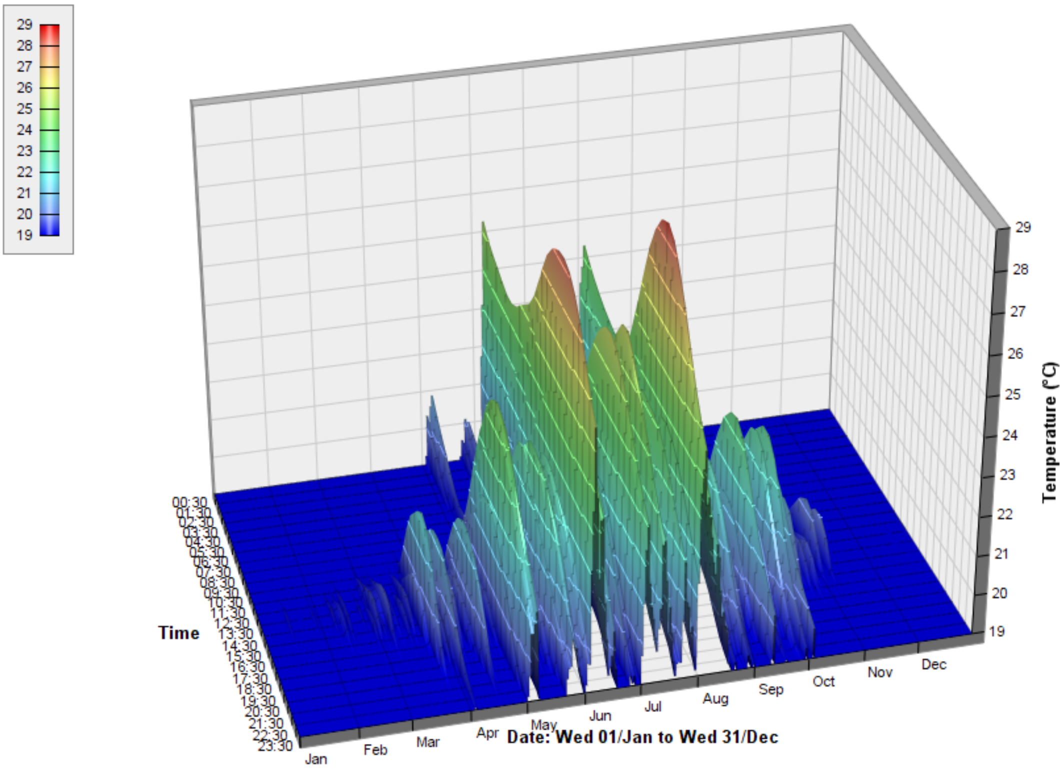


(a) Current insulation level

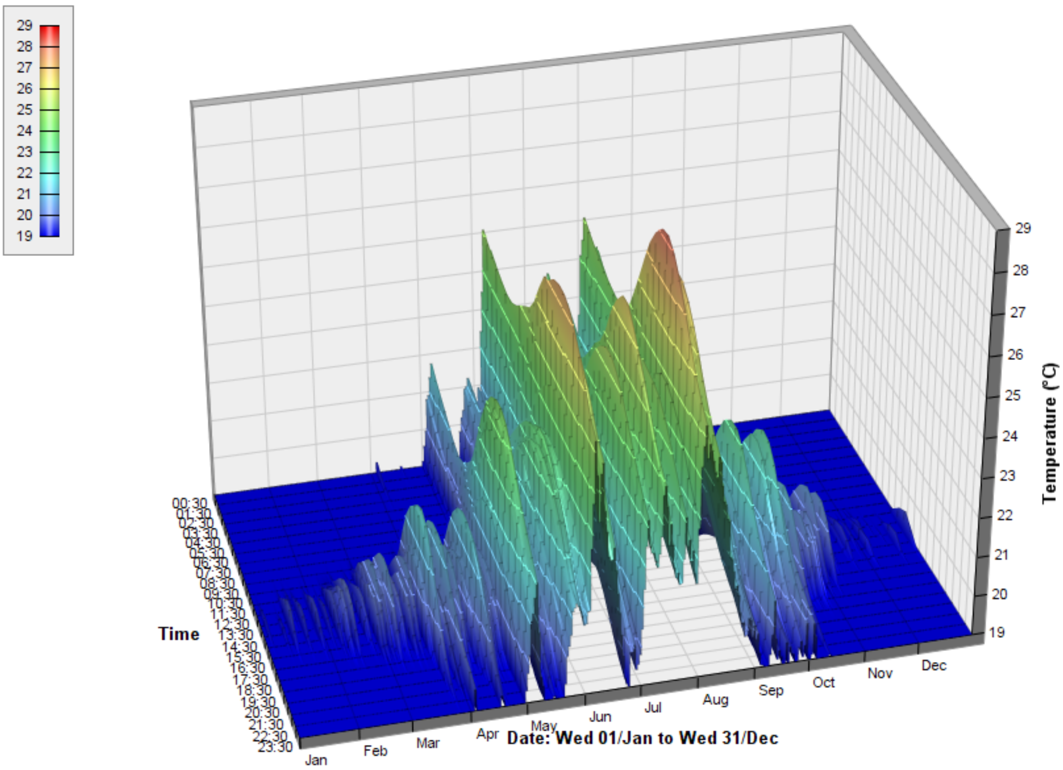


(b) Improved insulation level

Figure 5.9: Indoor air temperature in the living room of the family

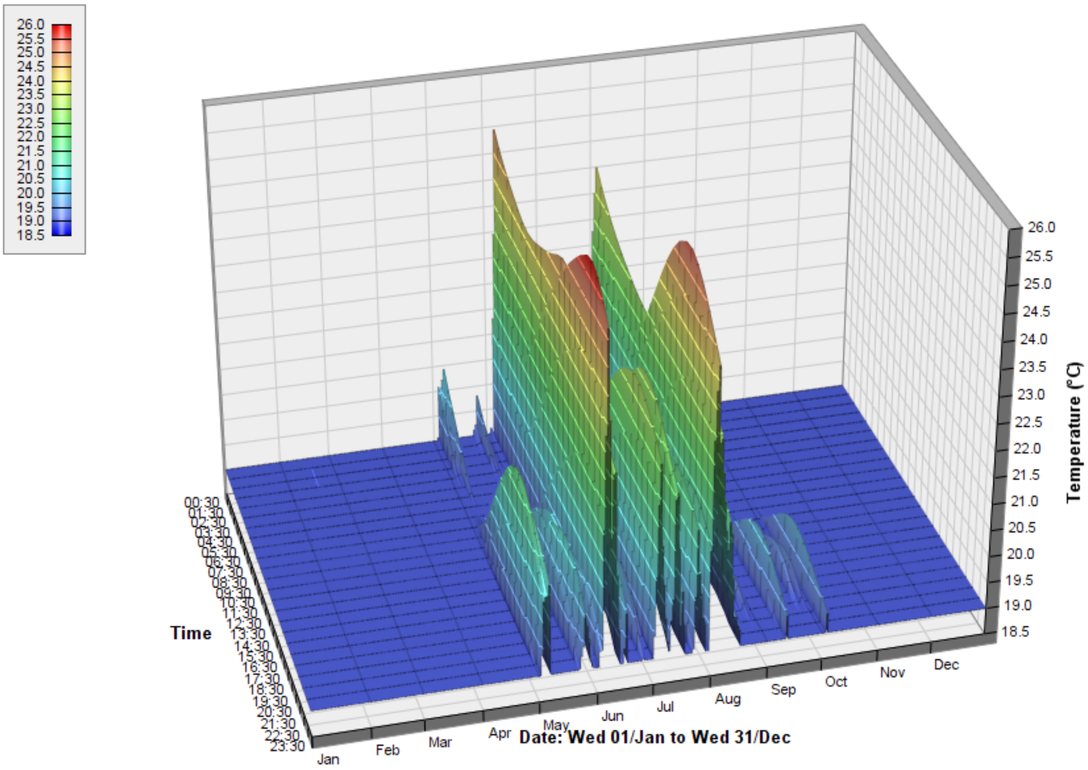


(a) Current insulation level

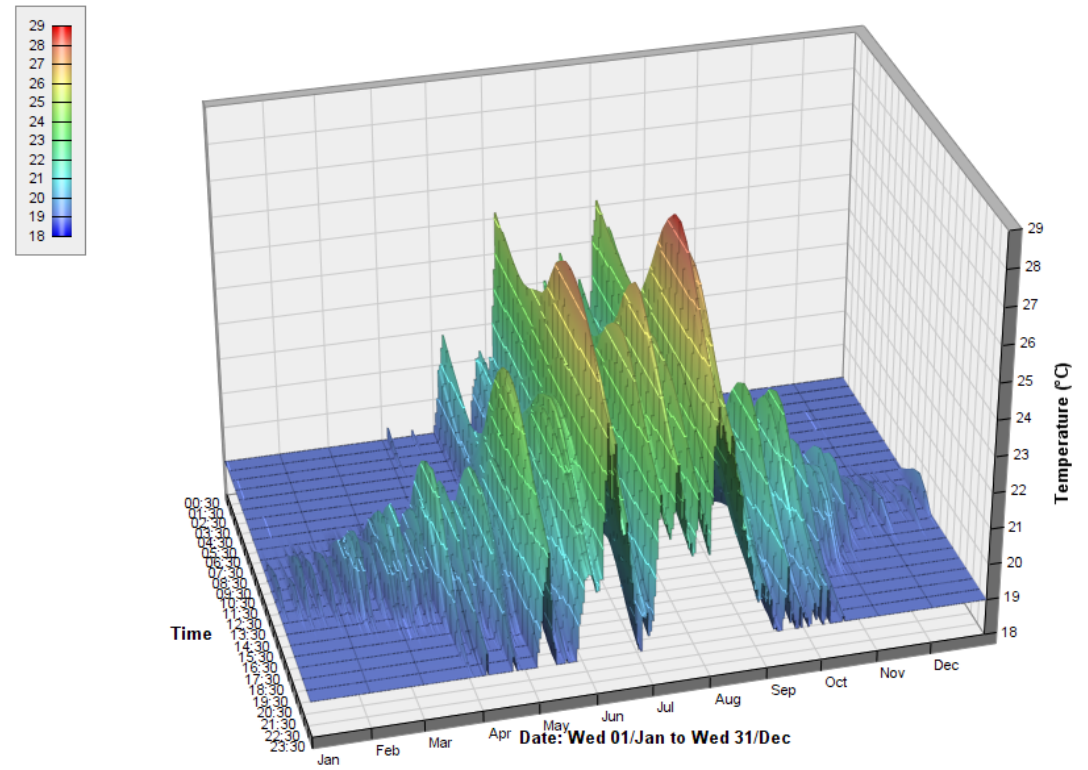


(b) Improved insulation level

Figure 5.10: Indoor air temperature in the dining area/kitchen of the family



(a) Current insulation level



(b) Improved insulation level

Figure 5.11: Indoor air temperature in the master bedroom of the family

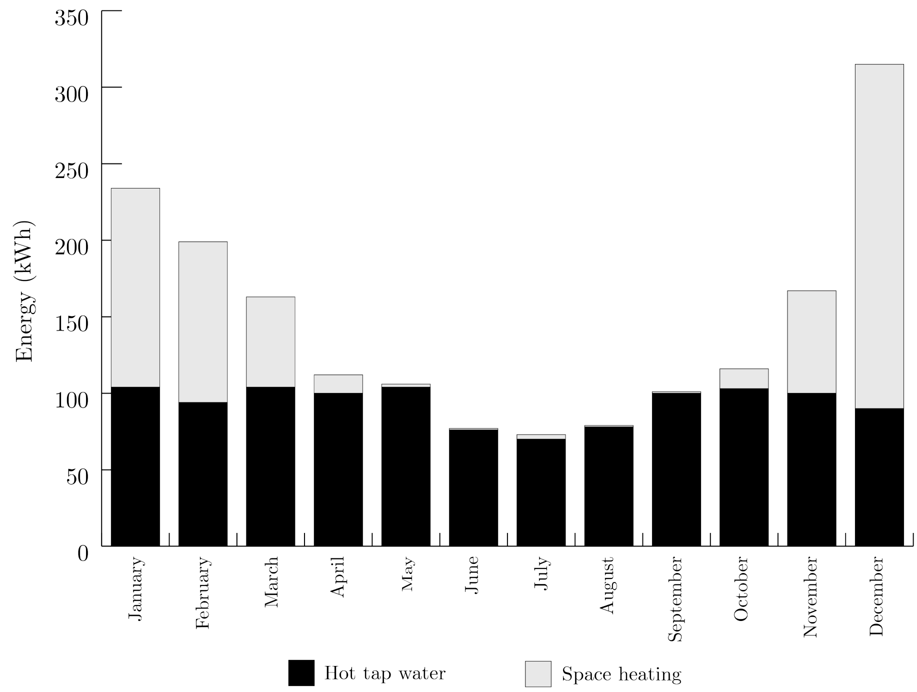
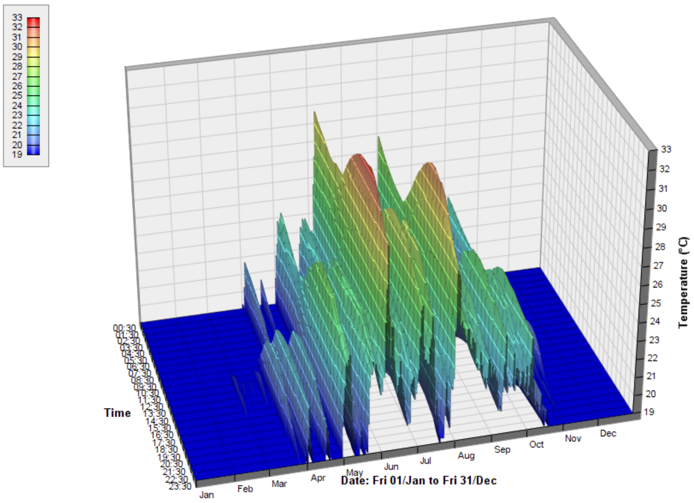
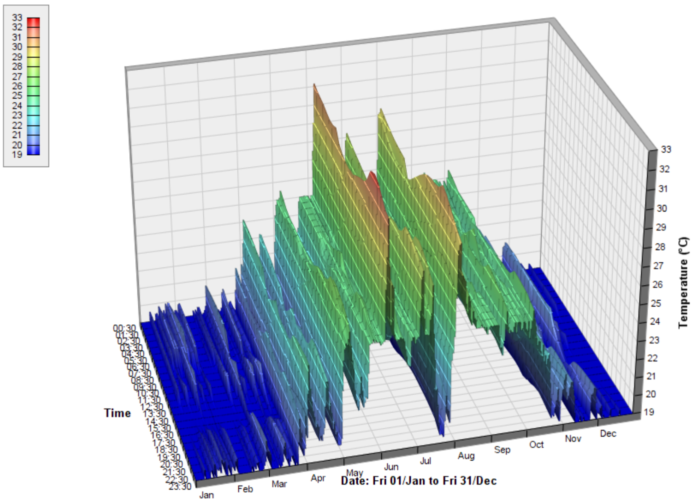


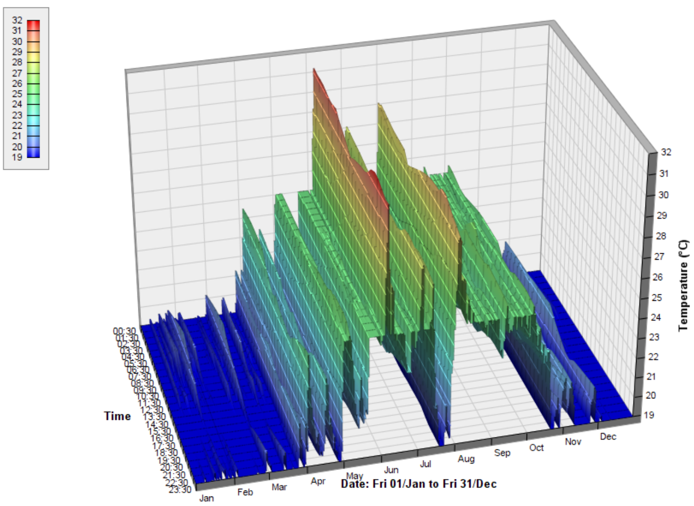
Figure 5.12: Energy consumed for hot tap water and space heating - Young couple's house



(a) Living room



(b) Master bedroom



(c) Attic - living space

Figure 5.13: Prediction of the indoor air temperature over the entire year at the young couple's house

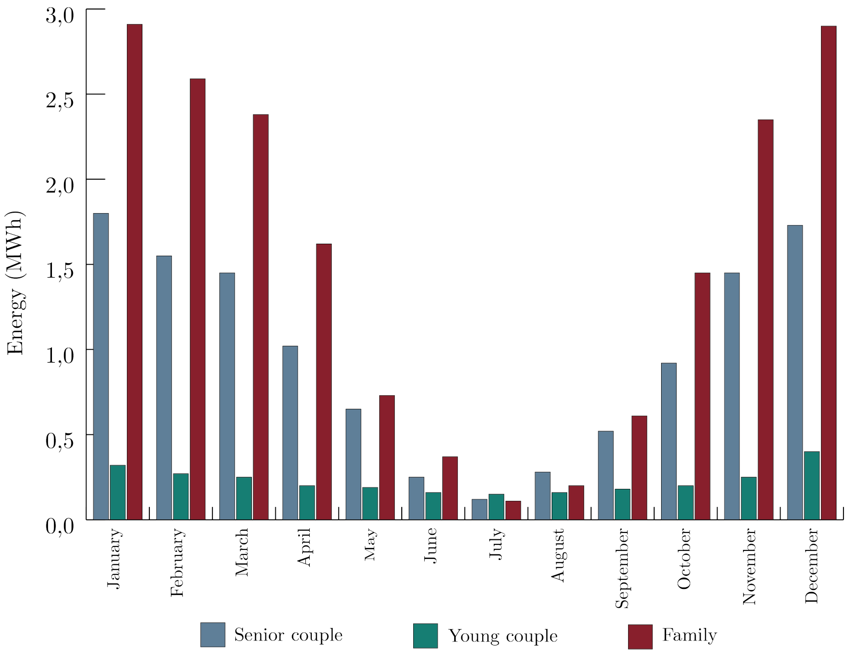


Figure 5.14: Comparison of the energy consumption for space heating, ventilation, auxiliary (pumps, fans) and hot water in the three households

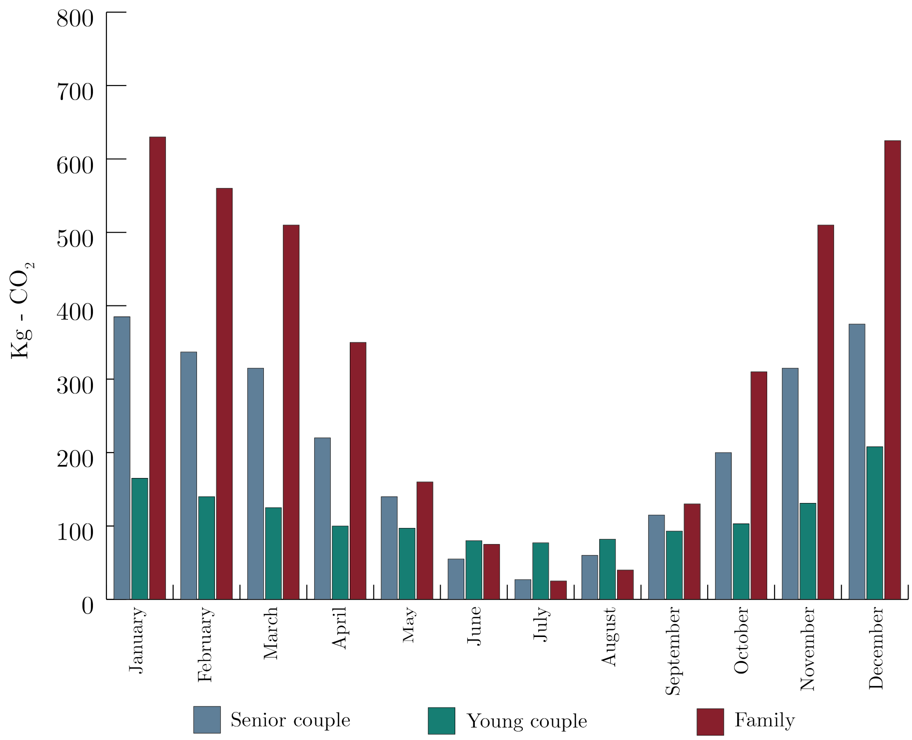


Figure 5.15: Comparison of carbon dioxide emissions from all the three households (only consumption)

Chapter 6

Discussion

This chapter discusses the improved and different ways this research could have been conducted to better answer the questions addressed in the previous chapters.

6.1 Study candidates

In occupant behaviour studies, the chosen candidates are the protagonists. Observing their behaviour helps to solve vital problems that go on to form the knowledge base for designers, researchers, and occupants themselves. Therefore it is important to convince and choose the appropriate candidates. A good grasp on the outcome and questions of the study is necessary, otherwise, it could lead to getting lost in details and losing the bigger picture, which leads to important questions not being answered. Observing the chosen candidates for two weeks revealed important ways the issue of bridging the energy performance gap could be tackled.

Apart from the willingness of the candidates, it is also important to research if an ample amount of information about their house characteristics is available or not. This helps in lesser assumptions and thereby achieving accurate results. Interviews and constant contact with the occupants help to get insights into their energy consumption and behaviour. Personally, this aspect played a much bigger role in avoiding mistakes that could have altered the end results of the study. Discussion of results with the occupants to see if they agree with it is also helpful. In this study, it helped eliminate reasons for why the problem was faced.

6.2 Further investigation into the heat pump's actual efficiency

The heat pump at the young couple's house had a lower efficiency than what the manufacturer had stated. This could play an important role while investigating the actual influence of occupant behaviour in other houses. As the two could be easily mistaken for one and another.

6.3 Actual lighting usage

This study did not research the actual energy consumed by the lighting present in the three houses. With highly efficient LED lighting and lower working hours than what the EPC assumes, it is definitely worthwhile to investigate this aspect further.

6.4 Neighbour effect

All three houses shared walls with their neighbours. This study did not research in detail to what extent this effect contributed to either lowering or increasing the space heating energy consumption of the houses. If pursued it could lead to valuable findings to bridge the energy performance gap.

6.5 Monitoring the electric stove usage

Figure4.16 shows how houses (senior couple - 70% and the family - 75%) with traditional and less efficient heating systems consumed the majority of the energy for space heating and hot water consumption. But the young couple's house (highly-efficient heat pump) shows that the energy consumed for space heating and hot water has significantly reduced to 38.5 %. This means that the electric induction stove, lighting, and other occupant controlled appliances become more and more significant. Since these appliances are solely dependent on the occupants, it will introduce a major prediction uncertainty in the future if necessary research is not done. In order to tackle this dynamic problem, we need to analyse real-time data, make informed decisions and predictions.

6.6 Occupant behaviour and Maslow's hierarchy of needs

Understanding human psychology could help reason and understanding the energy performance gap due to occupants. Like Maslow's hierarchy of needs, human energy consumption can be explained using the hierarchy of occupant behaviour in dwellings and why the energy performance gap exists. Maslow states that a human would strive to satisfy his/her needs higher up the hierarchy only after the lower ones were satisfied. This holds relevance when discussing how occupant behavior impacts the energy consumption of buildings.

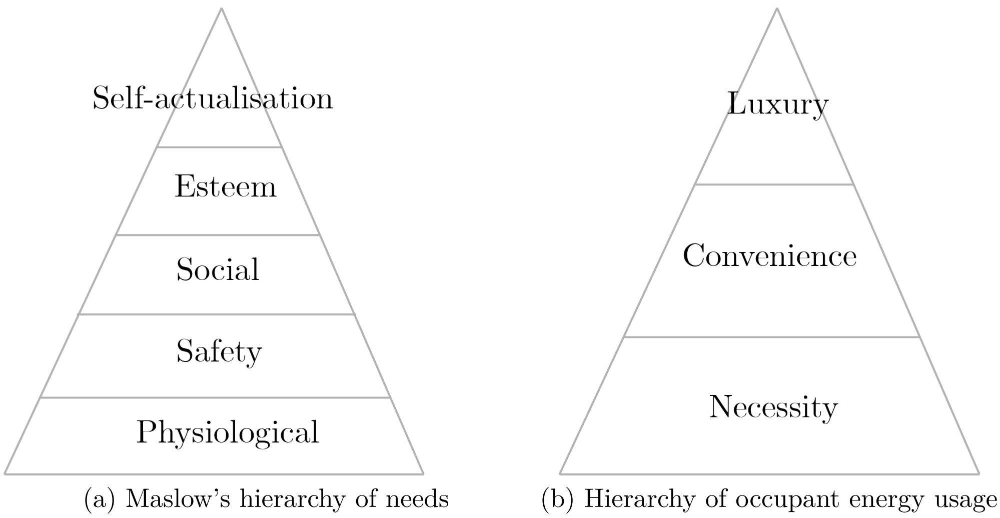


Figure 6.1: Maslow's hierarchy of needs and hierarchy of occupant energy needs

6.7 Recommendations and future scope

Future research could be carried out to study and inform the building designers, occupants and researchers.

Table 6.1: Classification of energy usage based on the hierarchy of energy needs

House	Necessity	Convenience	Luxury
Senior couple	Space heating	Washing Machine	Electric radiator
	Hot water	Refrigerator	Deep freezer
	Pump	Dryer	Entertainment unit
	Electric stove	Coffee machine	
	Ventilator	Dishwasher	
	Lighting		
Young couple	Space heating	Coffee machine	Television
	Hot water	Refrigerator	
	Electric stove	Washing machine	
	Pump	Dishwasher	
	HR ventilator		
	Lighting		
Family	Space heating	Washing machine	Electric water heater
	Gas stove	Dryer	Entertainment unit
	Pump	Dishwasher	
	Lighting	Refrigerator	

6.7.1 Building designers

- Use of CO_2 based window grilles for reducing space heating energy consumption.
- Use of clean and sustainable refrigerants to replace water as the heating medium, thereby increasing the efficiency furthermore.
- Scope of connecting the heat pumps to the district heating system and increasing the efficiency by several folds.
- Easier integration of weather data by the user depending on the location and the year of simulation.
- Studying and incorporating behaviour learning strategies to anticipate occupant preferences and preventing recurring energy loss behaviours (For instance - the frequent opening of a window in a well-insulated house).

6.7.2 Researchers

- Research into actual working hours and the energy consumption of lighting in a household. It is speculated from this study that the assumption made by EPC and the actual energy consumption varies up to -60 %, with EPC making a much more conservative approximation.
- Research the actual energy used by pumps to push water in floor heating systems and in conventional radiators and find ways to reduce the energy used by water pumps.
- Thoroughly testing the sensor set-up to avoid malfunctioning during the observation period.
- For data collection using sensors - accurately predicting battery run-time to avoid early shut down of the data collection set-up.

- Developing equipment to monitor high energy appliances, hot water usage, pumps, and others. If a monthly breakdown of these aspects is given to the occupant then the energy consumption could be significantly reduced.
- Studying the electric induction stove energy consumption and the cooking behaviour of the different households.
- Giving importance to interviews and information provided by the occupants regarding themselves and the house. This could often result in credible findings.
- Studying the effect of temporary occupants in the energy consumption of a household. This will become important since other aspects (for instance - insulation levels, heat pump, and others) have been optimised to their full potential.
- Establishing an energy consumption profile for different archetypes of people. This could help building designers to make valid assumptions while designing a building.

6.7.3 Occupants

- Installation of on-site PV panels.
- Choosing window grilles that are CO_2 operated than manually.
- Installation of water-saving showerheads.
- Prefer heat pumps in combination with Aquifer thermal energy storage. (ATES) as opposed to the conventional and less-efficient circulation heating systems.
- Wearing high insulation level clothing and maintaining an indoor set-point temperature close to the external temperature.

Chapter 7

Conclusion

Occupant behaviour is a multi-disciplinary field which could be a challenging field to study. This naturally leads to the difficulty of predicting and making reliable assumptions for future designs. Energy standards like the EPC and now BENG try to assign standards that could help in estimating the energy consumption of buildings. In static situations, these standards do a good job but due to the presence of occupants, the reality could be quite different.

In order to tackle this problem, one aspect is key - data. Setting monitoring equipment, analysing data and training machine learning algorithms to predict energy consumption while taking into account the occupant behaviour is the answer.

Evident from the study, occupant behaviour does affect the energy consumption of houses. Even more so than other typologies because the occupant has complete control of their surroundings. Precise quantification of the dominant factors and how much these factors affect energy consumption is subjective to the different types of occupants. This is seen in the three houses observed.

From the fig. 7.1, we see that the actual yearly energy consumption depends greatly on the floor surface area of the house even more so than the year it was built in or the number of occupants living in the house. EPC prediction is accurate (+0.60 %) when the house is old, which in this case is the family house which was constructed in 1934 and renovated in 2000. This is because, after a limit, the energy consumption of any house reached a stagnant phase because the effect of occupant behaviour is negligible. Also, with the older family's house, there are less sophisticated system (traditional circulation heater) and lower insulation levels for the energy performance deviation to be high. Whereas on the other hand, when you compare the EPC with the newly built houses, they are off by +39 % in the senior couple's house and by -45 % in the young couple's house. This is because occupant behaviour plays a much more significant role in newly built houses.

It also is seen that necessary energy use is dominant when compared to convenient or luxurious energy usage. two of the most important aspects of energy use are space heating and hot water consumption. Space heating energy demand is higher in houses with a higher floor area. Furthermore, the deviation between the EPC and space energy depends on occupant behaviour. In the young couple's house, the windows were rarely opened. Upon enquiry with the occupants, they were opened maybe once or twice in a month. They also mentioned this was because the contractor had advised them to not. Moreover, the set-point temperature in the house was between 18-19°C - lower than what the EPC assumes. Hence, the lower actual energy consumption. But in the senior couple's house, the window grilles serve potentially as an 'open leak' for the cold outside air to enter. This along with a higher set-point temperature and frequent opening of the windows in the kitchen and the master bedroom explains the higher energy consumption even after high levels of insulation.

Energy consumption for lighting is over-estimated (up to 60%) in EPC (refer figure 7.1, Chapter 6 - figure 4.16 and Chapter 4 -table 4.9). This is due to two reasons - 1. Use of highly-efficient and lesser quantity of light bulbs (LEDs) than what the EPC assumes and 2. The actual working hours are less due to occupant behaviour.

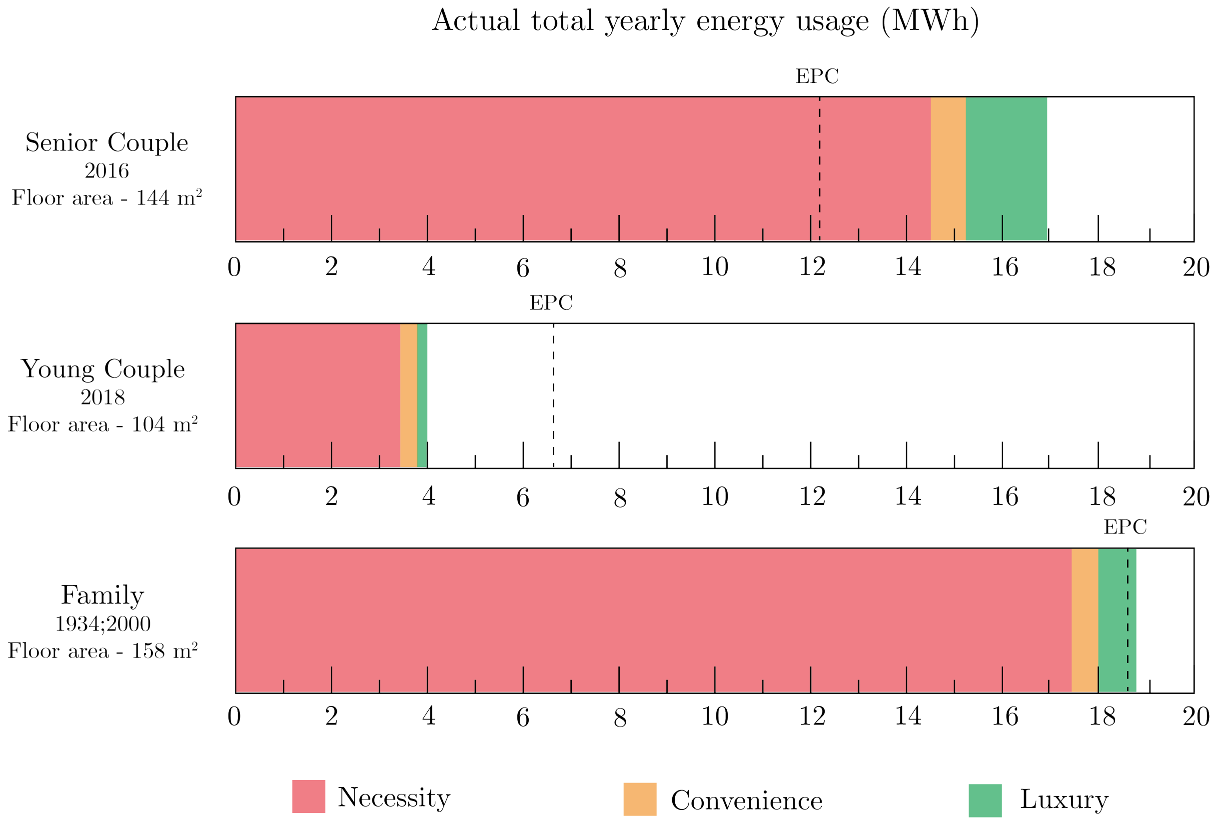


Figure 7.1: Actual energy usage vs EPC classified based on the hierarchy of occupant energy needs

7.1 Impact of occupant behaviour on the energy consumption of the three households

Occupant behaviour is observed to be dominant in newly constructed houses (Senior couple and the young couple). Certain actions of occupants caused a significant increase in energy consumption. These actions were

7.1.1 Senior couple

The senior couple's household consumed +39 % more energy than what the EPC predicted. This is attributed to occupant behaviour and the following actions

- Frequent opening of window grilles and windows for fresh air or exhausting stale air (kitchen).
- Use of a 2000 W - electric radiator in the non-insulated garage to store perishable food items.
- Frequent use of a large number of high power appliances like deep freezer, oven, 600 W electric radiators (bathroom - due to the low heating rate of the floor heating).
- Increased use of hot water due to the temporary occupants.
- Frequent use of the 7500 W electric stove for cooking due to lifestyle, temporary occupants and guests (EPC assumes a fixed amount of energy for building-related appliances without

specific attention to cooking).

7.1.2 Young couple

The young couple's household consumed -45 % less energy than what the EPC predicted. This is attributed to occupant behaviour and the following actions

- Actual set-point temperature in the house was lower than what EPC assumes.
- Occupants do not open windows- as suggested by the contractor in order to be a zero energy building.
- Less number of high power appliances.
- Usage of the 7100 W - electric stove is on an average once per day, which is less than the average scenario (senior couple's case).

7.1.3 Family

The family house consumed a meagre +0.60 % more energy than what the EPC predicted. This is attributed to reduced or even negligible influence of occupant behaviour on the total energy consumption and also due to

- The poorly insulated house has a great demand for space heating, so high that deviations that usually occur due to opening a window or setting an unusually high or low indoor temperature set-points are negligible.
- The electric hot water heater was placed in the kitchen due to the long distance between the circulation heater in the attic and the kitchen sink. Even though the energy this heater consumed is high, it does not cause a big deviation owing to the already high energy consumption.
- Since the poorly insulated house is surrounded by neighbours on 3 out of 6 sides (first floor - bottom and sides) there is a chance that the 'neighbour effect' played a major role in this scenario,

7.2 Reduction of the energy performance gap

There are ways to significantly reduce the energy performance gap by taking the following steps.

- **Space heating** - Space heating consumes a major part of a house's energy consumption (fig. 4.16). In the presence of a central circulation based heating system or a heat pump, an emphasis on its CoP is necessary. From the study, it was found that the CoP of the heat pump at the young couple's house was expected to be around 2.55 but in reality, it was only around 2.15 (1.90 - Hot tap water and 2.40 - Space heating). Measuring the actual CoP of a system and using it in the energy simulation for future building designs can significantly reduce the energy performance gap.
- **Hot tap water** - The hot water consumption is also one of the highest in all the three households. In addition to accounting for its actual CoP, the actual usage of hot water is quite different from person to person and household to household. Furthermore, a constant assumption is made in energy simulations, which is not the reality. The primary electricity used for hot tap water at the young couple's house was - November and December 2018 = 634 kWh, January 2019 = 397 kWh, February = 215 kWh, March = 96 kWh and April = 83 kWh. As we can see it is not constant throughout the months (even after correcting for its actual seasonal CoP), so necessary steps have to be taken to increase the accuracy of the assumption of the actual hot water usage.
- **Electric stove** - At the senior couple's and family's house the energy used for cooking is relatively low when compared to the entire energy consumption. But in the young

couple's house we see the electric stove consumes 26% of the energy when compared to the space heating - 25% (due to the highly efficient heat pump, negligible energy loss due to the opening of the windows, heat recovery system, low set-point temperature, and high insulation levels). As we move towards energy efficient homes - the energy used for cooking will become dominant, especially with larger households (families and student houses). This aspect needs to be carefully looked into while designing highly efficient zero-energy houses.

- **Unforeseen aspects** - In certain cases, like the electric water heater in the family house - the unforeseen aspect did not make a great difference to the yearly energy consumption. But in the senior couple's case, where a 2000 W electric radiator was placed in a non-insulated garage (to store edible and perishable food items) it did this unforeseen element consumed about 1690 kWh out of the yearly electricity consumption of 5041 kWh. The way to prevent these unforeseen circumstances is by establishing personal contact with future occupants to get an idea of their needs and expectations (refer fig.7.1 and solve it architecturally in the senior couple's case.

7.3 Improvements - Senior couple household

- Installation of PV panels since the appliance usage is high.
- Avoid using the electric radiators
- Installation of a highly-efficient heat pump
- Low water consumption shower heads for reduced hot water usage
- Completely transitioning to electricity.

7.4 Improvements - Young couple household

- Sourcing clean electricity from a common neighbourhood PV power plant, to maximise the efficiency of PV at optimum angles.
- Installation of PV solar water heaters, thereby reducing the operational energy of the heat pump.
- Installation of evapotranspiration based air coolers to avoid overheating during the hotter periods.
- Possibilities to connect to the district heating and cooling network.
- Low water consumption shower heads for reduced hot water usage.

7.5 Improvements - Family household

- Improve the insulation and glazing levels.
- Avoid using electric hot water devices.
- Installation of a highly-efficient heat pump.
- Transitioning to electricity and not being dependent on gas.
- Low water consumption shower heads for reduced hot water usage

7.6 Findings

The important findings of this study are

- Yes, in reality, the influence of occupant behavior on the energy consumption is significant in newly built houses; +39% - Senior couple, -45% - Young couple and negligible in the old family house; +0.60 % (when compared to EPC - static energy prediction).
- Floor area has a direct correlation and the highest impact on space heating (refer fig. 7.1).
- Temporary occupants play an important role in the hot water consumption and in turn the water consumption of a household (refer table. 4.2). Therefore accurate prediction of the actual energy consumption calls for investigating this aspect further.
- Opening windows and using window grilles play an important role in a new and well-insulated house. A few hours in a month (refer Chapter 4, section 5 - Window experiment) does not impact the monthly consumption but extended periods can cause notable increases in the space heating demand. In the highly insulated young couple's case, the energy loss on an average cold (9°C) and gloomy Dutch day, when windows were opened was = 0.68 kWh/hour. So if it is thought that the future occupants of a house are frequently expected to open the windows then an estimation of expected energy loss should be made to reduce the gap between the actual and the predicted energy consumption. On the other hand, in a poorly insulated house, opening windows and grilles can make little difference to the space heating demand. This is due to the already low insulation levels.
- Using the principles of 'hierarchy of occupant energy needs' can be useful to make decisions and assumptions during modelling and simulating the future energy consumption of a building.
- External temperature is a strong driving force of energy consumption (space heating and hot water). Accurate data to the shortest possible interval (10 or 30 minutes) should be used for energy modelling otherwise the deviation between the predicted and actual energy consumption values will be high.
- Collect data about the hot water usage of the occupants. Making an over-simplified assumption leads to major deviations. From the three households, a certain range of hot water usage was observed. On the basis of that, it is suggested that classifying different households depending on the number of occupants over a period of two to three years can greatly aid in accurately predicting the future hot water usage.

7.7 Sensors for data collection

In order to tackle the problem of energy performance gap due to occupant behaviour, one aspect is key - data. Setting monitoring equipment, analysing data and training machine learning algorithms to predict energy consumption while taking into account the occupant behaviour is the answer. Sensors yield valuable information in addition to the interviews and candidates themselves. Often in cases, the occupants might not be present in the house or simply not be aware of every aspect that goes on in their house. In this situation, sensors help investigate those aspects. But often the difficulty in using sensors in different fields of study is that the expertise is not available. And more often than not, this could discourage the researcher from using them. But nowadays with the presence of GitHub and open source websites, gaining access to codes that facilitate data collection has become quick and easy. The equipment used in this study is relatively inexpensive as well. This means that data-informed decisions with the help of sensors and controllers would become more common in the future. These devices can be remotely placed (with batteries and wireless connectivity) and accessed with such ease that their use becomes advantageous. On the other hand, having limited knowledge of electronics and programming costs time in terms of solving the issues that arise during the design and installation phases of the data collection period.

7.8 Sensors and actuators in place of sophisticated energy-siphoning HVAC systems

Modern HVAC systems nowadays consume up to 50% (young couple's house) of the total energy in a house in an effort to provide maximum comfort to its occupants. But in reality, the situation is different. Occupant actions like opening the windows could drastically reduce these HVAC system's potential to "save energy". But the reason these systems are chosen is that they are low maintenance or less complicated to operate during the operation phase which is the opposite of sensors and actuators. Sensors and actuators in houses could be a complicated affair. These systems have to be first programmed and be made automatic to respond dynamically to their changing environment. And this aspect is still a big challenge to overcome.

On the other hand, as it seen from the window experiment at the young couple's house that a great volume of air can enter the house with just opening the window for one hour (217m^3/hour) - quite enough and conforming to the Dutch standards of 25m^3/hour.person. Apart from ventilation, sensors and actuators could take into account the unique preferences of users living in the house and respond to their actions using machine learning algorithms. But an obstacle that needs to be addressed is - the multidisciplinary aspect. This idea needs an integrated collaboration of electrical engineers, computer science engineers, psychologists, architects, and building engineers. Currently, this is difficult but maybe in the future, with rapidly developing technology this is definitely a possibility.

7.9 Proposal for future homes

It is seen from the varying types of houses that there is often give or take when it comes to comfort and energy savings. In the case of the young couple, their house and behaviour is ideal and already consumes less energy than predicted. But from the energy simulation, it is seen that such high levels of insulation could lead to overheating in summer. There could be a better balance between energy and comfort. The proposal for future homes consists of

- Double glazing and insulation levels (similar to the senior couple's house) conforming to the regulations.
- Highly efficient heat pump combined with district heating.
- Sensor and actuators to periodically open windows to let fresh air in rather investing in sophisticated HVAC systems that consume almost half of the house's total energy consumption.
- Evapotranspiration based coolers for summers

With endless possibilities and rapid growth of technology, this field is expected to be active in the upcoming years.

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Appendix A

Floor plans - Senior couple's house

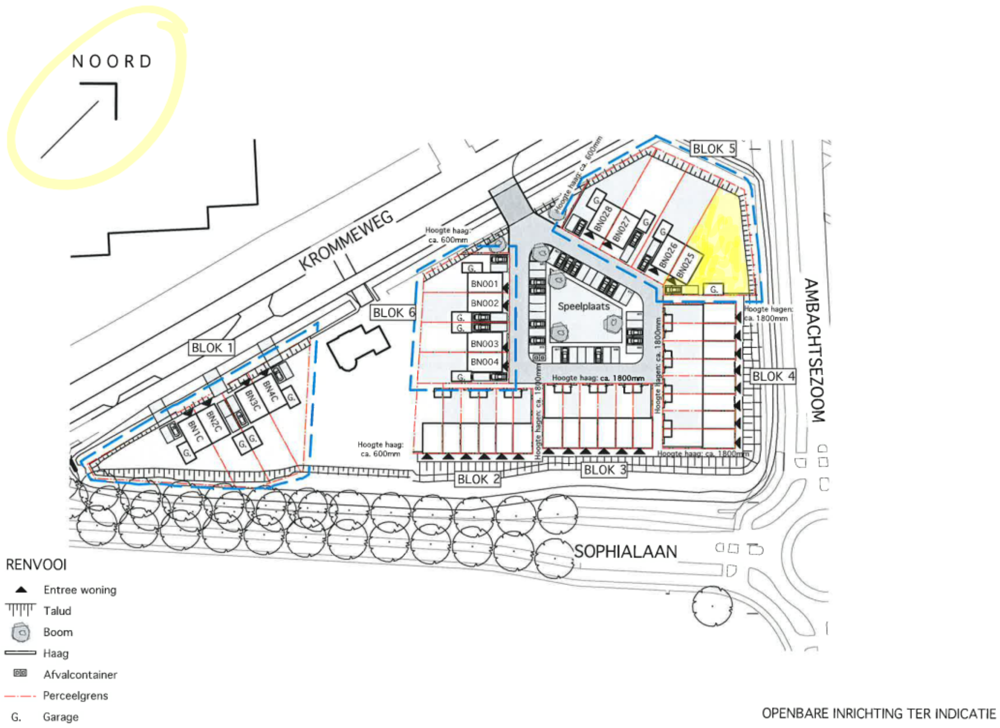

Figure A.1: Location and orientation

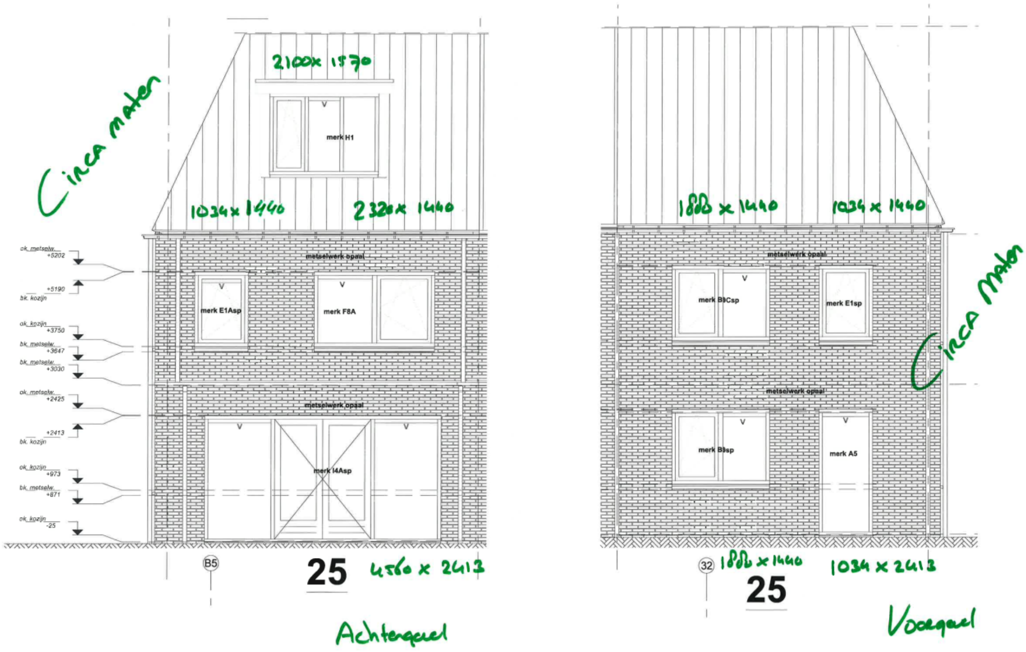

Figure A.2: Back and front elevations

Figure A.3: Side elevation

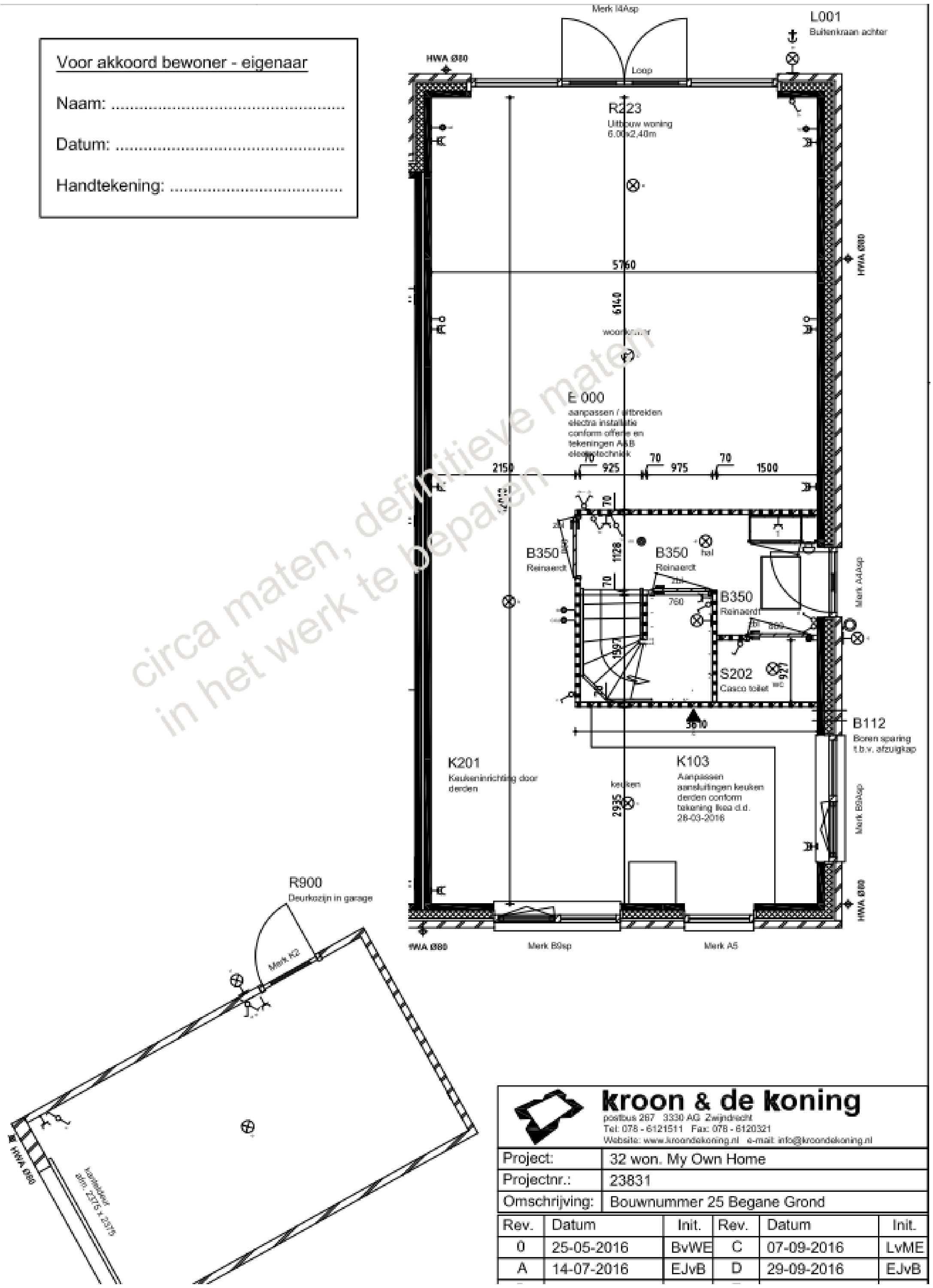

Figure A.4: Ground floor

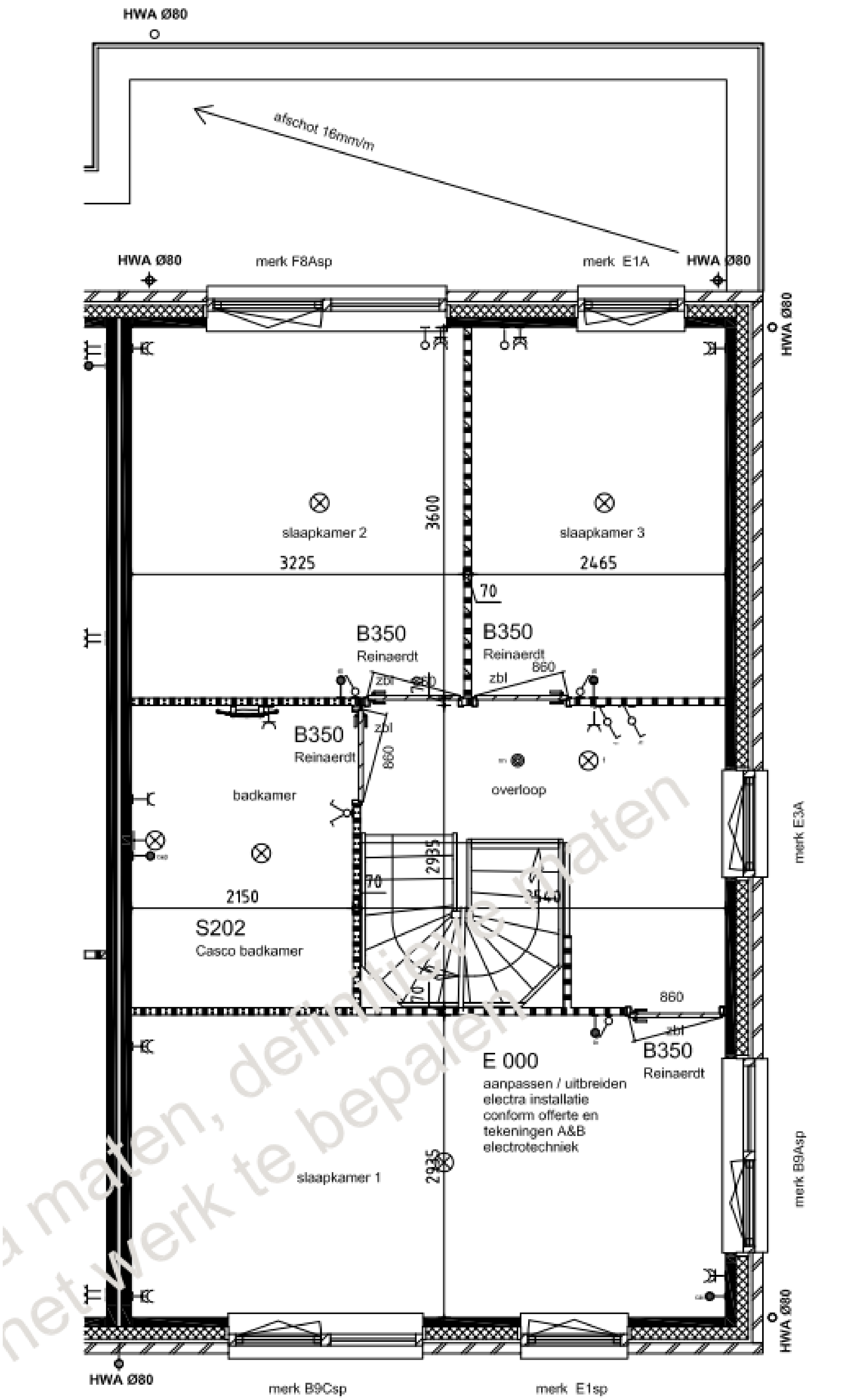

Figure A.5: First floor

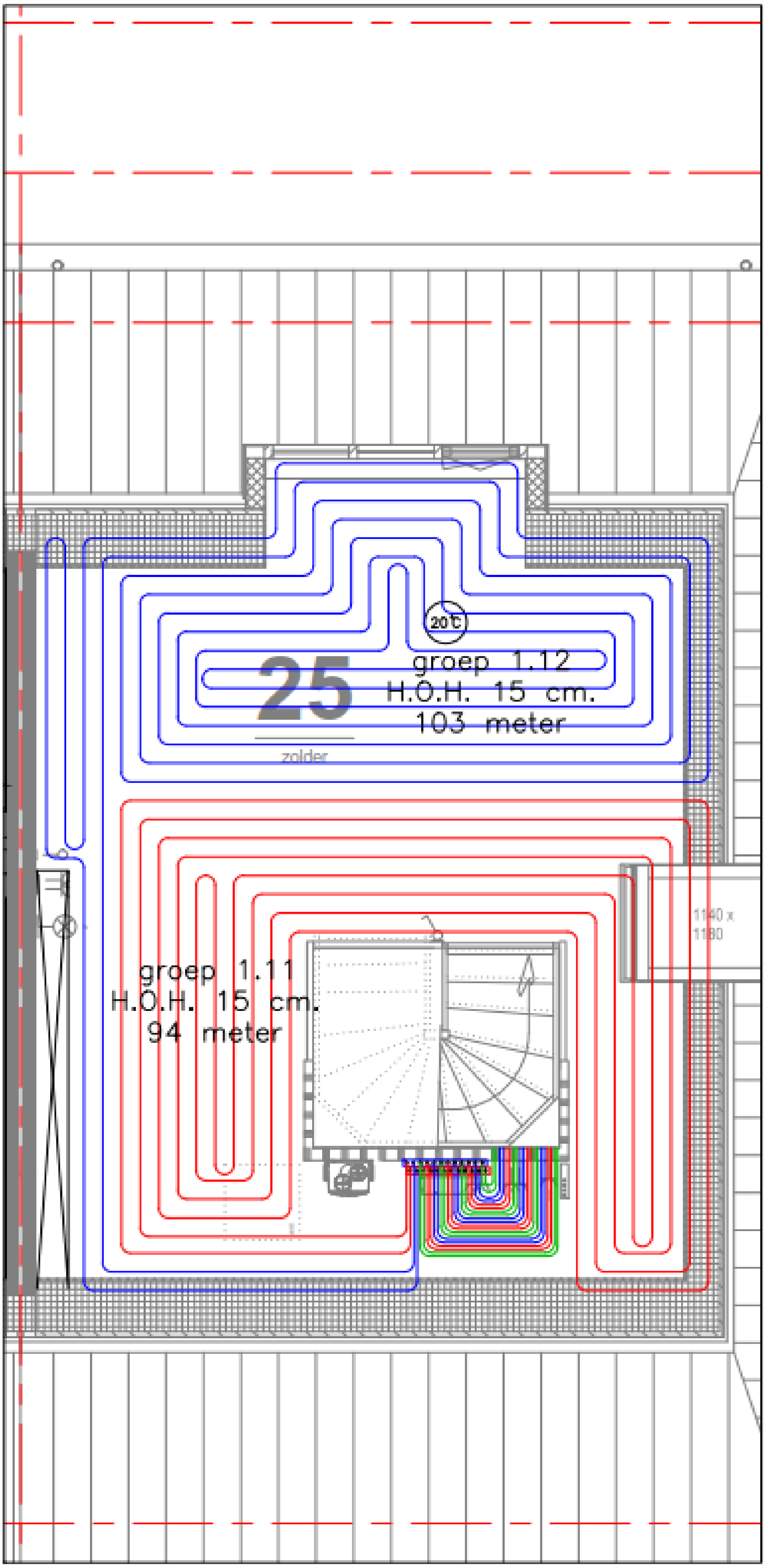

Figure A.6: Attic

Appendix B

Floor plans - Young couple's house

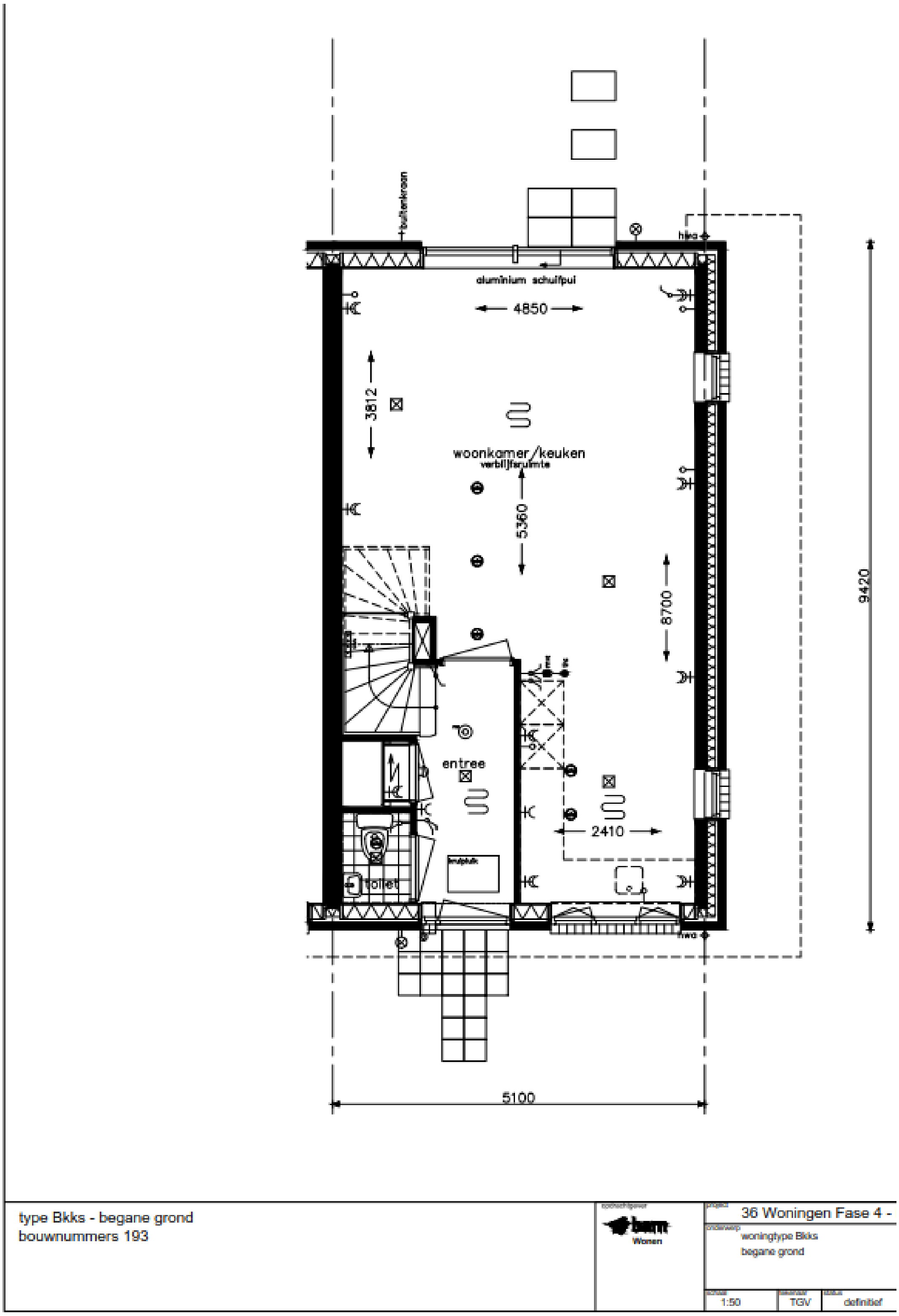

Figure B.1: Ground floor

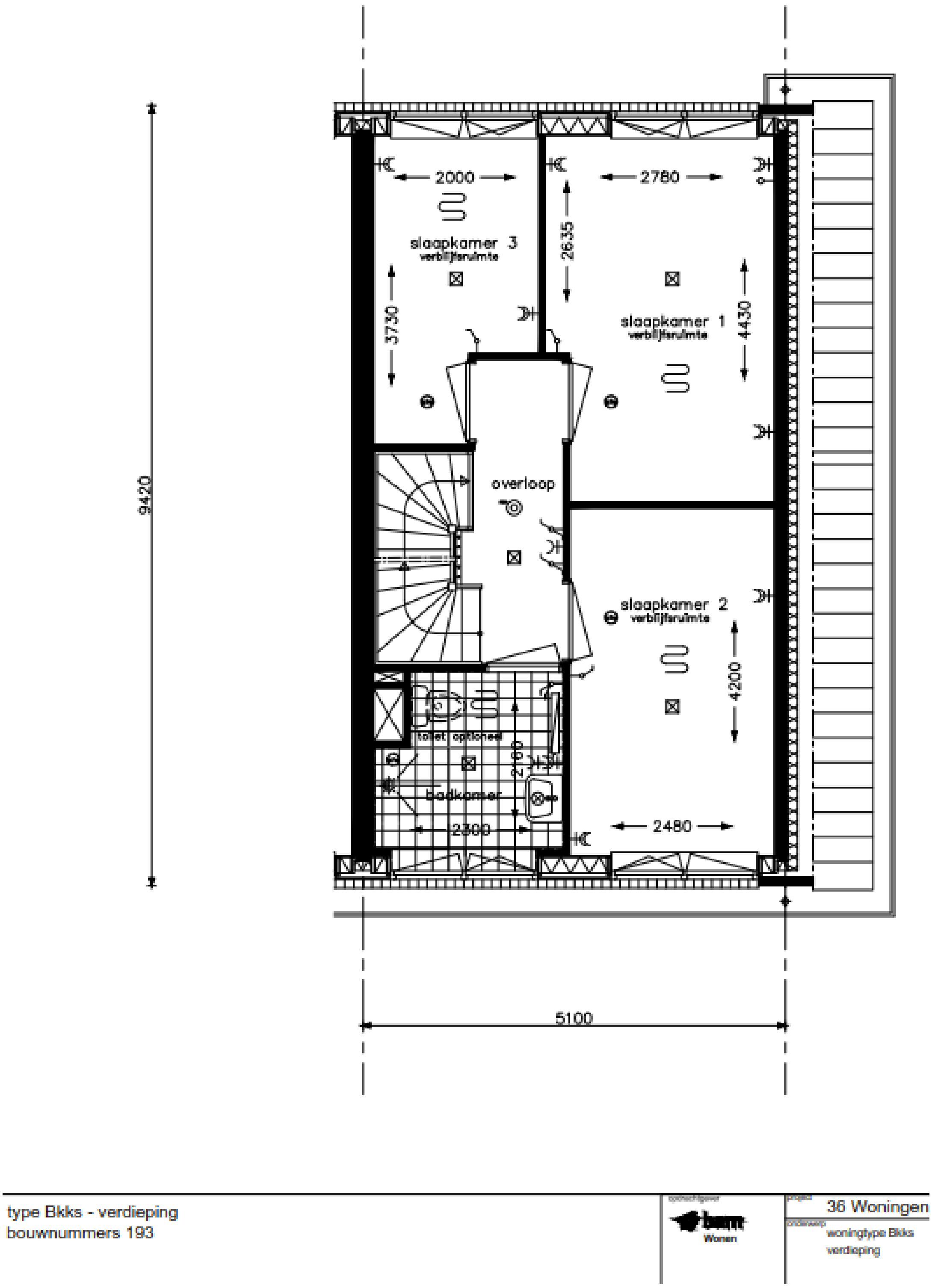

Figure B.2: First floor

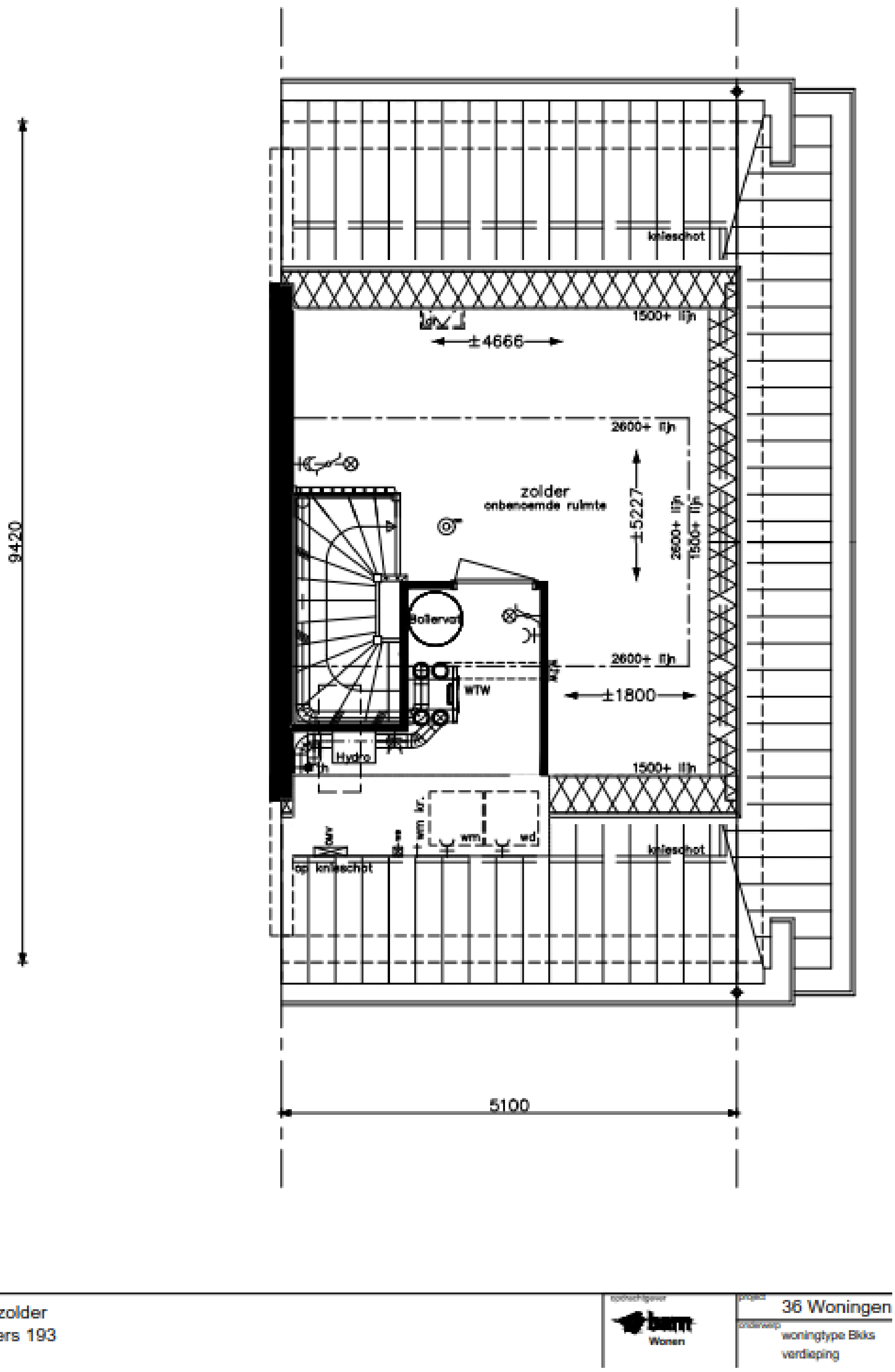

Figure B.3: Attic

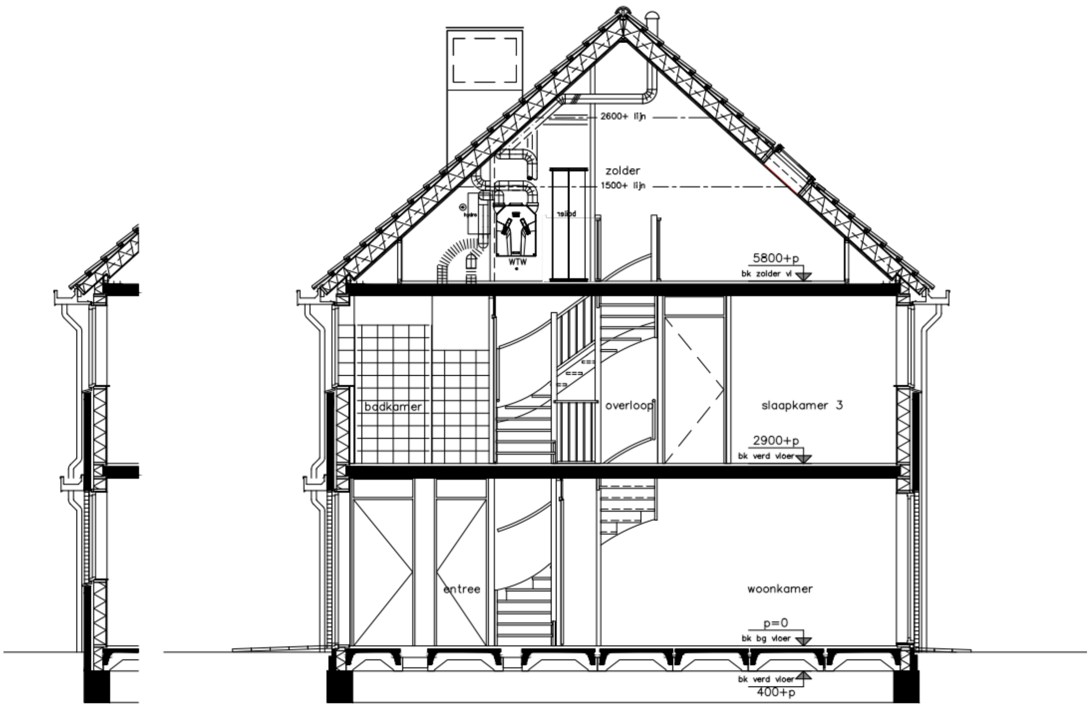

Figure B.4: Cross-section

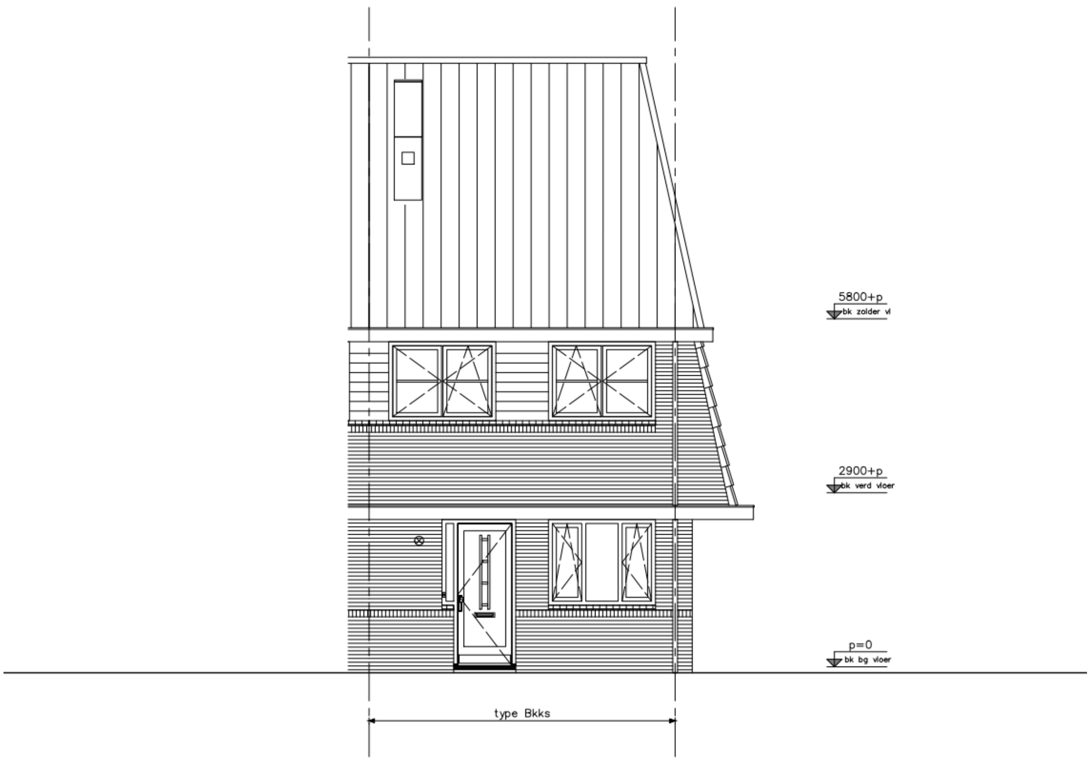

Figure B.5: Front elevation

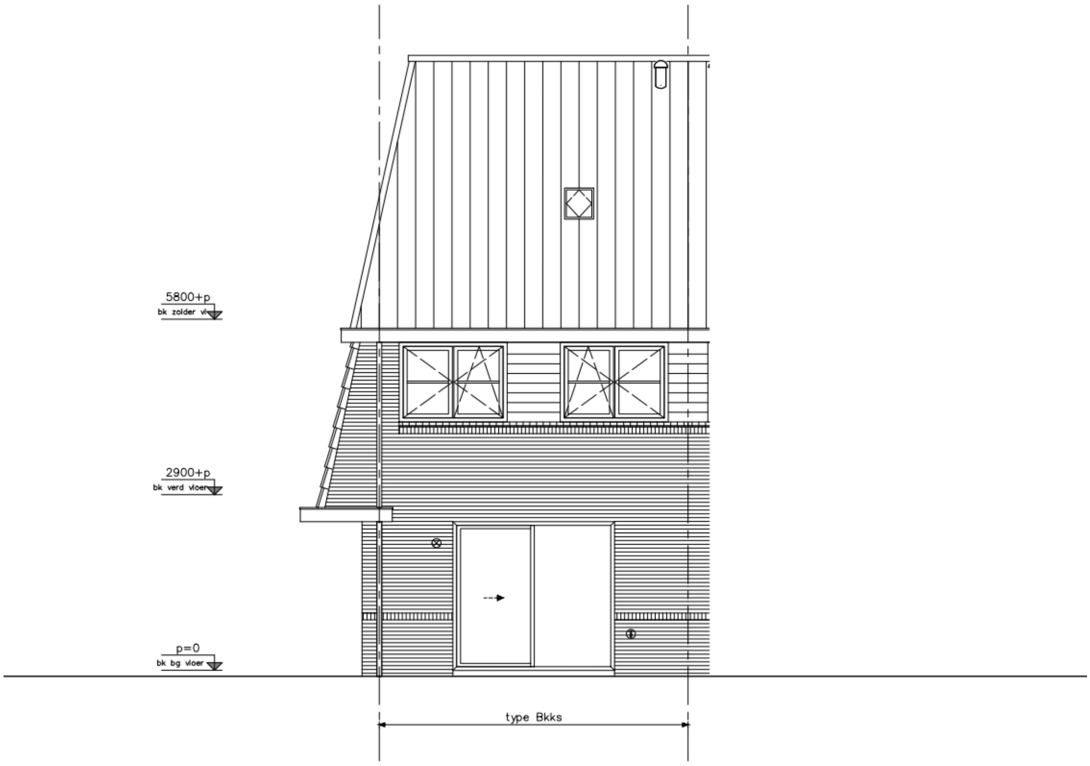

Figure B.6: Back elevation

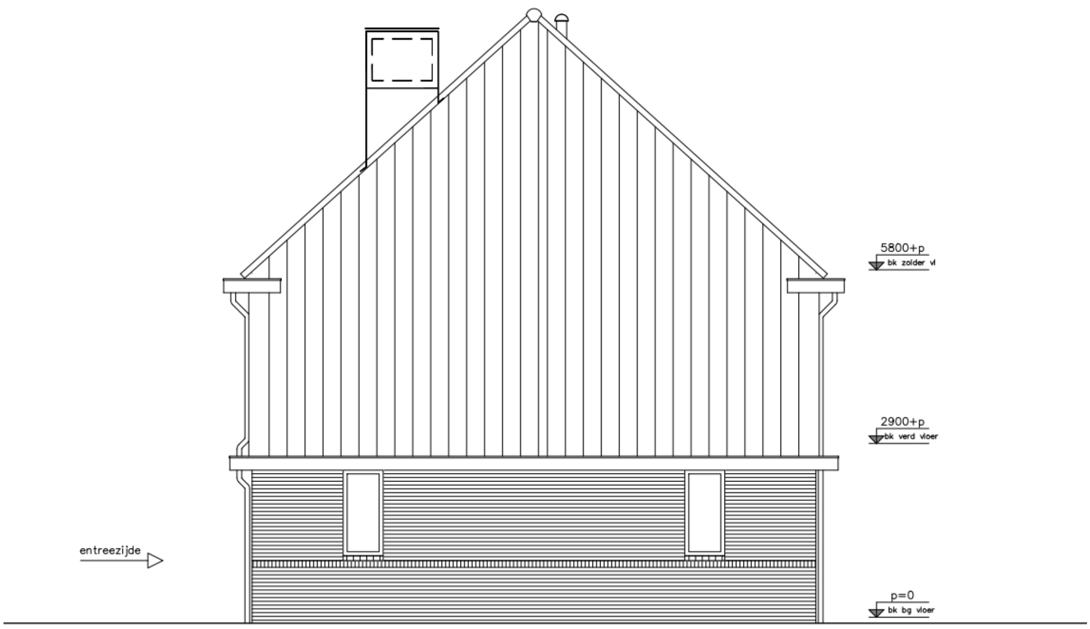

Figure B.7: Side elevation

Appendix C

Floor plans - Family's house

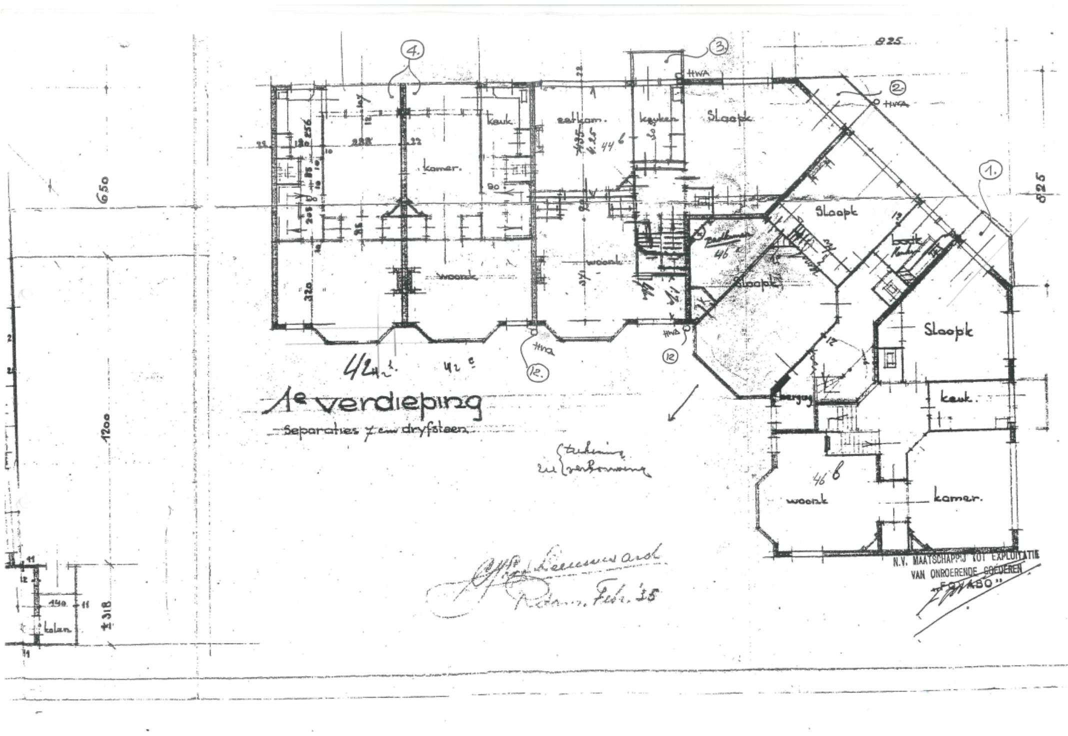

Figure C.1: Ground floor of the house

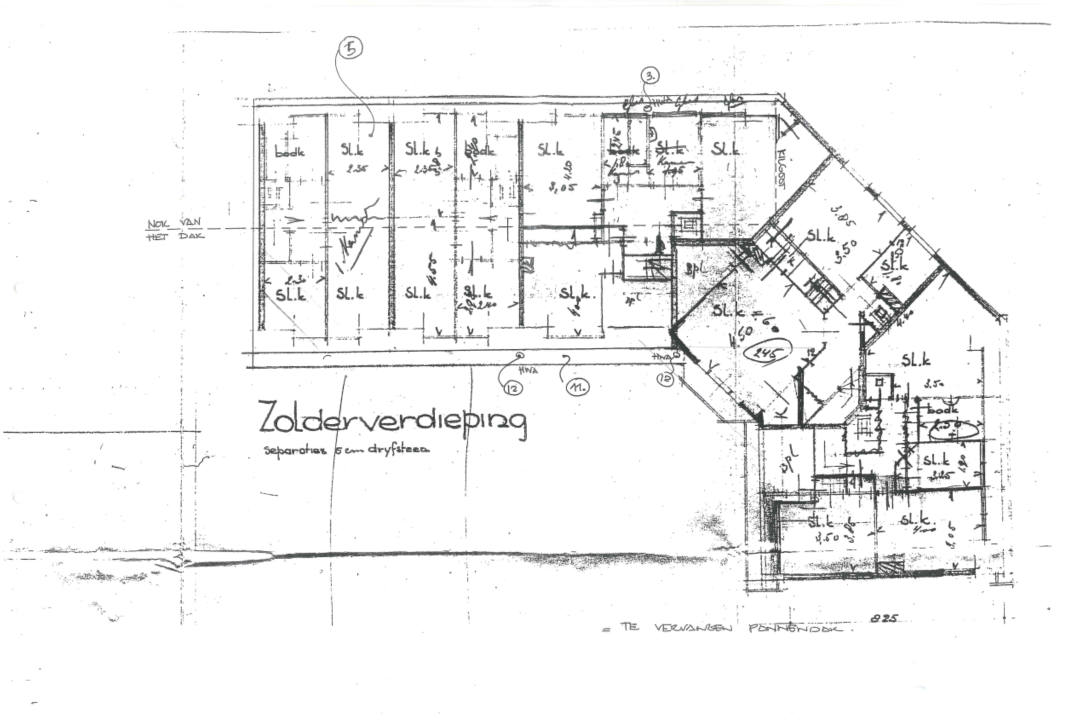

Figure C.2: First floor

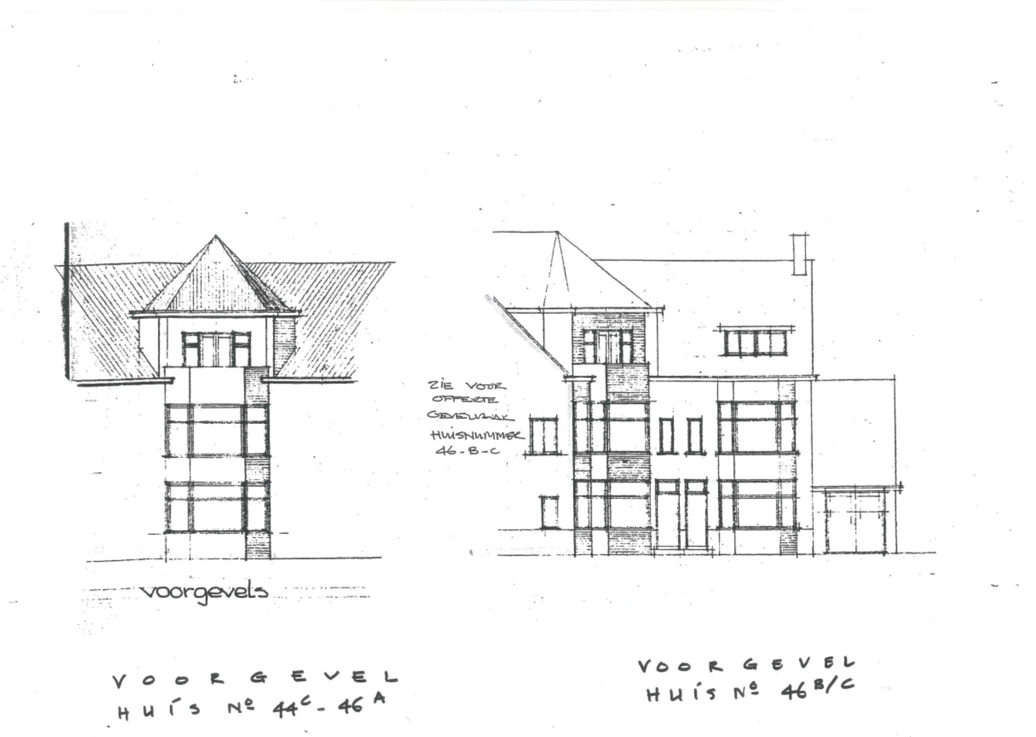

Figure C.3: Side elevation

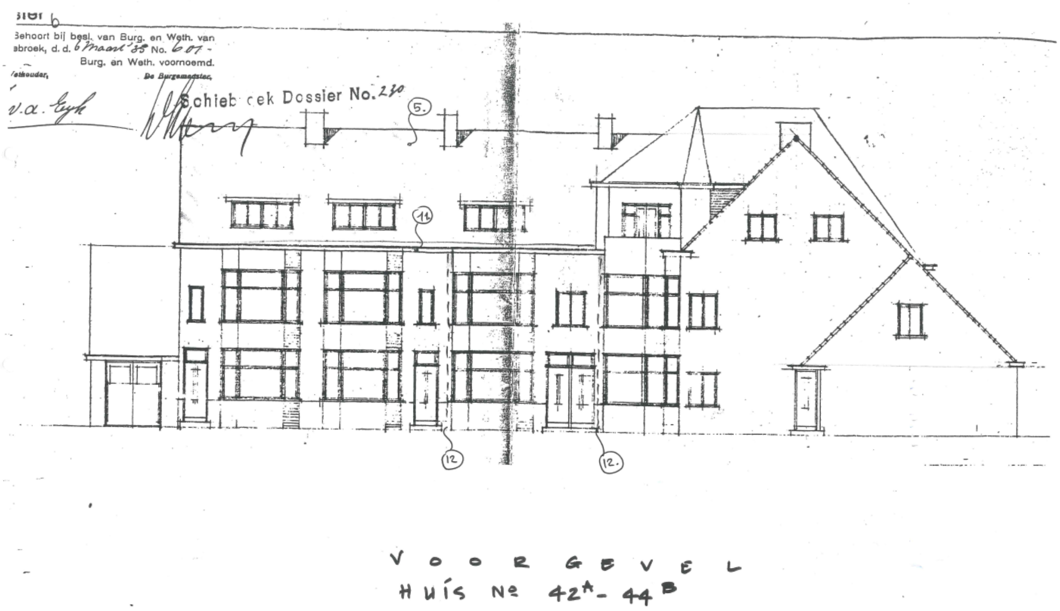

Figure C.4: Front elevation

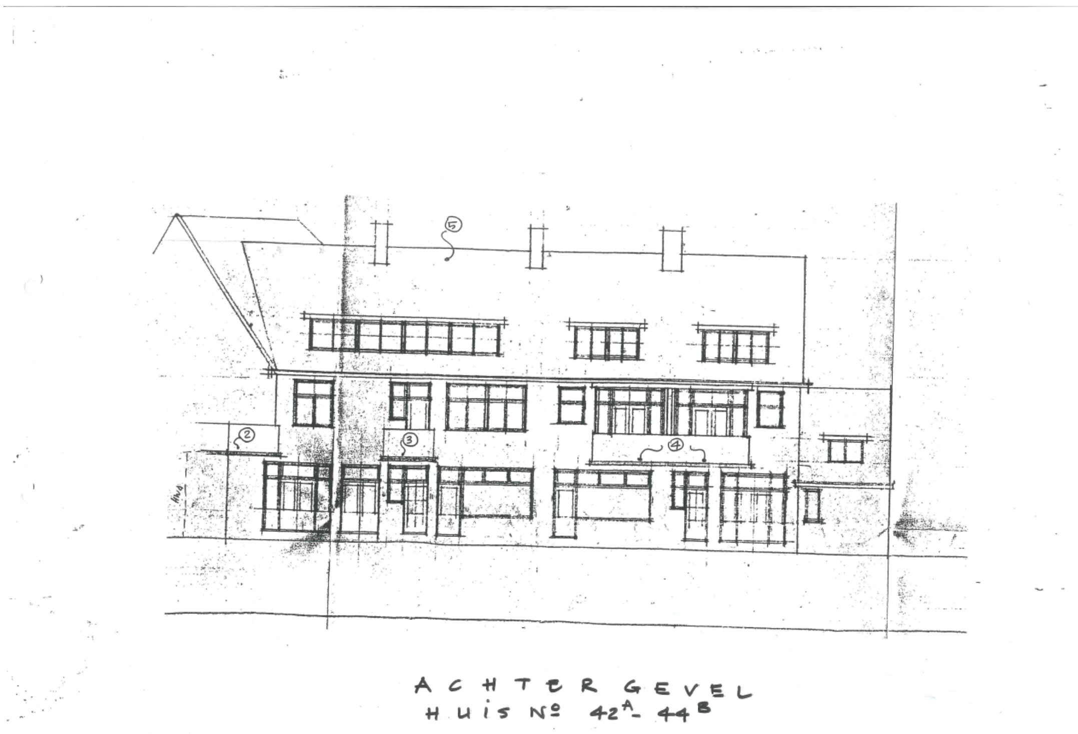

Figure C.5: Rear Elevation

Figure C.6: Rear elevation

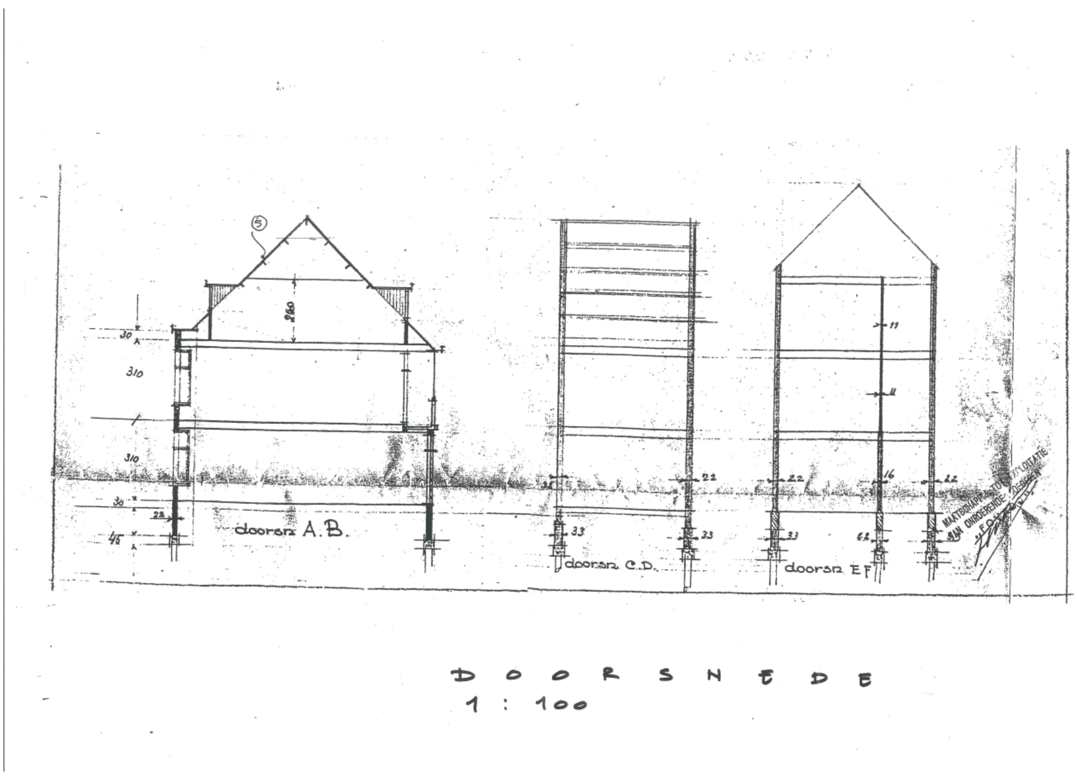

Figure C.7: Cross-section

Appendix D

EPC - Senior couple's house

Uniec$^{2.2}$

15.1602 MOH Hendrik Ido Ambacht - MOH Hendrik Ido Ambacht - 27 aug
Woningtype B - Beukmaat 5,1 m - 2e verd. dwarskap **0,57**

Algemene gegevens

projectomschrijving	*MOH Hendrik Ido Ambacht - 27 aug*
variant	*Woningtype B - Beukmaat 5,1 m - 2e verd. dwarskap*
straat / huisnummer / toevoeging	
postcode / plaats	
bouwjaar	
categorie	*Energieprestatie Woningbouw*
aantal woningbouw-eenheden in berekening	*1*
gebruiksfunctie	*woonfunctie*
datum	*10-08-2015*
opmerkingen	*Vak 1 - Vakvulling / Vak 2 - Vakvulling / Vak 3 - Vakvulling / Vak 13 - Vakvulling / Vak 5 - Vakvulling / Vak 6 - Vakvulling /*

Indeling gebouw

Eigenschappen rekenzones

type rekenzone	omschrijving	interne warmtecapaciteit	A_g [m²]
verwarmde zone	begane grond + 1e verdieping	traditioneel, gemengd zwaar	81,75
verwarmde zone	2e verdieping	traditioneel, gemengd zwaar	26,54

Infiltratie

meetwaarde voor infiltratie $q_{v;10;spec}$	*ja*
lengte van het gebouw	*5,10 m*
breedte van het gebouw	*9,11 m*
hoogte van het gebouw	*9,18 m*

Eigenschappen infiltratie

rekenzone	gebouwtype	$q_{v;10;spec}$ [dm³/s per m²]
begane grond + 1e verdieping	grondgebonden gebouw, tussenligging, met kap	0,43
2e verdieping	grondgebonden gebouw, tussenligging, met kap	0,43

Open verbrandingstoestellen

Het gebouw bevat geen open verbrandingstoestellen.

Bouwkundige transmissiegegevens

Transmissiegegevens rekenzone begane grond + 1e verdieping

constructie	A [m²]	R_c [m²K/W]	U [W/m²K]	g_{gl} [-]	zonwering	beschaduwing	toelichting
Begane grond vloer - vloer op/boven mv; boven kruipruimte - 42,0 m²							
Begane grondvloer	41,97	5,00					
voorgevel - buitenlucht, W - 28,9 m² - 90°							
gevel	20,17	4,23				minimale belem.	
Voordeur (1,034 x 2,413) (1 stuks)	2,50		1,57	0,00	nee	minimale belem.	
Kozijn (1,660 x 1,440) (1 stuks)	2,39		1,30	0,60	nee	minimale belem.	
Kozijn (1,034 x 1,440) (1 stuks)	1,49		1,30	0,60	nee	minimale belem.	
Kozijn (1,660 x 1,440) (1 stuks)	2,39		1,30	0,60	nee	minimale belem.	
achtergevel - buitenlucht, O - 28,9 m² - 90°							
gevel	19,01	4,23				minimale belem.	
Kozijn (2,100 x 1,870) (1 stuks)	3,93		1,30	0,60	nee	minimale belem.	
Achterdeur (1,034 x 2,425) (1 stuks)	1,49		1,30	0,60	nee	minimale belem.	
Kozijn (2,100 x 1,440) (1 stuks)	3,02		1,30	0,60	nee	minimale belem.	
Kozijn (1,034 x 1,440) (1 stuks)	1,49		1,30	0,60	nee	minimale belem.	
kopgevel - buitenlucht, N - 48,8 m² - 90°							
gevel	42,74	4,23				minimale belem.	
Kozijn (2,100 x 1,440) (1 stuks)	3,02		1,30	0,60	nee	minimale belem.	
Kozijn (2,100 x 1,440) (1 stuks)	3,02		1,30	0,60	nee	minimale belem.	

Lineaire transmissiegegevens rekenzone begane grond + 1e verdieping

constructie	l [m]	ψ [W/m'K]	omschrijving	+25%	toelichting
Begane grond vloer - vloer op/boven mv; boven kruipruimte - 42,0 m²					
vloerrand langsgevel	8,13	0,010	101.0.3.01	nee	
vloerrand kopgevel	8,41	0,474	103.1.0.01	nee	
vloerrand kozijn	2,07	0,661	102.0.3.02	nee	
voorgevel - buitenlucht, W - 28,9 m² - 90°					
o.k. kozijn	4,35	0,026	201.0.5.01	nee	
z.k. kozijn	13,47	0,034	202.0.5.01	nee	
b.k. kozijn	5,39	0,043	203.0.5.01	nee	
achtergevel - buitenlucht, O - 28,9 m² - 90°					
o.k. kozijn	5,23	0,026	201.0.5.01	nee	
z.k. kozijn	14,35	0,034	202.0.5.01	nee	
b.k. kozijn	6,27	0,043	203.0.5.01	nee	
kopgevel - buitenlucht, N - 48,8 m² - 90°					
o.k. kozijn	2,10	0,026	201.0.5.01	nee	
z.k. kozijn	2,88	0,034	202.0.5.01	nee	
b.k. kozijn	2,10	0,043	203.0.5.01	nee	
hoekgevel	11,60	0,072	205.1.5.01	nee	

Overige kenmerken vloerconstructies (inclusief evt. kruipruimten en onverwarmde kelders)

Begane grond vloer - vloer op/boven mv; boven kruipruimte

hoogte bovenkant vloer boven maaiveld (h)	*0,10 m*
omtrek van het vloerveld (P)	*10,20 m*
grootste dikte v.d. gevels/wanden ter hoogte v.d. bk vloer ($d_{bw;v}$)	*0,36 m*
gem. vert. afstand tussen MV en bk kelder-, kruipruimtevloer (z_o)	*0,80 m*
kruipruimteventilatie (ε)	*0,0012 m²/m¹*
warmteweerstand v.d. kelder-, kruipruimtewanden boven mv (R_{xw})	*4,50 m²K/W*
warmteweerstand v.d. kelder-, kruipruimtewanden onder mv ($R_{bw;o}$)	*4,50 m²K/W*
warmteweerstand v.d. kelder-, kruipruimtevloer (R_{bf})	*0,00 m²K/W*
grootste dikte v.d. wand t.h.v. de bk kelder-, kruipruimtevloer ($d_{bw;o}$)	*0,36 m*

Transmissiegegevens rekenzone 2e verdieping

constructie	A [m²]	R_c [m²K/W]	U [W/m²K]	g_{gl} [-]	zonwering	beschaduwing	toelichting
oorgevel - buitenlucht, W - 11,6 m² - 90°							
gevel	10,17	4,23				minimale belem.	
Kozijn (0,890 x 1,564) (1 stuks)	1,39		1,30	0,60	nee	minimale belem.	
voorgevel hellend dak - buitenlucht, W - 4,2 m² - 38°							
hellend dak	4,24	5,17				minimale belem.	
achtergevel - buitenlucht, O - 11,6 m² - 90°							
gevel	10,17	4,23				minimale belem.	
Kozijn (0,890 x 1,564) (1 stuks)	1,39		1,30	0,60	nee	minimale belem.	
achtergevel hellend dak - buitenlucht, O - 4,2 m² - 38°							
hellend dak	4,24	5,17				minimale belem.	
kopgevel - buitenlucht, N - 10,6 m² - 41°							
gevel	10,60	4,23				minimale belem.	
kopgevel hellend dak - buitenlucht, N - 26,3 m² - 41°							
hellend dak	26,32	5,17				minimale belem.	
kopgevel hellend dak - buitenlucht, Z - 15,3 m² - 90°							
hellend dak	15,30	5,17				minimale belem.	

Lineaire transmissiegegevens rekenzone 2e verdieping

constructie	l [m]	ψ [W/m¹K]	omschrijving	+25%	toelichting
voorgevel - buitenlucht, W - 11,6 m² - 90°					
hellend dak - gevel	6,84	0,105	403.1.0.01	nee	
hoekgevel	1,26	0,072	205.1.5.01	nee	
o.k. kozijn	0,89	0,026	201.0.5.01	nee	
z.k. kozijn	3,13	0,034	202.0.5.01	nee	
b.k. kozijn	0,89	0,043	203.0.5.01	nee	

Lineaire transmissiegegevens rekenzone 2e verdieping					
constructie	l [m]	ψ [W/m¹K]	omschrijving	+25%	toelichting
voorgevel hellend dak - buitenlucht, W - 4,2 m² - 38°					
daknok	2,43	0,030	404.0.0.01	nee	
achtergevel - buitenlucht, O - 11,6 m² - 90°					
hellend dak - gevel	6,84	0,105	403.1.0.01	nee	
hoekgevel	1,26	0,072	205.1.5.01	nee	
o.k. kozijn	0,89	0,026	201.0.5.01	nee	
z.k. kozijn	3,13	0,034	202.0.5.01	nee	
z.k. kozijn	0,89	0,034	202.0.5.01	nee	
kopgevel hellend dak - buitenlucht, N - 26,3 m² - 41°					
dakvoet	8,41	-0,009	401.2.3.01	nee	
daknok	8,41	0,030	404.0.0.01	nee	
kopgevel hellend dak - buitenlucht, Z - 15,3 m² - 90°					
kilkeper	6,81	0,010	421.4.0.01	nee	

Verwarming- en warmtapwatersystemen

verwarming/warmtapwater 1

Opwekking

type opwekker	*HR-combiketel*
positie HR-ketel	*binnen EPC begrenzing*
indeling LT/HT voor opwekker	*lage temperatuur*
toepassingsklasse (CW-klasse)	*4 (CW 4)*
toestel - HR-ketel	*Intergas Kombi Kompakt HRE 28-24*
aantal HR-ketels	*1*
transmissieverlies verwarmingssysteem - januari (H_T)	*84 W/K*
warmtebehoefte verwarmingssysteem ($Q_{H;nd;an}$)	*17.470 MJ*
hoeveelheid energie t.b.v. verwarming per toestel ($Q_{H;dis;nren;an}$)	*17.470 MJ*
hoeveelheid energie t.b.v. warmtapwater per toestel ($Q_{W;dis;nren;an}$)	*9.806 MJ*
opwekkingsrendement verwarming - HR ketel ($\eta_{H;gen}$)	*0,975*
opwekkingsrendement warmtapwater - HR ketel ($\eta_{W;gen}$)	*0,825*

Kenmerken afgiftesysteem verwarming

Type warmteafgifte (in woonkamer)					
type warmteafgifte	positie	hoogte	R_c	$\theta_{em;avg}$	$\eta_{H;em}$
vloer- en/of wandverwarming en/of betonkernactivering	buitenvloer of buitenwand	< 8 m	≥ 2,5 m²K/W	n.v.t.	1,00

regeling warmteafgifte aanwezig	*ja*
afgifterendement ($\eta_{H;em}$)	*1,000*

Kenmerken distributiesysteem verwarming

buffervat buiten verwarmde ruimte aanwezig	*nee*
verwarmingsleidingen in onverwarmde ruimten en/of kruipruimte	*nee*

distributierendement ($\eta_{H;dis}$)	*1,000*

Kenmerken tapwatersysteem

aantal woningbouw-eenheden aangesloten op systeem	*1*
warmtapwatersysteem ten behoeve van	*keuken en badruimte*
gemiddelde leidinglengte naar badruimte	*6-8 m*
gemiddelde leidinglengte naar aanrecht	*8-10 m*
inwendige diameter leiding naar aanrecht	*≤ 10 mm*
afgifterendement warmtapwater ($\eta_{W;em}$)	*0,742*

Douchewarmteterugwinning

douchewarmteterugwinning	*nee*

Zonneboiler

zonneboiler	*nee*

Hulpenergie verwarming

hoofdcirculatiepomp aanwezig	*ja*
hoofdcirculatiepomp voorzien van pompregeling	*ja*
aanvullende circulatiepomp aanwezig	*nee*

Aangesloten rekenzones

begane grond + 1e verdieping
2e verdieping

Ventilatie

ventilatie 1

ventilatiesysteem	*C. natuurlijke toevoer en mechanische afvoer*
systeemvariant	*Zehnder (Zehnder J.E. StorkAir) ComfoFan S CO2 + ZR-roosters*
luchtvolumestroomfactor voor warmte- en koudebehoefte (f_{sys})	*1,09 (forfaitair conform systeemvariant C.4a NEN 8088-1)*
correctiefactor regelsysteem voor warmte- en koudebehoefte (f_{reg})	*0,64 (forfaitair conform systeemvariant C.4a NEN 8088-1)*

Kenmerken ventilatiesysteem

werkelijk geïnstalleerde ventilatiecapaciteit bekend	*nee*
warmtepompboiler(s) in gebouw	*nee*
luchtdichtheidsklasse ventilatiekanalen	*onbekend*

Passieve koeling

max. benutting geïnstal. ventilatiecapaciteit voor koudebehoefte	*ja*
max. benutting geïnstal. spuicapaciteit voor koudebehoefte	*ja*

Kenmerken ventilatoren

totaal nominaal vermogen (P_{nom}) centrale ventilatie-units	*13,00 W (1 units)*

Aangesloten rekenzones

begane grond + 1e verdieping
2e verdieping

Resultaten

Jaarlijkse hoeveelheid primaire energie voor de energiefunctie		
verwarming (excl. hulpenergie)	$E_{H;P}$	17.918 MJ
hulpenergie		379 MJ
warmtapwater (excl. hulpenergie)	$E_{W;P}$	11.886 MJ
hulpenergie		0 MJ
koeling (excl. hulpenergie)	$E_{C;P}$	0 MJ
hulpenergie		0 MJ
zomercomfort	$E_{SC;P}$	2.517 MJ
ventilatoren	$E_{V;P}$	382 MJ
verlichting	$E_{L;P}$	4.990 MJ
geëxporteerde elektriciteit	$E_{P;exp;el}$	0 MJ
op eigen perceel opgewekte & verbruikte elektriciteit	$E_{P;pr;us;el}$	0 MJ

Oppervlakten		
totale gebruiksoppervlakte	$A_{g;tot}$	108,29 m²
totale verliesoppervlakte	A_{ls}	219,86 m²

Aardgasgebruik (exclusief koken)	
gebouwgebonden installaties	847 m³aeq

Elektriciteitsgebruik	
gebouwgebonden installaties	897 kWh
niet-gebouwgebonden apparatuur (stelpost)	3.036 kWh
op eigen perceel opgewekte & verbruikte elektriciteit	0 kWh
geëxporteerde electriciteit	0 kWh
TOTAAL	3.933 kWh

CO_2-emissie		
CO_2-emissie	m_{co2}	2.015 kg

Energieprestatie		
specifieke energieprestatie	EP	352 MJ/m²
karakteristiek energiegebruik	E_{Ptot}	38.072 MJ
toelaatbaar karakteristiek energiegebruik	$E_{P;adm;tot;nb}$	26.953 MJ
energieprestatiecoëfficiënt	EPC	0,566 -
energieprestatiecoëfficiënt	EPC	0,57 -

Het gebouw voldoet niet aan de eisen inzake energieprestatie uit het Bouwbesluit 2012.

Uniec 2.2 is gebaseerd op NEN7120:2011 "Energieprestatie van gebouwen" (inclusief het Nader Voorschrift) en NEN 8088-1 "Ventilatie en luchtdoorlatendheid van gebouwen" inclusief alle wettelijk van kracht zijnde correctiebladen.

Alle bovenstaande energiegebruiken zijn genormeerde energiegebruiken gebaseerd op een standaard klimaatjaar en een standaard gebruikersgedrag. Het werkelijke energiegebruik zal afwijken van het genormeerde energieverbruik. Aan de berekende energiegebruiken kunnen geen rechten ontleend worden.

MOH Hendrik Ido Ambacht - 27 aug — Frank Schipper, Aveco de Bondt

Resultaten

Jaarlijkse hoeveelheid primaire energie voor de energiefunctie		
verwarming (excl. hulpenergie)	$E_{H;P}$	17.918 MJ
hulpenergie		379 MJ
warmtapwater (excl. hulpenergie)	$E_{W;P}$	11.886 MJ
hulpenergie		0 MJ
koeling (excl. hulpenergie)	$E_{C;P}$	0 MJ
hulpenergie		0 MJ
zomercomfort	$E_{SC;P}$	2.517 MJ
ventilatoren	$E_{V;P}$	382 MJ
verlichting	$E_{L;P}$	4.990 MJ
geëxporteerde elektriciteit	$E_{P;exp;el}$	0 MJ
op eigen perceel opgewekte & verbruikte elektriciteit	$E_{P;pr;us;el}$	0 MJ

Oppervlakten		
totale gebruiksoppervlakte	$A_{g;tot}$	108,29 m²
totale verliesoppervlakte	A_{ls}	219,86 m²

Aardgasgebruik (exclusief koken)		
gebouwgebonden installaties		847 m³aeq

Elektriciteitsgebruik		
gebouwgebonden installaties		897 kWh
niet-gebouwgebonden apparatuur (stelpost)		3.036 kWh
op eigen perceel opgewekte & verbruikte elektriciteit		0 kWh
geëxporteerde electriciteit		0 kWh
TOTAAL		3.933 kWh

CO_2-emissie		
CO_2-emissie	m_{co2}	2.015 kg

Energieprestatie		
specifieke energieprestatie	EP	352 MJ/m²
karakteristiek energiegebruik	E_{Ptot}	38.072 MJ
toelaatbaar karakteristiek energiegebruik	$E_{P;adm;tot;nb}$	26.953 MJ
energieprestatiecoëfficiënt	EPC	0,566 -
energieprestatiecoëfficiënt	EPC	0,57 -

Het gebouw voldoet niet aan de eisen inzake energieprestatie uit het Bouwbesluit 2012.

Uniec 2.2 is gebaseerd op NEN7120;2011 "Energieprestatie van gebouwen" (inclusief het Nader Voorschrift) en NEN 8088-1 "Ventilatie en luchtdoorlatendheid van gebouwen" inclusief alle wettelijk van kracht zijnde correctiebladen.

Alle bovenstaande energiegebruiken zijn genormeerde energiegebruiken gebaseerd op een standaard klimaatjaar en een standaard gebruikersgedrag. Het werkelijke energiebruik zal afwijken van het genormeerde energieverbruik. Aan de berekende energiegebruiken kunnen geen rechten ontleend worden.

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Appendix E

EPC - Young couple's house

Technisch Adviesbureau Crone (024 3780199 - kantoor@croneadvies.nl)

Nul op de Meter woningen

Bodegraven - Fase 4

Gebouwd door BAM Woningbouw

Bouwnummer: **193**

Specificaties van de woning:
Zoals omschreven in de technische omschrijving in de verkoopstukken.

Energieprestatie; bepaald conform NEN 7120 "Energieprestatie van gebouwen":

Benodigde energie per jaar:	MJ primair	kWh elektrisch
Voor verwarming (excl hulpenergie):	5.617	609
hulpenergie:	2.107	229
Voor warmwater (excl hulpenergie):	18.091	1.963
hulpenergie:	0	0
Voor koeling (excl hulpenergie):	0	0
hulpenergie:	0	0
Zomercomfort (hier n.v.t. wegens aanwezige koeling):	1.148	125
Voor ventilatoren:	1.058	115
Voor verlichting:	5.088	552
Subtotaal gebouw-installaties:	33.109	3.593
Door PV-panelen op de woning opgewekte elektriciteit:		
Voor gebouw-gebonden gebruik:		3.593
Voor persoonlijk en huishoudelijk verbruik:		2.700
Totaal door PV op te wekken:		6.293

Conclusie: Uit onze berekeningen blijkt dat de PV-panelen gemiddeld minstens zoveel elektriciteit opwekken als bij genormeerd gebruik nodig is voor gebouw-installaties en daarenboven 2.700 kWh voor persoonlijk en huishoudelijk gebruik.

Nijmegen, 23 oktober 2017, S.J.J.M. Crone, eigenaar

193 - Bodegraven Fase 4 | S. Crone, Technisch Adviesbureau Crone

Uniec 2.2

STUDIEBEREKENING

EP-certificaat - 193 - Bodegraven Fase 4
Type Bk kopwoning

-0,02

Jaarlijkse hoeveelheid primaire energie voor de energiefunctie		
verwarming (excl. hulpenergie)	$E_{H;P}$	5.617 MJ
hulpenergie		2.107 MJ
warmtapwater (excl. hulpenergie)	$E_{W;P}$	18.091 MJ
hulpenergie		0 MJ
koeling (excl. hulpenergie)	$E_{C;P}$	0 MJ
hulpenergie		0 MJ
zomercomfort	$E_{SC;P}$	1.148 MJ
ventilatoren	$E_{V;P}$	1.058 MJ
verlichting	$E_{L;P}$	5.088 MJ
geëxporteerde elektriciteit	$E_{P;exp;el}$	0 MJ
op eigen perceel opgewekte & verbruikte elektriciteit	$E_{P;pr;us;el}$	34.542 MJ
in het gebied opgewekte elektriciteit	$E_{P;pr;dei;el}$	0 MJ

Oppervlakten		
totale gebruiksoppervlakte	$A_{g;tot}$	110,41 m²
totale verliesoppervlakte	A_{ls}	239,79 m²

Elektriciteitsgebruik	
gebouwgebonden installaties	3.592 kWh
niet-gebouwgebonden apparatuur (stelpost)	3.095 kWh
op eigen perceel opgewekte & verbruikte elektriciteit	3.748 kWh
geëxporteerde electriciteit	0 kWh
TOTAAL	2.939 kWh

CO_2-emissie		
CO_2-emissie	m_{co2}	-88 kg

Energieprestatie		
specifieke energieprestatie	EP	-13 MJ/m²
karakteristiek energiegebruik	E_{Ptot}	-1.434 MJ
toelaatbaar karakteristiek energiegebruik	$E_{P;adm;tot;nb}$	27.988 MJ
energieprestatiecoëfficiënt	EPC	-0,020 -
energieprestatiecoëfficiënt	EPC	-0,02 -

BENG indicatoren	
energiebehoefte	32,3 kWh/m²
primair energiegebruik	-6,4 kWh/m²
aandeel hernieuwbare energie	111 %

Alle bovenstaande energiegebruiken zijn genormeerde energiegebruiken gebaseerd op een standaard klimaatjaar en een standaard gebruikersgedrag. Het werkelijke energiegebruik zal afwijken van het genormeerde energiegebruik. Aan de berekende energiegebruiken kunnen geen rechten ontleend worden.

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Appendix F

Energy Models - IES(VE) 2018

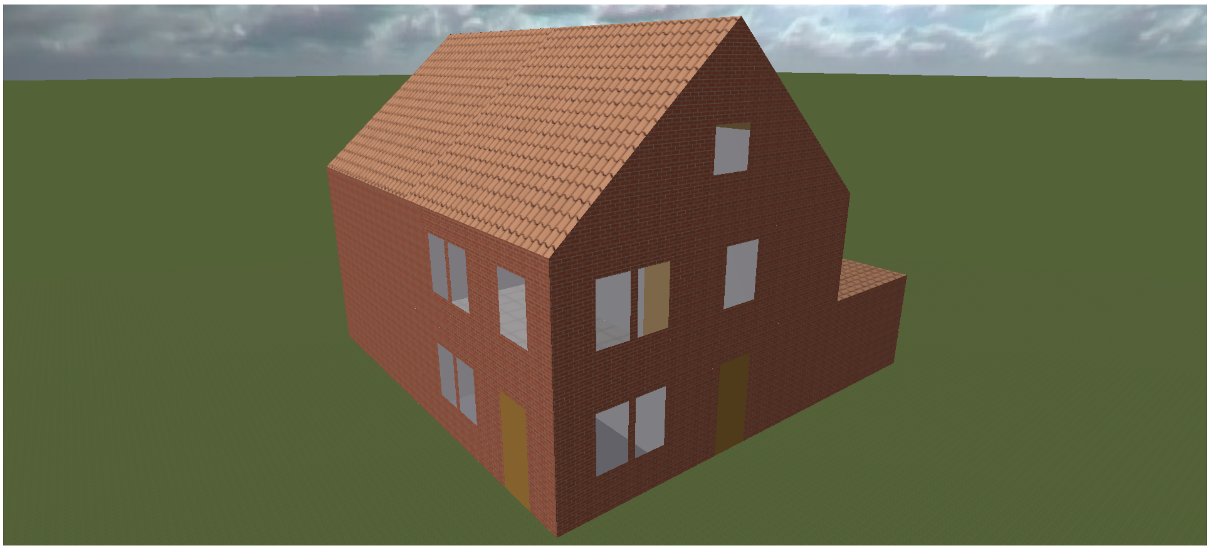

Figure F.1: Energy model of the senior couple's house

Figure F.2: Energy model of the young couple's house

Figure F.3: Energy model of the family's house

Cover by Szymon Łapaj