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Simulation-aided Performance Analysis of an Energy Self-Sufficient Off-Grid Housing Unit

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ABSTRACT

Various new solutions are emerging every year in the discourse on self-sufficient buildings. Some are necessary due to conditions such as remote locations (e.g. mountain huts), others are motivated solely by the desire of being independent of the electrical grid like the underlying case study of this master thesis, an off-grid self-sufficient small housing unit. With the support of a dynamic simulation, this thesis analyzes the question whether a fully self-sufficient solution for the case study object solely based on self-produced electrical energy is possible and which measures are necessary for this purpose. The limited living area sets boundaries to prohibit oversized and unrealistic energy supply and storage systems. First, a literature review was conducted to analyze definitions of ‘self-sufficiency’, so that evaluation methods for such concepts could be deducted from them. Then, an energy simulation model was developed and used to simulate different system set-ups and improvement measures, namely: an improved opaque envelope through vacuum panels, an improved transparent envelope through vacuum glazing, a bigger photovoltaic system, a larger electrical storage and heating through an air-to-air heat pump. The results illustrate that with the state-of-the-art technologies, a fully self-sufficient solution for the underlying case study cannot be achieved by only using self-produced electrical energy with limited space for the photovoltaic system and electrical storage. As an optimum, a solution with 99% electrical and 66% thermal self-sufficiency can be achieved, or 99 % thermal self-sufficiency and 51% electrical self-sufficiency. The reason for this is the fact that the losses are high due to a large surface-area-to-volume-ratio. Furthermore, the demand is highest, when the production is lowest, e.g. in December. The necessary surfaces for the photovoltaic system, to cover the demand in winter, are far beyond the available space.

Keywords: self-sufficient unit, building simulation, off-grid system, EnergyPlus

KURZFASSUNG

Im Diskurs um autarke Gebäude erscheinen unaufhörlich neue Lösungsansätze. Manche werden bestimmt durch die Rahmenbedingungen, wie zum Beispiel die abgelegene Lage einer Berghütte. Andere wiederum entstehen allein aus dem Verlangen heraus, unabhängig und nicht an das Netz angeschlossen zu sein, wie auch hier in der vorliegenden Fallstudie. Mit dynamischer Gebäudesimulation wird untersucht, ob ein Minimalsystem auf kleinstem Raum, basierend nur auf selbst erzeugter elektrischer Energie, vollständige Energieautarkie trotz limitiert verfügbaren Platzes für Photovoltaiksystem und Speicher erreichen kann und mit welchen Mitteln dies möglich ist. Durch den limitierten Platzbedarf sind dem, im Folgenden dargelegten Vorhaben, Grenzen gesetzt, die die Entwicklung eines überdimensionalen Systems, fernab von jeglicher Realität, verhindern. Zuerst wurden unterschiedliche Definitionen von energieautarken Gebäuden durch eine Literaturrecherche zusammengetragen, sodass daraus Evaluationsmethoden für solche Systeme abgeleitet werden konnten. Dann wurde ein Simulationsmodell in EnergyPlus entwickelt, welches dazu verwendet wurde, unterschiedliche Systeme sowie Verbesserungsmaßnahmen umzusetzen: Eine verbesserte opake Hülle durch Vakuumdämmplatten, eine verbesserte transparente Hülle durch Vakuumverglasung, die Größe des Photovoltaiksystems, die Größe des Batteriespeichers und Raumheizung durch eine Wärmpumpe. Die Ergebnisse zeigen auf, dass mit aktuellen technischen Möglichkeiten ein Gebäudesystem basierend auf nur selbst erzeugtem Strom auf kleinem Raum nicht energieautark funktionieren kann, wenn der Platz für Photovoltaik und Batterien limitiert ist. Der maximale energieautarke Anteil, welcher erreicht werden konnte, beträgt 99% elektrisch und 66% thermisch oder 99% thermisch und 51% elektrisch. Der Grund hierfür sind die hohen Transmissionsverluste durch die Gebäudehülle auf Grund des hohen Oberfläche-zu-Volumen-Verhältnisses. Außerdem ist der Energiebedarf am höchsten, wenn am wenigsten Energie zu Verfügung steht, wie beispielsweise im Dezember. Die erforderliche Fläche für das Photovoltaiksystem, um den Bedarf zu decken, übersteigt bei weitem die verfügbaren Flächen.

Keywords: Energieautarkes Gebäude, netzunabhängiges System, Gebäudesimulation, EnergyPlus

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1 INTRODUCTION

1.1 Overview

In order to generate deeper understanding on the matter of off-grid and energy self-sufficient housing, the following basic question has to be discussed: what is a self-sufficient building? For a long period of time, all buildings were self-sufficient. They relied on the sources that nature around them provided and if these were scarce, the consequence was reduced comfort, like lower inside temperatures. Today, fuels, biomass, gas and electricity can be transported over long distances. From the point of view of a single building, endless energy sources are available and the only question that arises is how much the user is willing to pay. What the term “self-sufficient building” constitutes nowadays, is not easy to answer and many researches provide definitions; some are similar and others contradictory. For this thesis the following definition based on the results of profound literature review, in detail described in Chapter 2.1, was deducted:

“A building is energy self-sufficient, if it relies on its own energy resources for generating the useful electrical and thermal energy required to sustain an acceptable indoor comfort standard, meaning specifically, that the building does not require substantial additional amounts of energy from other renewable resources from other regions. What “acceptable comfort standard” and “substantial additional amount of energy” mean has to be quantified and conclusively argued individually fitting the building concept.” (Based on McKenna et al. 2015; Müller et al. 2011; Rae and Bradley 2012)

Although in general some parallels can be found between self-sufficient buildings and concepts like (net-/nearly) zero energy buildings (net ZEB/nZEB/ZEB) or plus energy buildings, it is important not to confuse them, as the latter are often not specifically defined and are usually calculated with an energy balance over the year.

The focus of this thesis is to analyze the impact of the following factors in the underlying case study of a self-sufficient unit though simulation: construction, ventilation with heat recovery, energy production and storage, as well as the application of an air-to-air heat pump. The exact inputs are discussed in Chapter 3.5. For the comparison of the importance of these factors, the functioning of the system is emphasized rather than the achievement of a minimum energy demand. The procedure for the evaluation is described in detail in Chapter 3.6. In self-sufficient housing, a balance between consumed, produced and stored energy at any timestep is essential for proper functioning. In this context, what would be considered a failure of the entire system is not an increase in heating or cooling costs over the year, but a decrease in occupant comfort. It is of no importance how much energy can be generated over the year – what matters most is to guarantee that enough energy is produced and stored at any given time to be able to cover a basic demand.

The main objective in this study is to determine how a system, fully based on self-produced electricity (including heating and hot water user), can achieve self-sufficiency in a climate like Austria. Therefore, an Austrian off-grid tiny housing unit called 'wohnwagon' (ww wohnwagon GmbH 2017) provided the basis for this case study. For the evaluation, the approach of thermal building simulation was chosen to grasp the dynamic variations within such a system. For each model, thermal and electrical self-sufficiency degrees were calculated and compared among each other.

1.2 Motivation

Self-sufficient buildings are not much addressed in the scientific discourse. According to McKenna et al. (2015), these solutions can be suitable under specific circumstances, for example in remote locations with no connection to local public infrastructure. Other motivational reasons for self-sufficient systems might be the availability of resources (McKenna et al. 2015).

Most notable examples (see Chapter 2.2) have no connection to the public electric or thermal grid, therefore are individual solutions that do not receive much attention. However, there are several reasons which speak in favor of more intensive research in this field.

Even though there are few examples of self-sufficient buildings, it is still preferable that these solutions use renewable resources and do not rely on fossil fuels. These face challenging requirements and innovative solutions are necessary to achieve a good comfort level using only renewable resources. The analysis through simulation can point out effective solutions and component combinations before the system is built.

Concerning the legal framework, the Energy Performance of Buildings Directive (EPBD 2010) sets as a goal until 2020 that all new buildings need to be nearly zero-energy buildings. These are buildings with a low energy demand, which is covered by renewable resources preferably produced on-site or nearby (European Parliament, Council of the European Union 2010). A lot of effort has been made in this field. However, the evaluation of the quality of such a building considers the annual energy balance with no regard to simultaneity, a fact that led to a lot of criticism for net-ZEBs and is further discussed in Chapter 2.3. In a self-sufficient building, all the system components (energy producing systems, energy storage system, heating devices, cooling devices, etc.) must fit together and complement each other to be able to cover the demand with local resources at any given time. Therefore, they might provide innovative solution approaches for net-ZEBs and point out energy intensive sections of demand. However, this does not mean that self-sufficient buildings constitute the only solution for the grid challenges of net-ZEBs. There are other solution suggestions like conventional grid reinforcement, demand-side management of industry and households and the construction of grid storage capacities constantly being worked on.

2 BACKGROUND

2.1 Energy self-sufficiency

What is energy self-sufficiency? Before heading to the definitions used in the scientific literature, first, some basic definitions from dictionaries are listed. According to the Oxford dictionary, 'self-sufficiency' is:

„Needing no outside help in satisfying one's basic needs, especially with regard to the production of food." (Oxford University Press 2017)

In the Collins dictionary, it is defined as follows:

"If a country or group is self-sufficient, it is able to produce or make everything that it needs; able to provide for or support oneself without the help of others. (CollinsDictionary.com 2017)"

The definition of 'autarky' is strongly connected to the term 'self-sufficiency':

„Economic independence or self-sufficiency." (Oxford University Press 2017)

„(Esp. of a political unit) a system or policy of economic self-sufficiency aimed at removing the need for imports." (CollinsDictionary.com 2017)

The term autarky comes from the Greek language 'autarkeia' with 'autos' meaning 'self' and 'arkein' - 'suffice' (CollinsDictionary.com 2017). Therefore, the definitions of the words 'self-sufficiency' and 'autarky' are strongly linked. For this reason, these words are used as synonyms in this thesis.

The term 'self-sufficiency' concerning the energy supply is mostly used in connection with regions or with photovoltaic (PV) systems of buildings.

From the point of view of communities, in producing electricity using renewable energy systems, there is a notion of more independence concerning the energy demand and therefore also self-sufficiency (McKenna et al. 2015) which leads to confusions about the definition of this term. All reviewed papers by McKenna et al. (2015) and discussed examples by Müller et al. (2011) deal with self-sufficiency on a regional level, not on a building level. In most cases, electricity and heating are focused on; traffic and grey energy connected to goods and services are often left out. (McKenna et al. 2015)

McKenna et al. (2014) address the challenge that the terms energy self-sufficiency, energy autonomy and energy independence are used as synonyms without clear definitions. In general, the terms conjoint that local and regional energy resources are used, however, there is no agreement what this exactly signifies regarding special and temporal boundary conditions. Due to this, definitions and categorization are proposed by McKenna et al. (2014) as follows:

- **tendency to self-sufficiency** and decentralized energy supply, but autarky is not an explicit goal;
- **on-grid or soft self-sufficiency:** the region over the year is self-sufficient, however it uses infrastructure beyond the system boundaries including the electric grid, electricity from other sources, gas, heat, etc. to balance the mismatch of demand and supply;
- **off-grid / hard self-sufficiency:** the region is energetically separated from the surrounding and is a stand-alone solution with sufficient energy storage possibilities.

Although it is understandable that there is a need for the quantification of the capability of the system to supply itself, the true meaning of the words ‘self-sufficiency’ and ‘autarky’ stated in the beginning of the chapter implies an independence of the system, a standalone solution. The dependence on the grid is a contradiction to the definition of the word itself and therefore ‘tendency to self-sufficiency’ and ‘soft self-sufficiency’ are misleading as thoroughly analyzed and are not applied to the underlying study case. These considerations correlate with the definition provided by Müller et al. (2011, p.5801–5802):

“We define a region to be energy autarkic when it relies on its own energy resources for generating the useful energy required to sustain the society within that region. To qualify as sustainable, additional criteria – such as the decarbonization of the energy subsystem – must be met. […] Specifically, we define energy autarky as a situation in which a region does not import substantial amounts of energy resources from other regions, but rather relies on its own resources to satisfy its need for energy services.”

McKenna et al. (2014) criticize Müller et al. (2011) for this definition as it does not differentiate between ‘hard’ and ‘soft’ self-sufficiency, whereas ‘soft’ or ‘balanced’ self-sufficiency according to this definition is not autarky as it relies on the external sources compensating the mismatch of production and demand. Although Müller et al. (2011) never address a temporal resolution, it is evident that the significant part is the self-supply and the independence like stated in the definition and no importance is given to overproduction or a balance over the year.

Rae and Bradley (2012) chose a very similar definition to Müller et al. (2011), saying that the concept of self-sufficiency is the ability of the system to provide enough energy to meet the demand and to function without external support, meaning it must provide energy storage to account for the temporal mismatch between demand and supply. Although the grid-connected systems are not excluded, however, the capability to function independently is crucial. Nevertheless, in the same paper, they back away from this definition as they see self-sufficiency and independence from other regions in the true meaning of the word as unachievable. Due to this fact, they chose the balancing method to achieve the state of being net energy neutral or even negative and identify it as a degree of self-sufficiency, although, as stated above, this contradicts the concept and meaning of autarky. They see ‘stand-alone’ solutions as another degree of self-sufficiency, where a community can generate and store all the energy it needs with no requirement of energy imports and minimal reliance on outside expertise and materials. Based on these different statements, McKenna et al. (2015) conclude that energy self-sufficiency cannot be simply generalized. Other researchers even question whether energy autarky does exist at all:

„No city, in fact no country or region in the world, is fully self-supporting for all types of resources.“ (Hansson 2010, p.278)

“After all, regions are open systems that exchange information, persons, materials and also energy with one another, with mutual benefit.” (Müller et al. 2011, p.5802)

Müller et al. (2011) concludes that energy autarky should be a programmatic vision rather than a technical term. The underlying idea is that by generating energy locally, economic values are created, which contribute to the viability of the whole region. Carried by this motivation the unattainable vision of self-sufficiency the application of these goals leads to more independence and autonomy. In this thesis, the term ‘self-sufficiency’ is used not only as a programmatic vision, but also as quantifiable measure helping to express in how far the system can provide comfortable conditions by itself. It is considered as necessary as self-sufficient solutions do exist anyway in e.g. remote locations and can provide innovative solutions for other buildings.

However, there are arguments against self-sufficiency. The electrical grid has provided an improvement of the living standard and productivity over decades, especially because of supply reliability. Furthermore, the smoothening of the load curve due to the linkage of all users and energy producers reduces the total load due to simultaneity effects. Furthermore, the specific costs of a big plant are lower than those of a small one (economy of scale) and can be divided among a large group of people, although in contrast to that stand the increased losses due to the distance of distribution (McKenna et al. 2015). The load balancing is a challenge and without a connection to the grid the storage capacities must be designed for a worst-case scenario if there is no willingness for compromises concerning comfort.

2.2 Energy self-sufficient buildings

2.2.1 Overview

What is an energy self-sufficient building? According to Sartori et al. (2010), the term ZEB (Zero Energy Building) may include grid-connected as well as self-sufficient buildings, defining these as not connected to the infrastructure (electricity grid, district heating and cooling system, gas pipe network, biomass and biofuels distribution networks), while the term ‘net’ implies the fact that a grid interaction (energy fed in and taken out) takes place. Furthermore, the term autarky on a building level is used by Märtel (2017) and Tjaden, Weniger and Quaschning (2014) concerning PV systems in connection with self-consumed electricity and not on the basis of an annual balance.
Connected to the term ‘self-sufficient building’, the term ‘off-grid’ is mentioned on a regular basis. If we call a system off-grid, it usually means disconnected from the electrical or a district heating grid. However, it is necessary to address, where the difference lies between the electrical grid and the grid of infrastructure (e.g. streets), which is necessary to bring the biomass or biogas to the building. There is no trivial answer to this question. Coming back to the statement of Müller et al. (2011) which stated that energy autarky should be a programmatic vision rather than a technical term leading to more independence and autonomy, one can derive that off-grid system solutions do not make sense. However, as discussed in Chapter 1.2, there are conditions that make off-grid solutions necessary (e.g. remote location) or very attractive (e.g. high availability of renewable resources). Therefore, the following definition based on the literature review was deducted to be used in this thesis work for energy self-sufficient buildings:

“A building is energy self-sufficient, if it relies on its own energy resources for generating the useful electrical and thermal energy required to sustain an acceptable indoor comfort standard, meaning specifically, that the building does not require substantial additional amounts of energy from other renewable resources from other regions. What “acceptable comfort standard” and “substantial

additional amount of energy" mean has to be quantified and conclusively argued individually fitting the building concept." (Based on McKenna et al. 2015; Müller et al. 2011; Rae and Bradley 2012)

Furthermore, existing solutions for energy self-sufficient buildings were collected and analyzed. Table 1 gives a recap of the examples in detail discussed in the Chapters 2.2.2 to 2.2.8. All examples show a common approach in the following fields: the reduction of energy demand and the production of energy by renewable resources. However, looking closer at these examples, significant differences in the details can be observed. Most systems are off-grid and use a back-up system that relies on biomass. One example, however, is on-grid and has no battery storage. The underlying definition of the word energy self-sufficient differs between the examples and reflects the missing definitions of the discourse.

Table 1: Overview of examples of energy self-sufficient concepts

Example	Claim	Description
Energy self-sufficient house in Freiberg, Germany	Self-sufficient	This off-grid system has solarthermal system and PV modules with electrical and thermal energy storage as well as a biomass back-up system for heating.
Schiestlhouse at Hochschwab, Austria	Self-sufficient	This off-grid system has solarthermal system and PV modules with electrical and thermal energy storage. Two back-up systems being a cogeneration unit and a wooden stove are necessary to achieve self-sufficiency, although the building is not occupied in winter.
Monte Rosa, Mont Blanc hut in France	90% self-sufficient	The Monte Rosa hut is an off-gird system with a solarthermal system and PV modules with electrical and thermal energy storage. Additionally, cogeneration unit and a gas stove for cooking are used, whereas cooking is not considered in the energy balance.
Energy self-sufficient solar house in Freiburg, Germany	Self-sufficiency not fulfilled	This off-grid building example has a solarthermal system and PV modules with electrical and thermal energy storage. As a back-up system and seasonal storage, a fuel-cell with hydrogen tanks is used. The results of this research state that self-sufficiency was not fulfilled because the heating demand cannot be covered by passive methods meaning solar gains only.
Ekihouse in Madrid, Spain	Self-sufficient	The Ekihouse has a PV system that is connected to the grid with no additional battery storage. Air-conditioning for cooling is used, no additional system for heating is previewed as the location is in Spain.
LIFE Cycle Habitation in Böheimkirchen, Austria (LCH)	Self-sufficient	The LCH has PV modules and solar thermal modules to achieve self-sufficiency. A cogeneration unit is used as a back-up system. For cooking, biogas and a thermal oil solar cooker are used.
Wohnwagon, mobile unit	Self-sufficient	This off-grid mobile unit, being the basis for the case study, has a solar thermal module and PV modules with electrical and thermal energy storage. A biomass oven is used as a back-up system for heating.

2.2.2 Energy self-sufficient house in Freiberg, Germany

Figure 1 shows an off-grid single-family house with 206 m² floor area. The systems used are 45 m² solar collectors (45°) with a 9 m³ water tank (long term storage) and an 8 kWp PV system with 58 kWh electrical storage. These systems cover

100% of the electrical and 65% of thermal energy demand. A biomass heating system with 25 kW is used when the solar system does not provide enough heating. A simulated wood demand is calculated to be two to three cubic meters wood per year. The surplus of electric energy from February to November can be used for e-mobility. (Leukefeld 2015)

Figure 1: Energy self-sufficient house, Freiberg, Germany (Talis Berufsstart Architekten | Bauingenieure 2013)

2.2.3 Schiestlhouse at Hochschwab, Austria

The off-grid energy self-sufficient building (492 m²) is an alpine hut with no connection to the electrical grid. The south-oriented PV system to be seen in Figure 2, consists of 52 m² 60° inclined panels and 8 m² in the facade integrated panels with a total of 7.5 kWp and a 100-kWh gel battery storage.

Figure 2: Schiestlhouse, Hochschwab, Austria (POS Architecture 2018)

The solar thermal system is 63 m² big and is fully integrated into the south façade (Ipser et al. 2012) and the energy is stored in buffer storages. This is sufficient for 65% of the electricity demand. Additionally, a cogeneration unit (27 kW) working with rapeseed oil and a wooden stove (11.6 kW) are used for cooking and loading of the buffer storage. This system are necessary despite the fact that the building is not occupied in winter (Wolfert and Rezac 2006).

2.2.4 Monte Rosa, Mont Blanc hut in France

The ETH Zurich planned this self-sufficient mountain hut (1154 m²) which is represented in Figure 3.

Figure 3: Monte Rosa, Mont Blanc hut, France (ArchDaily 2016)

It is claimed that the system is 90% self-sufficient (without cooking), meaning that the south-west oriented solar collectors (60 m²) and the PV system (16 kWp) can cover 90% of the total energy demand. According to Baumgartner and Ambrosetti (2010), a coverage of over 90% is not ecologically and economically feasible. A cogeneration unit (12 kW_{el} & 27 $kW_{thermal}$), powered by rapeseed oil, synthetic diesel or eco-diesel, covers the other 10% of the energy demand. The energy is stored in a 288 kWh battery (Voss and Musall 2013) and a 5500-liter heating storage tank. As in the case of the Schiestlhouse, a ventilation with heat recovery is used to reduce ventilation losses. The cooking solution is not considered in the self-sufficiency degree. Several gas devices are used; however, an induction stove is used in case of solar overproduction. An intelligent building automation system, which is taking into account weather and occupancy forecasts, is used to increase the self-sufficiency of the system (Baumgartner and Ambrosetti 2010).

2.2.5 Energy self-sufficient solar house in Freiburg, Germany

The Fraunhofer Institute for Solar Energy Systems ISE conducted a research project in the years 1989 to 1995, concerning an energy self-sufficient solar single-family house (145 m²). For warm water and heating, 12 m² of solar collectors (40° inclined) and a one cubic meter stratified storage tank are used which covers

80 – 90% of the thermal energy demand. For the residual demand, a fuel cell is used. A ventilation with heat recovery is put in place to reduce the ventilation losses. A PV system (2.5 kWp), shown in Figure 4, is installed to cover the electricity demand with a 20-kWh battery storage.

Figure 4: Energy self-sufficient solar house, Freiburg, Germany (lib.znate.ru 2012)

Energy can also be seasonally stored with the help of the fuel cell. The research report states that energy self-sufficiency is not fulfilled, whereas thermal self-sufficiency in that research is understood as the coverage of the heating demand solely by passive methods (solar gains through windows and transparent insulation). (Voss 1997)

2.2.6 Ekihouse in Madrid, Spain

The Ekihouse is an industrialized solar house prototype (54.6 m²). It has a 10 kWp PV system, see Figure 5, that is grid-connected and a ventilation system with 90% heat recovery, including air-conditioning.

Figure 5: Ekihouse, Madrid, Spain (Irulegi et al. 2014)

It was designed for Madrid and therefore the focus is on the reduction of the cooling load by the utilization of phase changing materials (PCM), and the possibility for cross ventilation and shading. It is stated that an additional heating system would be needed if the temperatures dropped below 0°C which is not the case for Madrid. It is not explained, how the self-sufficiency of the system is calculated or proven (Irulegi et al. 2014).

2.2.7 LIFE Cycle Habitation in Böheimkirchen, Austria

The LIFE Cycle Habitation (LCH) is a planned building concept designed for 80 living units. A rendering of the planned project in shown in Figure 6.

Figure 6: Concept LCH (NÖN.at)

The main goal is to use thermal energy provided by the solar thermal system or by the biomass back-up cogeneration unit (CHP – combined heat and power), which is also used to reduce the electricity demand. Thermal appliances, such as washing machines and dishwashers, are supplied with hot water instead of using electrical energy for water heating. Cooking in the community center is provided by a version of an indirect operated solar cooker, whereas biogas is used in the individual living units. This would lead to a demand of 28 m³ of biogas per day. To provide the electrical and thermal energy, a PV system of 250 m² and a solar thermal system of 767 m² was calculated (Wimmer and Eikemeier 2014).

2.2.8 Wohnwagon, mobile unit, case study

The small off-grid unit, see Figure 7, documented in the provided energy certificate (Leukefeld 2016) consists of a 1.71 kWp PV system and a 1.52 m² evacuated tube collector, as well as a back-up wooden stove (10 kW) which is necessary to cover 65% of the thermal energy demand.

Figure 7: Wohnwagon – mobile unit (ww wohnwagon GmbH 2018a)

The demand for wood is about 600 - 650 kg per year. Furthermore, 94% of the electricity demand can be covered by the PV system, whereas it is not specified which balancing accuracy (annual, monthly, etc.) is applied. Further details are given in Chapter 3.3.

2.3 Energy self-sufficiency evaluation methods

2.3.1 Energy evaluation

There is a wide variety of balancing and calculation approaches for building performance evaluation. The most common type is the energy certificate method, which, as the key information, expresses an energy demand per square meter per year. In Austria, it is prescribed by law to provide this certificate in case of sale or rent of a building (Austrian National Council 2012). A year is used as the assessment period and the energy demand and production is balanced over this entire period (Austrian Standards Institute 2008). However, energy cannot be simply stored over the whole year or otherwise the storage capacities would have to be huge. In such balancing methods, the grid is assumed to be the storage for the surplus electrical energy, which has led to problems in the last years. As most net-ZEB use a PV system to achieve the net-zero goal, excess solar power in the summer is fed into the grid when not needed. If a lot of buildings feed the electricity into the grid in an unexpected moment, e.g. the weather forecast was wrong, this can even destabilize the grid. The question arises, what value energy constitutes when it is not needed or even destabilizes the network (Knotzer and Weiss 2014). Additionally, if the net-ZEB requires energy from the grid during peak time, there is no difference between a net-ZEB building and a conventional one (Salom et al. 2011). This approach completely ignores the simultaneity of energy production and demand. This imbalance is called “mismatch” (Knotzer 2014a). In general, the reasonableness of an annual balance is actively discussed on an international level (Knotzer and Weiss 2014). According to Salom et al. (2011), the annual balancing method is insufficient to describe the energy performance of a building which is an active element of the electrical grid. These occurrences have gained a lot of importance in the last years, which has led to research in the field of grid interaction indicators in order to provide a more holistic representation of a net-ZEB (Voss et al. 2010), (Cao et al. 2013), (Salom et al. 2014), (Verbruggen et al. 2011), (Salom et al. 2011). Therefore, the Solar Heating and Cooling program of the International Energy Agency (SHC) has developed a net-ZEB evaluation tool. This tool takes a step away from the annual balancing method and focuses on balances on a monthly timescale. However, in the description it is clearly stated that this calculation method needs a grid connection and cannot be applied for off-grid solutions (Solar Heating and Cooling Program 2017).

To sum up, the conventional energy certificate method is experiencing challenges representing buildings that are not only energy consumers, but also producers. Similar challenges concerning self-sufficient buildings can be expected.

In literature, some evaluation methods for self-sufficiency can be found. Tjaden, Weniger and Schnorr et al. (2014) use the following indicators, see Equation (1), for buildings with PV systems:

$$f_{self-sufficiency} = \frac{E_{used\ directly} + E_{taken\ from\ battery}}{E_{energy\ demand}} \qquad (1)$$

$f_{self\text{-}sufficiency}$ … degree of self-sufficiency

E … energy

The self-sufficiency degree shows similarities to the load match index for net-ZEB in Equation (2) used by Voss et al. (2010).

$$f_{load,i} = min\left[1, \frac{on\ site\ generation + battery\ balance}{load}\right] * 100\ [\%] \qquad (2)$$

$f_{load,i}$ … load match index

i … time interval (h,d,m)

For both formulas, the maximum value possible is 100%, as all the generated power exceeding the load is considered part of the electricity grid. This can be argued since the not-needed and not-storable energy can be labelled as useless, especially in the case of the off-grid system. This contradicts the calculation method used by McKenna et al. (2015) in Equation (3), where a value over 100% can be achieved.

$$f_{self-sufficiency} = \frac{E_{produced}}{E_{energy\ demand}} \qquad (3)$$

$f_{self\text{-}sufficiency}$ … degree of self-sufficiency
E … energy

In current calculation methods, the importance of the user behavior is only addressed in a very simplified way, e.g. by standard users, and the focus is solely laid on the technology (Menconi et al. 2016). In the case of the “Ekihouse” (Irulegi et al. 2014), it is assumed that the user will make the right decision: with a flexible façade, the solar gains can be regulated individually, and the equipment can be controlled as well. However, the house was not tested with realistic usage and it is not specified, which behavior was assumed for the simulation or sizing of the building.
According to Baumgartner and Ambrosetti (2010) from ETH Zurich, the simulation results can be very precise, however, the biggest insecurity factor is the human behavior that is hard to predict.
In the research project “energy self-sufficient solar house” in Freiberg, it was impossible to compare the simulation and measurement results as the energy flows influenced by the user outweigh all the calculable influencing factors and it was not achievable to quantify the user behavior (Voss 1997). The critical question arises: “What use is there in looking at the building without a user?” At the end, the energy demand of the building in the running phase remains the important factor and evaluation methods often fail addressing this topic.
Galvin and Sunikka-Blank (2014) analyzed the causes of falling domestic consumption in Germany. Their results show that 50% of these savings can be assigned to technological improvements (30% to heating systems upgrade, 20% to building envelope retrofits, 1% to replacement of the old with new building stock), however, over 45 % of the savings have occurred due to non-technical factors. Furthermore, Sorrell (2015) looks at the energy demand in a bigger picture, talking about wealth, economic growth, rebound effects, the energy market and socio-technological aspects, that is more complex than can be possibly reflected in calculations. It is concluded, that reducing energy is harder than expected due to oversimplifications. Additionally, it is stated, that the demand for energy will not

decrease in the absence of rising energy prices. These research results show the importance of assumptions concerning the occupant, which must be handled with caution and accuracy.

McKenna et al. (2015) points out a need for research in evaluation methods and indicators on self-sufficiency and therefore proposes the following criteria to be determined and measured:

- degree of supply through local sources and definition of system boundaries
- considered energy sources (e.g. electrical, thermal)
- considered application fields and industry (in case of regional scale)
- degree of usage of grid systems outside the boundary conditions
- degree of local financing of the infrastructure
- degree of local marketing
- proportion of renewable energy sources
- timescale

These criteria are addressed throughout the thesis.

To sum up, the standard state-of-art building evaluation models are not applicable for energy self-sufficient buildings. Therefore, for this thesis, calculation methods i.e. thermal self-sufficiency degree and electrical self-sufficiency degree, were deducted based on the literature review on self-sufficient building, also in detail described in Chapter 3.6.

2.3.2 Evaluation of thermal comfort and air quality

The ÖNRORM EN 15251 (Austrian Standards Institute 2007) "Indoor environmental input parameters for design and assessment of energy performance of buildings, addressing indoor air quality, thermal environment, lighting and acoustics" provides the following categories concerning comfort requirements:

- Category I – High level of expectations and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons.
- Category II – Normal level of expectations and should be used for new buildings and renovations.
- Category III – An acceptable, moderate level of expectations and may be used for existing buildings.
- Category IV – Values outside the criteria for the above categories. This category should be accepted for a limited part of the year.

The categories are further described in Table 2.

Table 2: Summary of requirements according to comfort categories according to ÖNROM EN 15251 (Austrian Standards Institute 2007)

<table>
<tr><th>Category</th><th>Expected % dissatisfied</th><th>ϑ for heating period (operative temperature) [°C]</th><th colspan="2">ϑ in summer* (operative temperature) [°C]</th><th>Air flow people [$ls^{-1}p^{-1}$]</th></tr>
<tr><td>I</td><td>15</td><td>21 - 25</td><td rowspan="4">$\vartheta_{in}=0.33*\vartheta_{ex}+18.8$</td><td>Max +2
Min -2</td><td>10
(750ppm)</td></tr>
<tr><td>II</td><td>20</td><td>20 - 25</td><td>Max +3
Min -3</td><td>7
(900ppm)</td></tr>
<tr><td>III</td><td>30</td><td>18 - 25</td><td>Max +4
Min -4</td><td>4
(1200ppm)</td></tr>
<tr><td>IV</td><td><30</td><td></td><td></td><td><4
(<1200ppm)</td></tr>
</table>

*This formula applies when ϑ_{ex} (exponentially weighted moving average outdoor temperature) is between 10 to 30 for upper limits.

These values are the basis for the assumptions concerning the comfort requirements of the user, see Chapter 3.5.3 and the evaluation of thermal self-sufficiency of the building, see Chapter 3.6.3 .

3 METHODOLOGY

3.1 Outline

The thesis focuses on a case study, a housing unit called “wohnwagon”, an Austrian mobile self-sufficient tiny house concept (ww wohnwagon GmbH 2017) which aims to be self-sufficient, in detail described in Chapter 3.3. As discussed in Chapter 2.3, standard building evaluation approaches, like the energy certificate, experience challenges representing buildings that do not only consume but also produce energy. Therefore, for the analysis of the system, a simulation approach was chosen. In the first step, the Base Case, discussed in detail in Chapter 3.4.2, is simulated with predefined comfort standard described in Chapter 3.5.3.

For the evaluation, the system is set to a free running mode, meaning no active heating system is applied, to obtain the conditions that would occur in the off-grid system. In case the demand is not met by the system set-up, the following solutions are possible: either the given set-up (e.g. building envelope) is improved, a supplementary system is introduced, or the energy production system and storage capacities are increased. Therefore, building elements, heating system and energy supply systems were varied in the simulation. This is further described in Chapters 3.4.3 to 3.4.6. To evaluate how significantly these factors influence the functioning of the system, the results are quantified in the following categories: thermal and electrical degree of self-sufficiency. The calculation methods are described in Chapter 3.6. By examining these results, conclusions can be drawn concerning which factors should be considered in the design of energy self-sufficient buildings. Inputs and assumptions necessary for the simulation are specified in Chapter 3.5. Aspects concerning ecology, embodied energy and costs are not considered in this thesis; these provide interesting points for further research.

3.2 Research question

The question raised in this thesis can be worded as follows: can the study case unit be fully energy self-sufficient by solely using self-produced electrical energy? The given system consists of a thermal envelope with the average U-value of 0.35 $Wm^{-2}K^{-1}$, a 1.71 kWp photovoltaic system and a 6.4 kWh electrical battery. The fresh air is provided by infiltration, as the air tightness in the Base Case model is so low.

If the energy self-sufficiency by using self-produced electrical energy cannot be reached, to which extent can the given constellation cover the demand and how much additional energy is needed to achieve the defined comfort requirements? The requirements are reflecting the idea of the entire concept 'wohnwagon', namely the reduction to a minimalist lifestyle, meaning here relaxed comfort requirements according to category III of ÖNORM EN 15251 (Austrian Standards Institute 2007) are applied.

Furthermore, the last question arises within this research context: which measures concerning the thermal envelope, the heating and ventilation equipment, and energy generation are necessary to achieve self-sufficiency in this case?

3.3 Case study description

The case study is a small housing unit of 27 m² consisting of a main area with bay (24 m²) and a bathroom (3 m²). An exemplary layout is represented in Figure 8.

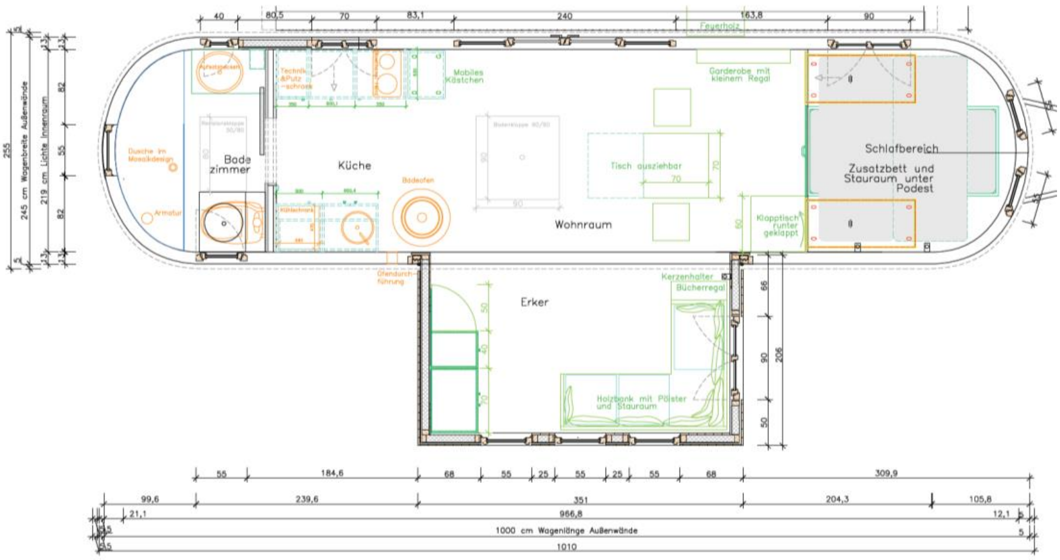

Figure 8: Floor plan of 'wohnwagon' (ww wohnwagon GmbH 2018b)

Furthermore, beneath the living, kitchen and bath area, there is an additional space which here is called cellar. It is 17 m² big and 0.55 m high that can be used for storage, however the important part here is that it serves as space for the equipment. The cellar is within the thermal envelope. The current system consists of a PV system 1.71 kWp, a battery storage 6.74 kW and a biomass back-up heating of 10 kW. The biomass heating feeds into a 300-litre boiler which is used for heating and hot water. Access PV energy that cannot be used or stored in the electrical battery is fed into the boiler as well by an electric heating element. Radiators heat the main area and bathroom. The cellar is not specifically heated, however there are gains through equipment present in this area. An overview of the system is given in Figure 9. Originally the system, described in Chapter 2.2.8, also included a solar thermal system, however it represented a significant problem, as the solar energy in summer fed into the boiler was far more than needed. Hence, this led to regular overheating within the unit and therefore was excluded from the concept.

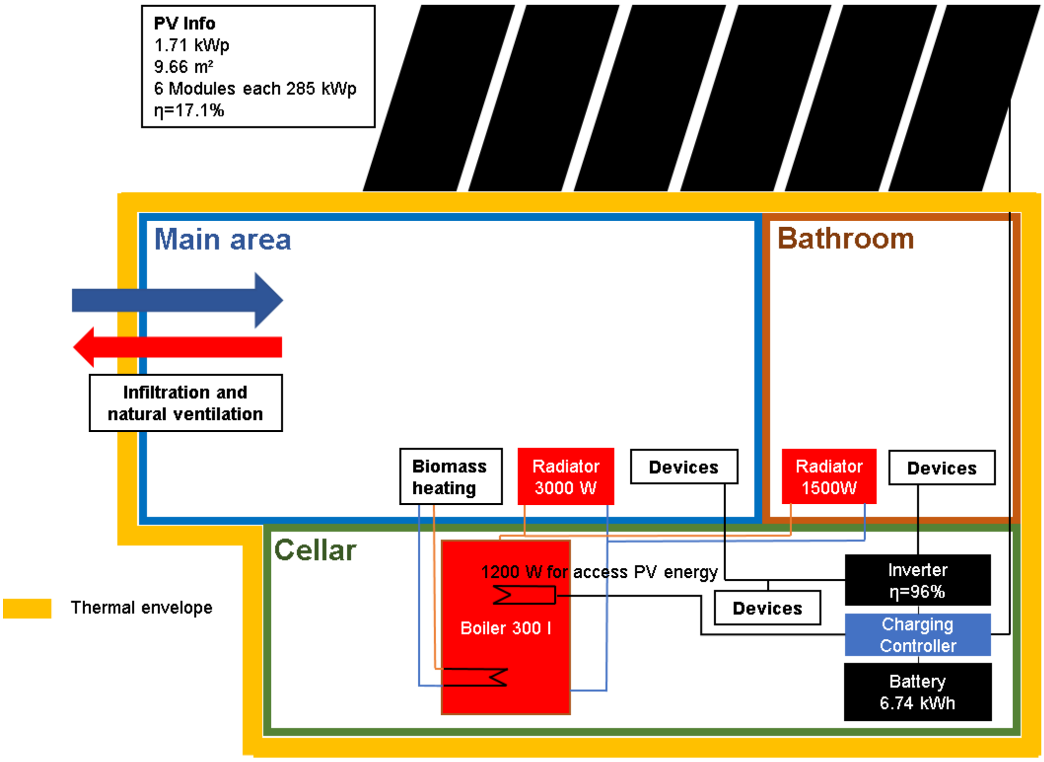

Figure 9: Current set-up of the 'wohnwagon' system

There was no available data on the air tightness of this unit, nor was a blower door test conducted for its evaluation. The unit has no mechanical ventilation system and the fresh air is provided by infiltration and natural ventilation through windows. No data on use patterns of window opening were available.
The wall construction is a light-weight stud-wall construction with sheep wool insulation. Only in the bay area, there is a massive wood construction with sheep wool insulation used. For the floor as well as for the roof a cross laminated timber (CLT) construction with extruded polystyrene foam XPS is used. A summary of the constructions is given in Appendix A.

3.4 Energy simulation

3.4.1 Overview

The used simulation program is EnergyPlus (U.S. Department of Energy's Building Technologies Office 2017). The simulation is run in 15 minutes intervals. The evaluation of the results is carried out hourly. The total evaluation period is one year. The main objective is to attain self-sufficiency with the available space only.

For the simulation, the unit, with the same layout as shown in Figure 8, is separated in three different zones depicted in Figure 10. The ‘main area’ is represented in dark blue, being the biggest zone; the bathroom is shown in orange, and an unheated zone underneath, the cellar, is holding the equipment (light blue colored).

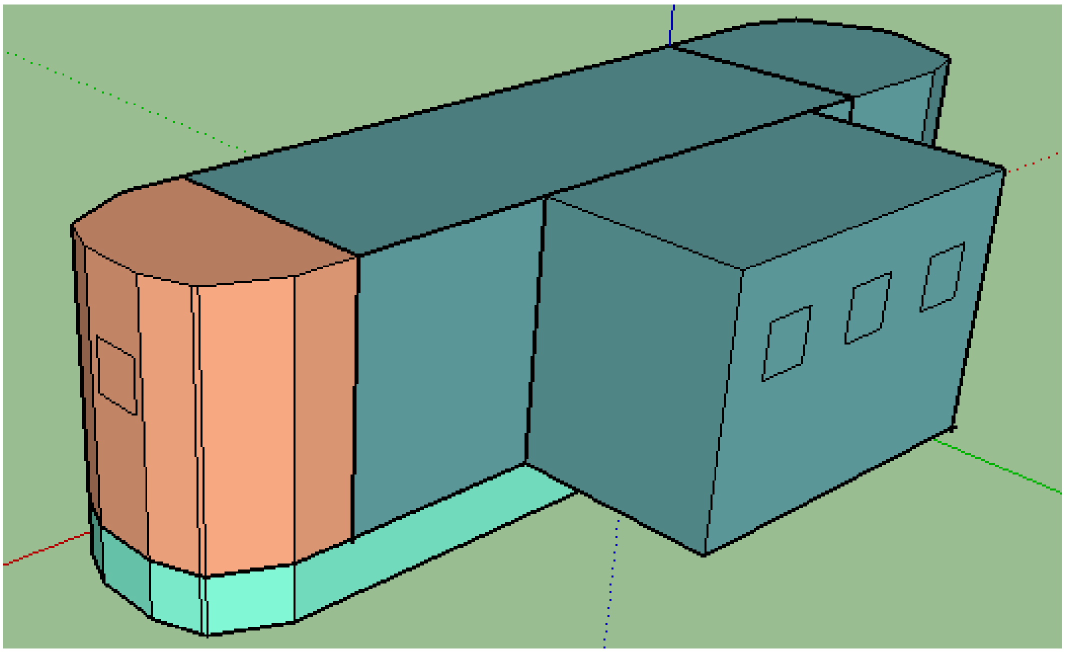

Figure 10: Zoning for simulation in EnergyPlus

The location of the unit is Krems/Donau, Austria, 48.41° N 15.60° E (www.gps-coordinates.net 2017). The weather file was retrieved from the program Meteonorm (Meteotest AG 2018) for the coordinates stated above.

Some simplifications of the model were necessary to allow the modeling within EnergyPlus. The biomass system was excluded because the assumption of the heating profile of such a system would have added significant uncertainties to this work. The heating element in the boiler fed by access photovoltaic electricity when the battery is full was very hard to be model in EnergyPlus. More sophisticated programs are necessary to implement this system which would exceed the scope of this work. Due to these limitations, an approach using only electrical energy production was chosen for this thesis. Deducted from this fundamental decision, the Base Case is a simplified version of the set-up described in the previous Chapter 3.3, meaning the radiators, the biomass heating and the boiler are not considered. Then several improvement steps are explored in Cases 1 to 4, which are in detail discussed in Chapter 3.4.3 to 3.4.6. The size availability limits the sizing of all components. A summary of implemented measures is depicted in Table 3.

Table 3: Simulation matrix

		Base Case	C1 Envelope	C2 Air exchange	C3 Heating system	C4 Energy supply and storage
Thermal envelope	Opaque	Sheep wool insulation	Vacuum insulation panels	Sheep wool insulation	Vacuum insulation panels	Vacuum insulation panels
	Transparent	Double glazing	Vacuum glazing	Double glazing	Vacuum glazing	Vacuum glazing
Air exchange	Natural	If indoor temperature is above 26°C and outside is cooler	If indoor temperature is above 26°C and outside is cooler	If indoor temperature is above 26°C and outside is cooler	If indoor temperature is above 26°C and outside is cooler	If indoor temperature is above 26°C and outside is cooler
	Mechanical	-	-	87% 17.38 m^3h^{-1}	87% 14.4 m^3h^{-1}	87% 14.4 m^3h^{-1}
	Infiltration	$0.27h^{-1}$	$0.27h^{-1}$	$0.005h^{-1}$	$0.005h^{-1}$	$0.005h^{-1}$
Energy supply and storage system	Photovoltaic	1.71 kWp	1.71 kWp	1.71 kWp	1.71 kWp	3.42 kWp
	Battery	6.74 kWh	6.74 kWh	6.74 kWh	6.74 kWh	10.02 kWh
Heating	Air-to-air heat pump	-	-	-	Packed Terminal Heat Pump (PTHP)	-

The analyzed aspects from the electricity point of view are the electrical demand, production, and missing electricity, as the system is off-grid. From the thermal side, the occurring indoor temperatures in the main area are looked at and analyzed if these can fulfill basic comfort requirements. The temperatures in the cellar, are not analyzed as this area is hardly entered. Also the bathroom is not specifically looked at, because the user spends only a very limited time there and it is assumed that temperature fluctuations are accepted in this area.

3.4.2 Base Case

The Base Case is the existent version of the 'wohnwagon' without active heating. A photovoltaic system (1.71 kWp, 9.66 m²) is feeding into a battery storage (6.74 kWh), if no electricity is needed. The electricity is used only for electric devices (including electrical water heating), not for space heating, meaning no active heating systems are used.

The construction is like the original set-up, a cross laminated timber with insulation in the bay zone and a stud wall construction in the rest of the unit, the U-values vary between 0.38 and 0.43 $Wm^{-2}K^{-1}$ for the opaque construction and the double-glazing windows have the following properties: U_g=1.1 $Wm^{-2}K^{-1}$ and U_f=1.5 $Wm^{-2}K^{-1}$. Further details on the construction are given in Chapter 3.5.1 and Appendix A. As no data is available on air tightness, minimum requirements of OIB 6 (Austrian Institute of Construction Engineering 2015) are assumed. Solely by infiltration, 17.71 m^3h^{-1} fresh air can be provided which is more than required by comfort category III (14.4 m^3h^{-1}) (Austrian Standards Institute 2007). Additionally, ventilation between the zones is considered, as the rooms are not tight. To capture some of the nature of human behavior, natural window ventilation is considered above 26°C indoor air temperature in case the outside air temperature is cooler. An overview of the system set-up is shown in Figure 11.

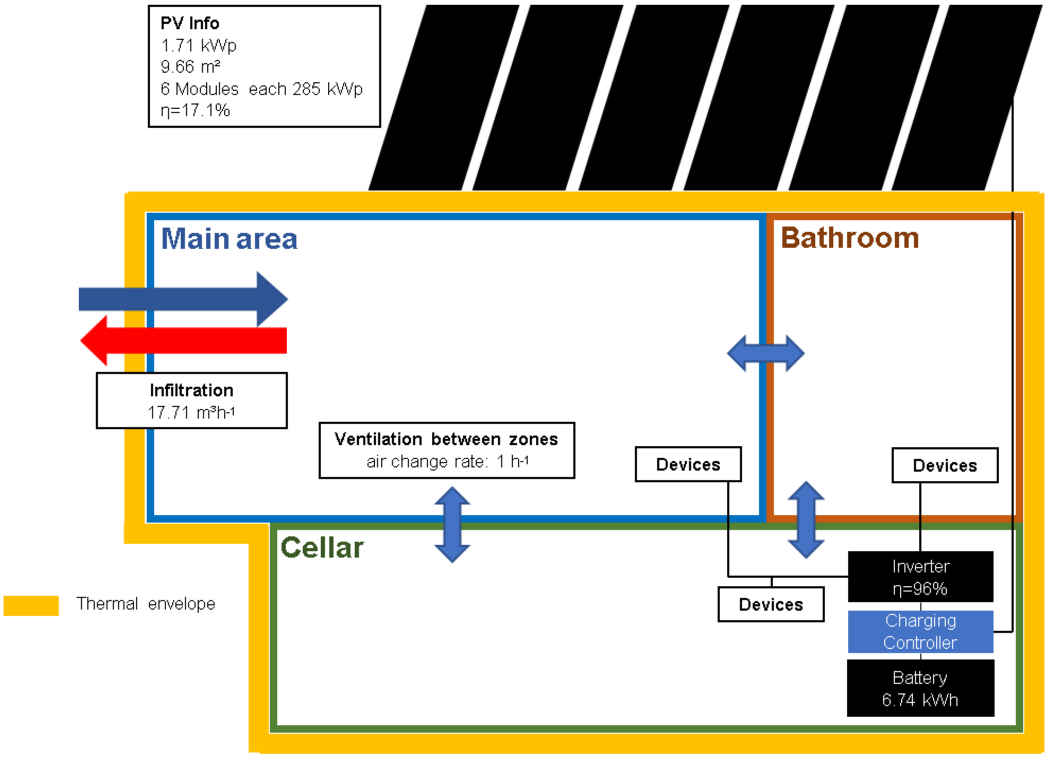

Figure 11: Representation of the Base Case system set-up

3.4.3 Case 1: thermally improved envelope

In Case 1, it shall be analyzed how far the building envelope not exceeding a wall thickness of 20 centimeters can be improved to increase the self-sufficiency of the system. The system set-up is the same as in the Base Case, shown in Figure 11, only the thermal quality of walls and windows is improved. Due to the fact that in this mobile unit the wall thicknesses should be very low to increase the inner space, the U-values of the original constructions are higher than the maximum allowed values according to OIB 6 (Austrian Institute of Construction Engineering 2015). Therefore, other insulation materials like vacuum panels (λ=0.02 $Wm^{-1}K^{-1}$ (Kingspan Group 2017)) shall be analyzed.

To reduce the transmission losses through the transparent elements, triple glazing is not a preferable option, since it is very heavy. Therefore, vacuum double glazing (U_g=0.5 $Wm^{-2}K^{-1}$ (Schneider 2018)) is analyzed as an improvement measure. Also, for the frame an improved U_{frame}-value(U_f) of 0.9 $Wm^{-2}K^{-1}$ is chosen.

3.4.4 Case 2: ventilation and infiltration

In this case, the impact of controlled ventilation with heat recovery shall be analyzed. The question arises, how much energy can be saved through the application of a controlled mechanical ventilation with heat recovery of 87% (Glen Dimplex Deutschland GmbH 2018). A representation of the system is shown in Figure 12.

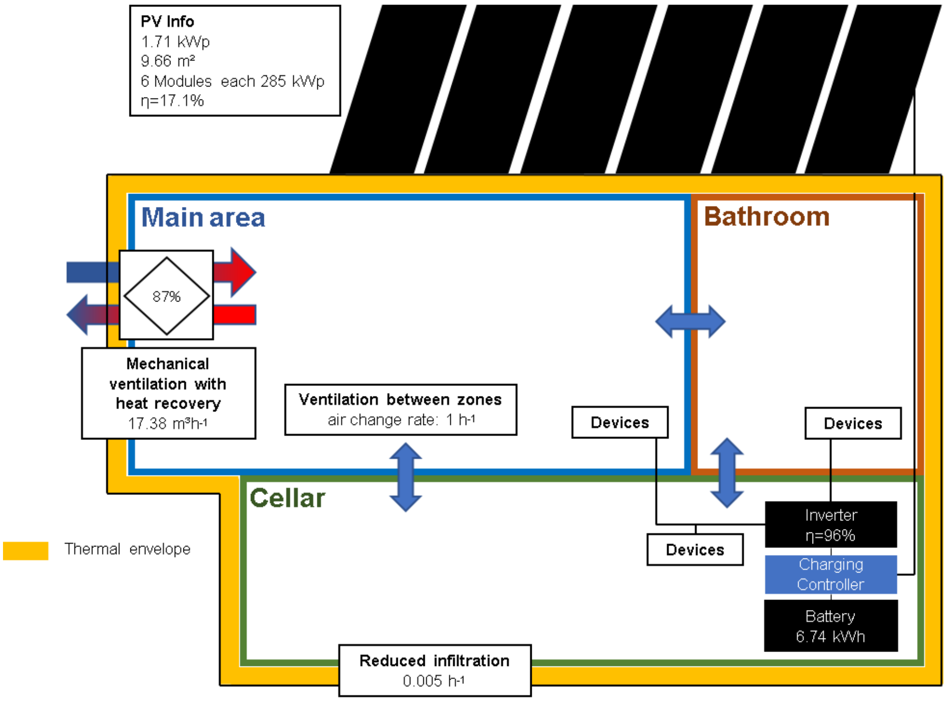

Figure 12: Representation of Case 2 ventilation and infiltration

To allow the comparison between a natural and mechanical ventilation, 17.71 m^3h^{-1} ventilation rate is considered for both systems in total for ventilation and infiltration. At the same time, the air tightness of the unit is increased to the level of a passive house (n_{50} = 0.6 h^{-1}) resulting in an infiltration rate of n = 0.005 h^{-1}. For more details on the calculations see 3.5.1 and formula (4). Still, window opening if the outside temperature is cooler during cooling season is considered.

3.4.5 Case 3: air-to-air heat pump

Using results from Case 1 and 2, an improved building envelope as well as ventilation concept are the basis for Case 3. Heating a space electrically is very exergy consuming. Given the boundary conditions concerning the envelope from the Base Case, a huge photovoltaic system as well as vast storage capacities would be necessary which would go far beyond the limits of the small place provided in and on this unit. Therefore, first, the applications of the improvement measures concerning building envelope and ventilation are essential. Then, in this simulation case, an air-to-air heat pump (Packed Terminal Heat Pump PTHT) is applied, to use the scarce electricity in winter more efficiently than with a direct electric heating. An overview of the system is depicted in Figure 13.

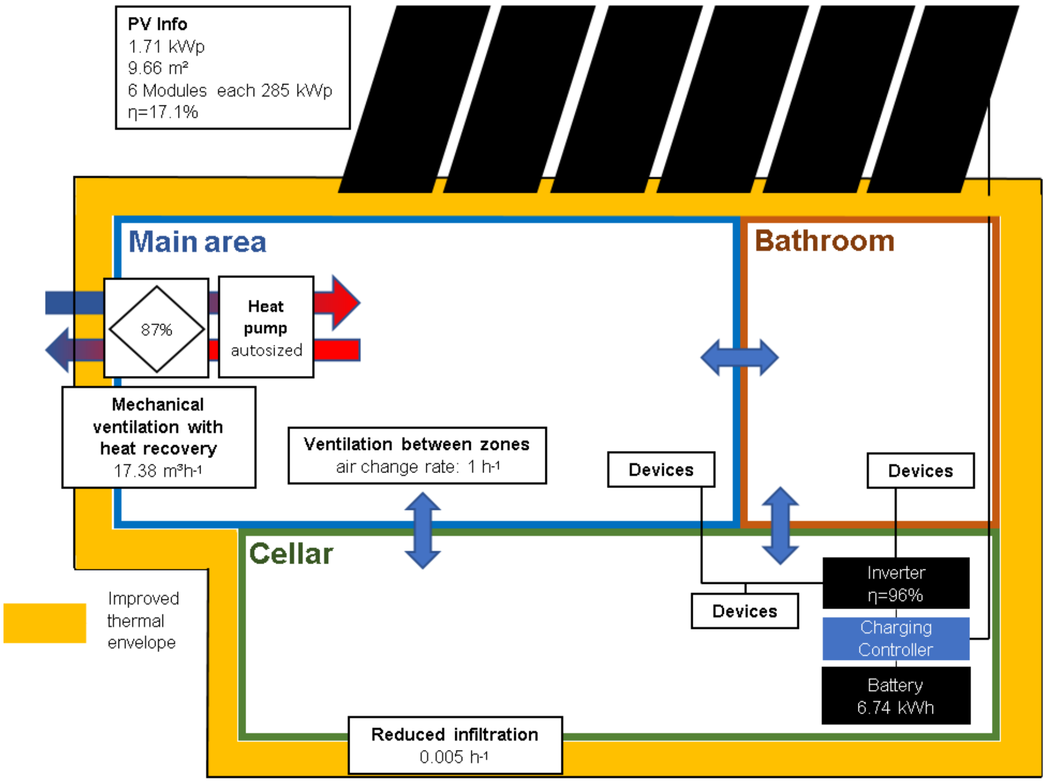

Figure 13: Representation of Case 3 heating system

The PTHP is autosized in EnergyPlus. It shall be checked whether products similar to the auto-sized model are available on the market.

3.4.6 Case 4: energy supply and storage

In the next step, the energy supply and storage systems were increased based on the available space. In this case study, it is important to keep in mind the limited space availability. For the photovoltaic, only the roof area is available. There is space for 6 more photovoltaic modules, resulting in a maximum size of 3.42 kWp. Concerning the battery storage, the size of the battery in the Base Case is 63 cm x 42 cm x 49 cm (BMZ GmbH 2018). As the boiler is not needed anymore in the proposed set-up based on self-produced electricity only, there is potential free space that can be used for an additional battery. The system set-up is identical to the one represented in Figure 13, only that the PV size and battery were increased.

3.5 Input parameters for energy simulation

3.5.1 Building components and envelope

The constructions considered for the simulation are a stud-wall construction with sheep wool insulation and a massive wood construction with external insulation. The applied material is wood, not only because of its ecological advantages but also because of the weight, which is of high importance in the case of a mobile unit, because transportation may be needed from time to time. The decision on which construction is preferable cannot be solely made based on the U-value. Kouba et al. (2002) conducted simulations of different cooling down and heating up processes in different building constructions. As one can expect due to the higher storage mass, the massive construction compared to stud-wall constructions reacted much slower to changing boundary conditions. This depicts a very positive effect in the case of off-grid systems, as a heating outage is not very unlikely.

Standard transmission heat loss calculations are almost solely based on the standardized U-value calculations and the storage capacity of the building is only considered in a very simplified way, according to ÖNROM B 8110-6 (Austrian Standards Institute 2014). The standard calculations are steady state, whereas in reality the constructions are exposed to dynamic boundary conditions of the internal and external environment. Byrne et al. (2017) describe in detail the variations possible concerning convective and radiative surface resistances due to air flow patterns, exposure levels, surface emissivity and the environment, just to mention a few. Also, heat transfer effects are often time dependent, or transient. Boundary conditions can change at a rate which is faster than the building envelope can respond. These are strong arguments for the analysis of construction variations in a self-sufficient system with dynamic methods.

In Table 4, the U-values of the used opaque components are listed. A detailed list of constructions can be found in Appendix A Constructions and materials.

Table 4: Overview U-values of the opaque constructions

Constructions	**U-value [$Wm^{-2}K^{-1}$]**
Exterior wall light weight	0.43 $Wm^{-2}K^{-1}$
Exterior wall massive wood	0.38 $Wm^{-2}K^{-1}$
Roof	0.35 $Wm^{-2}K^{-1}$
Floor – main area	floor to equipment zone – within thermal envelope
Floor – bay	0.31 $Wm^{-2}K^{-1}$
Floor – equipment room	0.25 $Wm^{-2}K^{-1}$

The considered material characteristics are conductivity, density and storage capacity. Humidity of the materials and their variations are not considered in the simulation, however represent interesting further research possibility as at such small space variations of humidity can be strong and humidity is a significant factor concerning the thermal comfort, see ÖNORM EN 15251 (Austrian Standards Institute 2007).

No information on the air tightness is available, therefore minimum n_{50}-values according to the OIB 6 (Austrian Institute of Construction Engineering 2015) were assumed (3 h^{-1} for naturally ventilated buildings). From these values, the infiltration can be derived by formula (4) depending on the shielding of the building (Zeller 2013). The unit is assumed to be exposed to strong winds.

$$n = e * n_{50} \tag{4}$$

e … shielding factor depending on intensity of winds

$e_{weak\ wind}$ … 0.06 [-]

$e_{strong\ wind}$ … 0.09 [-]

This results in an infiltration rate of n being 0.27 h^{-1} for the case of natural ventilation. For the improved envelope, an air tightness level of a passive house of n_{50} = 0.6 h^{-1} is assumed, resulting in an infiltration rate of 0.005 h^{-1}.

The windows are double glazed with 90% Argon filling, resulting in a U-value of 1.1 $Wm^{-2}K^{-1}$. The wooden frames of the windows have a U-value of 1.5 $Wm^{-2}K^{-1}$.

The window quality is improved by vacuum glazing and a better frame. See Table 5 for a summary of the data. There are more and bigger windows which are oriented south to increase the solar gains of the low winter sun. In the summer period, there is an awning used to avoid overheating from May until September.

Table 5: Window data

	U_g	g-value	Visible transmittance	U_f
Original set-up: Double glazing	1.1 $Wm^{-2}K^{-1}$	0.61 - 0.64	0.8	1.5 $Wm^{-2}K^{-1}$
Improved set-up: Vacuum glazing	0.5 $Wm^{-2}K^{-1}$	0.54	0.73	0.9 $Wm^{-2}K^{-1}$

3.5.2 Energy supply concept

As already mentioned in Chapter 3.1, the system consists of a photovoltaic system with a battery storage. The biomass heating, boilers and radiators are not modeled as some sophisticated parts of the system cannot be represented in EnergyPlus. Details on the different systems of the concept are shown in Table 6.

Table 6: Description of the integrated HVAC system components

System components	Description
PV system	6 - 12 BenQ SunVino PV panels mono (285 Wp) (BenQ Group 2017) oriented south (45°C)
Battery storage	6.74 – 20.12 kWh storage capacity, 95% charging/discharging efficiency (BMZ GmbH 2018)
Inverter	The inverter is considered in a simplified way with an efficiency of 94% (Victron Energy B.V. 2018)

For Case 1, the specific panels with this set-up as well as the battery size are taken from the underlying case study unit. Based on the available roof space 6 additional photovoltaic modules were added. For the batteries, according to the manufacturer, in the shell of a same sized battery, storage of 10.06 kWh can be included.

3.5.3 User

The user behavior has a significant impact on the energy demand and is a major factor contributing to uncertainty in building energy use calculations. This case study does not focus on user behavior specifically, as it is a very complex topic currently intensively researched by the EBC (Energy in Buildings and Community) Annex 66 of the International Energy Agency IEA (Lawrence Berkeley National Laboratory 2018). However, it shall not be ignored in this context that defining the user behavior, specifically in a self-sufficient unit, is not trivial. A study shows that the autarky degree[1] of a PV system strongly depends on the electricity percentage used at night hours and winter, which is vastly defined by the user. The higher these proportions the lower the autarky degree (Tjaden, Weniger and Quaschning 2014).

For the assumptions concerning the user behavior, first, the concept of the underlying analyzed object, an off-grid tiny house unit, is looked at. The main motive is the reduction to the minimal lifestyle. Analyzing analytically, if the user wants to live in such a small minimalist space not connected to the electricity grid, it is very likely that this user is willing to reduce the requirements to a minimum, and therefore the energy demand.

As a basis, the data provided (Leukefeld 2016) by wohnwagon (ww wohnwagon GmbH 2018a) was used. Further, it was compared with values given by norms and studies as a reasonableness check. For the occupancy, a simple schedule was assumed based on the assumption of one occupant, who is leaving the house at standard working hours, see Appendix B Schedules and load profiles. For the activity level, the values from the EnergyPlus manual (U.S. Department of Energy's Building Technologies Office 2017) for sleeping, cooking, walking about and cleaning were chosen, see also Appendix D Schedules and load profiles. For the clothing calculation, the dynamic clothing model based on the outside temperature was chosen (U.S. Department of Energy's Building Technologies Office 2017).

Requirements for thermal comfort

As mentioned above, corresponding to the whole concept, the user requirements are reduced to a minimum, meaning the Category III is considered as the basis for simulation and evaluation. It is important to point out that these are very low requirements. When the occupant is not present, the requirements are more relaxed to save energy.

For the heating period, the middle value of 21.5°C (18°C - 25°C) is designated as the heating set-point. The argument for not taking the lowest value derives from the fact that the heating set-point is related to the indoor air temperature solely. However, for the user, the operative temperature consisting of air temperature as well as surface temperature is decisive for human comfort. In winter, if no surface heating is used and the heating set-point is set to 18°C, the operative temperature will not reach 18°C and the comfort category of III will not be reached. A summary of the defined minimum values is given in Table 7.

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[1] The term "autarky degree" is mostly used relating to PV systems is the ratio of self-consumed PV electricity to total used electricity. (Märtel, 2017).

Table 7: Summary of indoor comfort requirements

Requirements	**Occupant present**	**No occupant present**
Heating set-point (air temperature) [°C]	21.5	16
Heating period temperatures acceptable range according to EN15251 (Austrian Standards Institute 2007) [°C]	18 – 25 according to category III, EN15251 (Austrian Standards Institute 2007)	-
Summer temperatures: acceptable range for naturally ventilated buildings according to EN15251 (Austrian Standards Institute 2007) [°C]	ϑ_{in}=0.33*ϑ_{ex}+18.8; +/-4 according to category III, EN15251 (Austrian Standards Institute 2007)	-
Air flow people [ls-1p-1]	4 (this volume flow maintains 1200 ppm) according to category III, EN15251 (Austrian Standards Institute 2007)	Infiltration only

Electrical devices

There exists no information on user behavior in the OIB 6 directive on energy saving and thermal insulation (Austrian Institute of Construction Engineering 2015). The Austrian Standards Institute specifies 3.75 Wm^{-2} for the inner gains, including occupants, lighting and electrical equipment. However, this is a constant value and does not capture dynamic variations over the day. Furthermore, the fact must be considered that the calculations are referring to average living areas, which for Austria would be 44.6 m² per capita (Statistik Austria 2017). This value is 1.7 times higher than the living space available in this case study (27 m²). In general, calculations based on the floor area can hardly be applied here, as these refer to average living areas. Therefore, other inputs for the calculation must be chosen. The energy use was based on the electric consumption assessment from the energy certificate provided (Leukefeld 2016), verified and corrected by information from Ziegler (2016). A list of implemented devices is represented in Table 8.

Table 8: Devices and energy use for simulation

Device	Power [W]	Usage
Mobile phone charging	10	3 h per day
Notebook[2]	50	6 h per day
Kettle[3]	2000	0.125 h per day
Refrigerator	125	2 h per day
Measurement devices and pumps	10	24 h per day
Washing machine (washing/skidding)[4]	50/200	4.5 h per week
Kitchen device[2]	50	0.25 h per day
Hairdryer or other[2,5]	1600	0.25 h per week

A significant amount of the energy used by washing machines is used for heating up water. To reduce the electricity demand, the washing machine is connected to the hot water system. Based on the surveyed running times by Ziegler (2016), one washing per week is assumed (2.25 h) during the mid-morning hours on the weekend. The power of 50 W was measured during washing and 200 W for skidding[4].

Estimating the energy demand of the fridge is not trivial and strongly dependent on the user behavior (frequency of opening the door; the temperature of the food put inside). As it was not possible to find measured load profiles, assumptions must be made. According to the producer, 254 Wh in 24 hours are consumed (Liebherr Hausgeräte GmbH 2018). It is not exactly known under which testing conditions these manufacturer specifications were conducted, still these are the only data available. By dividing the energy demand by the number of assumed hours of running (Leukefeld 2016), the power is derived. The running times are distributed over the day in 15 minutes periods, the same as the simulation intervals.

According to the research by Ziegler (2016), one to three kitchen appliances per person, each with a power of about 50 W, can be assumed in an average household. Here, one appliance per household is used, as the cattle is already considered separately. This could be a coffee machine, a mixer, a blender, a toaster, etc. Given the fact of the limited space, this number is rather over- than underestimated. For the running time of these devices, 15 min per day are assumed, based on reasonable thinking as no data on use time of small kitchen devices was found.

Furthermore, there are typically another two household appliances per household (Ziegler 2016). Looking closer at this fact, different household appliances must be

[2] Added or altered based on Ziegler, 2016)
[3] arendo (2018)
[4] Based on conducted measurements
[5] Braun, 2018)

thought through to decide whether these might be used on a small space. Typical household appliances are: fridge – already considered separately; vacuum cleaner – very unlikely to be used on such a small place; iron – possible; hairdryer – is considered once a week, also representative for other small household devices. According to Ziegler (2016), there is usually one entertainment device per household (TV not included). However, this was neglected because of limited space, and smaller entertainment devices like portable speakers do consume very little energy. For an internet device, no appropriate data was found.
A significant percentage of people do not have a dryer or microwave (Ziegler 2016), hence these were not considered. Although one to two TVs per household are considered as a standard (Ziegler 2016), due to energy efficiency and space reasons, these were not taken into account. However, the number of notebooks were intentionally overestimated, (usually zero to 1.5 notebooks per person (Ziegler 2016)) as nowadays people often use notebooks for watching TV, movies, etc.

Lighting

The lighting regulation is modeled depending on the exterior lighting. According to Zumtobel Lighting GmbH (2016), lighting levels for the main area (300 lx) and bathroom (200 lx) were assigned; availability of light is dependent on occupancy hours and sleeping hours. In total, 10 LED lights (7 in the main room and three in the bathroom) are mounted in the unit, each consuming a power of 6 W.

Cooking

Analyzing the examples of self-sufficient buildings from Chapter 2.2, the cooking part is one of the challenging aspects of this concept. The approach of the Monte Rosa hut described in Chapter 2.2.4 does not consider cooking in the energy balance; others use cooking solutions based on gas, biogas, thermal oil or wood. Electric stoves need a power of around 1500W per one cooktop. Having for example two cooktops makes the electric stove the device with the highest power i.e. three kilowatt, compared to other devices listed in Table 8. The assumptions concerning the electric stove would impact the results significantly (energy use and internal gains) and would add to uncertainty of the model. No sufficient prior research work was found to allow a solid base for assumptions. It is challenging to find cooking systems for self-sufficient solutions that meet convenience desired today. Cooking is an aspect that is strongly dependent on personal preferences. Therefore, cooking is excluded from the model.

Hot water

Concerning the hot water demand, the Austrian Standards Institute (2011) states in ÖNROM B 8110-5 that 35 Whm^{-2}d^{-1} warm water heating demand is required. The water temperature levels are based on Ziegler (2016), 45°C for domestic hot water temperature and 10°C for supply water temperature. The calculations for the underlying unit can be depicted as follows:

$$\frac{energy}{m^2\,day} * area = c_{p-Water} * \Delta T * kg$$
$$\frac{35\,Wh}{m^2 d} * 27\,m^2 = \frac{4182\,J}{kg\,K} * (45-10)\,K * X\,kg \qquad (5)$$
$$\frac{35\,W * 3600\,s}{m^2 d} * 24\,m^2 * \frac{kgK}{4182\,J} * \frac{1}{35\,K} = 23\,kg \approx 23\,l$$

As discussed above, square-meter-based calculations for energy demand may underestimate the energy use. Therefore, this number is compared to other sources. It can be seen, that the value of 20 liters is also stated in the provided energy certificate (Leukefeld 2016). Ziegler (2016) reviewed different models for domestic hot water demand and provided a summary presented in Table 9. The water demand for bathing was excluded as no bath tub is present in the example.

Table 9: Domestic hot water use

	Short load (e. g. washing hands)	**Medium load (e. g. cooking)**	**Shower**
Flow rate [l/min]	1	6	8
Mean draw off [l/day]	1	6	40

Based on a study conducted in Vienna using 1000 questionnaires, people shower 4 to 10 times a week (Ziegler 2016). Further, Ziegler (2016) states that the probability for showers is highest between 06:00 and 08:00 a.m. and the probability for short and medium load is evenly distributed between 05:00 a.m. and 10:00 p.m.. Based on these sources, it is assumed that a shower is taken every day at 06:30 p.m., using 20 liters of water. These numbers are representative for either very short showers or showers just taken every two days. The rest of the water use (one liters for short load and six liters for medium load) is spent in the evening at 6:00 p.m. due to simplification reasons. The applied water over the day use is shown in Figure 14.

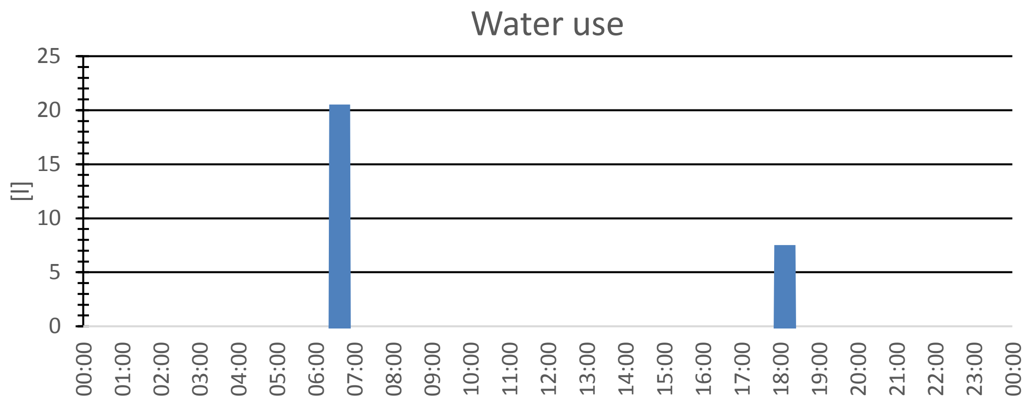


Figure 14: Water use over the day

In the real case unit, biomass and excess photovoltaic electricity supply the domestic hot water system. However, these mechanisms are excluded from the simulation as explained in Chapter 3.1 and are replaced by electric heating methods. An efficiency of 100% is assumed.

The exact load profiles used in the simulation can be found in Appendix D Schedules and load profiles.

3.6 Performance evaluation

3.6.1 General

The state-of-the-art performance evaluation is using energy ratings described in "ÖNORM EN 15603 – Energy performance of buildings – Overall energy use and definition of energy ratings" (Austrian Standards Institute 2008). However, the question arises, whether this is a sensible approach in the case of self-sufficient buildings. As energy ratings do not manage to represent net-ZEB buildings in a reasonable way, neither will they represent sensible information about the quality of self-sufficient buildings.

For the evaluation of the cases presented in Chapters 3.4.2 to 3.4.6, quantification methods are necessary. If it shall be examined how to evaluate a self-sufficient system in the true meaning of the word, implying that it is not connected to the grid, the real question of "Does it work?" arises. This question is answered for electricity in Chapter 3.6.2 and for thermal conditions in Chapter 3.6.3. Calculations are conducted separately for thermal conditions and for electricity to give more transparency where the self-sufficiency concept cannot be fulfilled.

The results were evaluated with MATLAB (The MathWorks 2017), represented in graphs, and discussed giving possible reasons for the outcomes.

Concerning the thermal as well as the electrical self-sufficiency ratio, is it indeed necessary to reach a ratio of 100%? In order to obtain self-sufficiency at any time, the system would have to be designed for the most challenging day(s) of the year, making equipment capacities necessary that are not usually needed. The author wants to specifically emphasize on ‘sufficiency’ as part of the word ‘self-sufficiency’. However, it is difficult to decide on where to set the line.

It shall be defined for this work that a system that can provide self-sufficiency 99% of the time, is still considered self-sufficient. The value 99% is equivalent to four days in total in which comfort requirements are not met or 1% of the electricity demand over the year cannot be covered. These numbers seem like a manageable and acceptable measure. However, similar values were only found to be addressed in one other paper (Baumgartner and Ambrosetti 2010), where 90% self-sufficiency is set as design specification. This is not considered as sufficient for this study case, as 10% correspond to 36 days of the year in total where the comfort requirements are not met or not enough electricity is available.

3.6.2 Energy self-sufficiency

“To work”, from the point of view of electricity, constitutes the availability of electricity. The electrical energy self-sufficiency degree is also used by Märtel (2017) for photovoltaic systems. McKenna et al. (2015) employ this term for the quantification of the self-supply of a region. The maximum value possible is 100%, as all the generated power exceeding the load is considered part of the electricity grid, unlike this happens in methods that balance the energy over the year. The annual balance over the year does not express whether the system is working or not, therefore is not used as a criterion for the evaluation of the self-sufficient system. Based on the underlying literature, a ratio of produced energy used on-site to the total energy demand is deducted, shown in Equation (6).

$$f_{electric\ self-sufficiency} = \frac{E_{used}}{E_{energy\ demand}} \tag{6}$$

or

$$f_{electric\ self-sufficiency} = \frac{E_{energy\ demand} - E_{lacking}}{E_{energy\ demand}}$$

$$f_{electric\ self-sufficiency} = 1 - \frac{E_{lacking}}{E_{energy\ demand}}$$

$f_{electric\ self-sufficiency}$ … degree of electrical energy self-sufficiency

E … energy

The energy surplus that is produced and cannot be used on site, hence, has no importance for the evaluation.

3.6.3 Thermal self-sufficiency

“To work”, from the point of view of thermal comfort, constitutes the availability a certain comfortable indoor environment. The daylight autonomy (nbi new buildings institute 2018) served as the basis for the Equation (7). It gives the percentage of the time the system can create comfortable conditions without external energy supply.

$$f_{thermal\ self-sufficiency,\ III} = \frac{h_{within\ comfort\ requirements,\ Cat\ III}}{h_{the\ occupant\ is\ present}} \tag{7}$$

$f_{\text{thermal self-sufficiency, III}}$ … degree of thermal energy self-sufficiency for category III according to ÖNORM EN15251 (Austrian Standards Institute 2007)

h … hours

The index ‘within the comfort requirements’ in Equation (7) is pointing toward the comfort category according to ÖNROM EN15251 (Austrian Standards Institute 2007) determined in Chapter 3.5.3. Table 10 shows the depiction of thermal environment categorization in ÖNROM EN 15251 (Austrian Standards Institute 2007).

Table 10: Quality of indoor environment in percent according to four categories

Percentage	**15**		**7**	**58**	**20**
Thermal environment	IV	IV	III	II	I

This manner of representation is also used to give an overview of the temperature distribution over the whole year.

4 RESULTS AND DISCUSSION

4.1 Base Case

With the Base Case set-up, an electrical self-sufficiency of 93% and a thermal self-sufficiency of 56% was achieved.

The electrical self-sufficiency degree is already very close to the desired 99%, although achieving these last percent may be very difficult. The facility produces enough electricity e.g. in December, as can be seen in Figure 15, however the storage capacity is not sufficient to store the access energy for the period where the photovoltaic system is not providing to meet the entire demand.

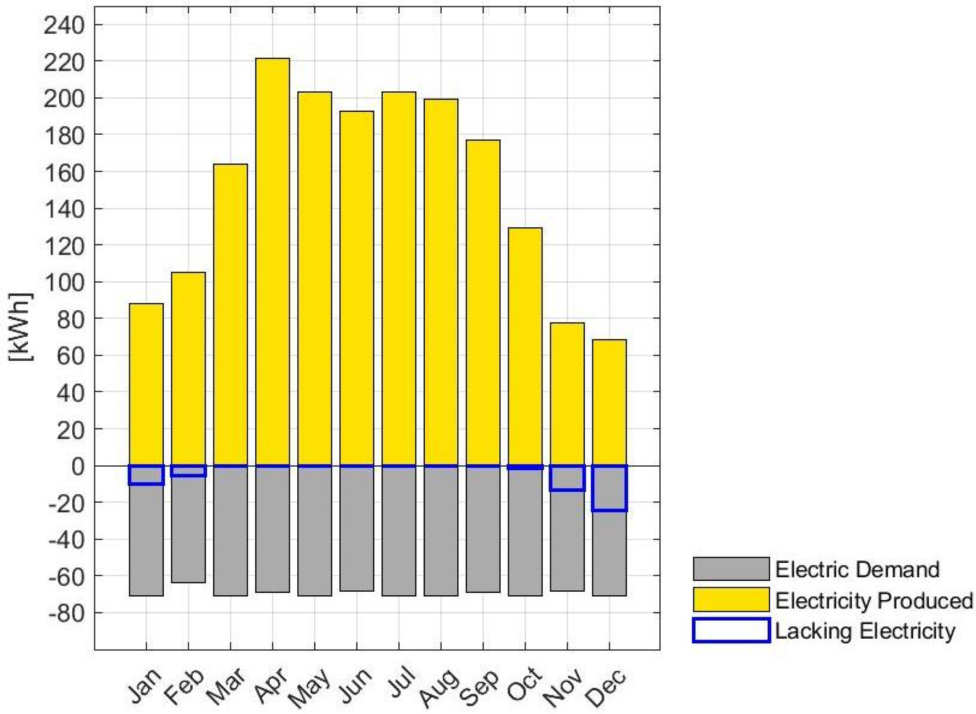


Figure 15: Electric demand, production, and shortage of electricity per month, BC, electrical self-sufficiency of 93%

The storage capacity in the base case is 6.74 kWh, however, only 80%, i.e. 5.4 kWh of it can be used to avoid damage to the battery. An average daily energy demand for electric equipment is 2.3 kWh per day, meaning that a fully charged battery can hold the energy for 2.3 days, which is evidently not sufficient. However, between March and October, full self-sufficiency is achieved.

Concerning the thermal environment, Figure 16 shows that most of the time during the year at the location Krems/Donau, the temperatures are cold and heating is required. Only during the summer months of June, July and August, the temperatures oscillate around the minimum required comfort temperature by the ÖNORM EN15251 (Austrian Standards Institute 2007).

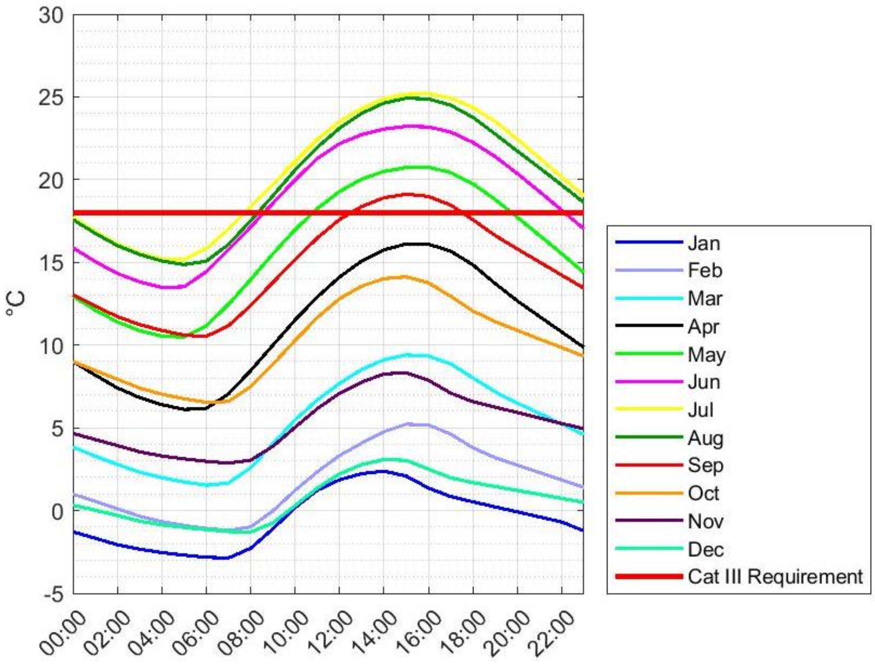


Figure 16: Average day for each month of the year

Concerning the thermal self-sufficiency, the achieved 56% ratio is very low. Specifically, looking at the months of November to February in Figure 17, the temperature is below 18°C for more than 90% of the time, which corresponds to thermal category IV. These temperatures should only be accepted for a very limited part of the year (Austrian Standards Institute 2007).

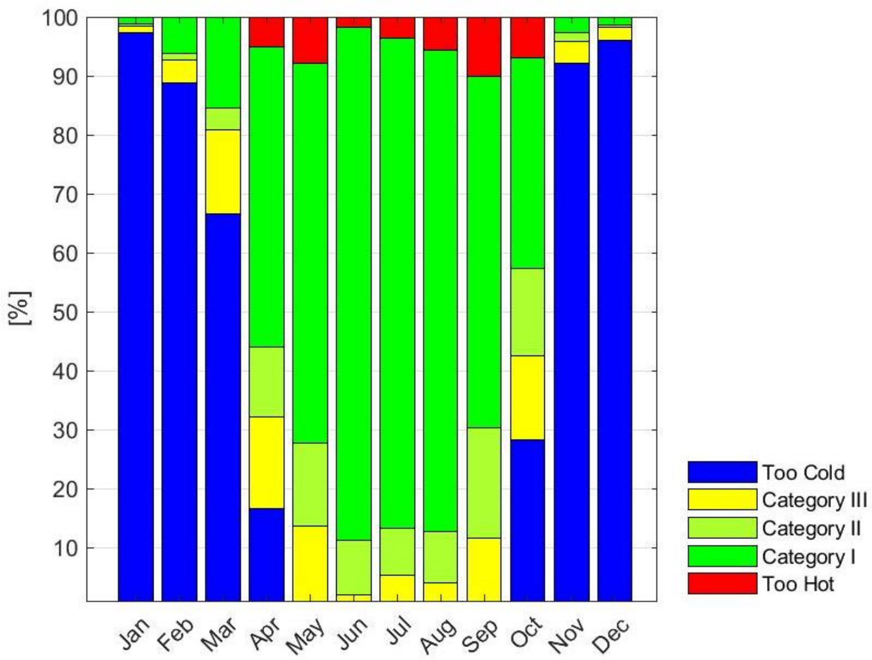


Figure 17: Evaluation of indoor temperatures according to thermal categories, BC, thermal self-sufficiency 56%

The results show that an active heating system is necessary to maintain an acceptable indoor climate in the case study object, and solely passive methods like inner and solar gains are not enough to fulfill the self-sufficiency requirements defined in Chapter 3.5.3 and 3.6.2. However, for the months of May to September, self-sufficiency above 90 % was fulfilled.

4.2 Case 1: envelope

When the envelope is improved with sophisticated materials like vacuum glazing and vacuum insulation panels, the thermal self-sufficiency can be improved to 66%. The massive wood construction with vacuum insulation (W5), also having the best U-value, shows the best performance, as depicted in Figure 18. A summary of the key information about the constructions is given in Table 11. Through the implemented changes on the building envelope, the self-sufficiency was raised by 10%. As 1% of the time corresponds to 3.6 days, this means that for 36 days, the comfort requirements were additionally met. Evidently, the electrical self-sufficiency stays the same.

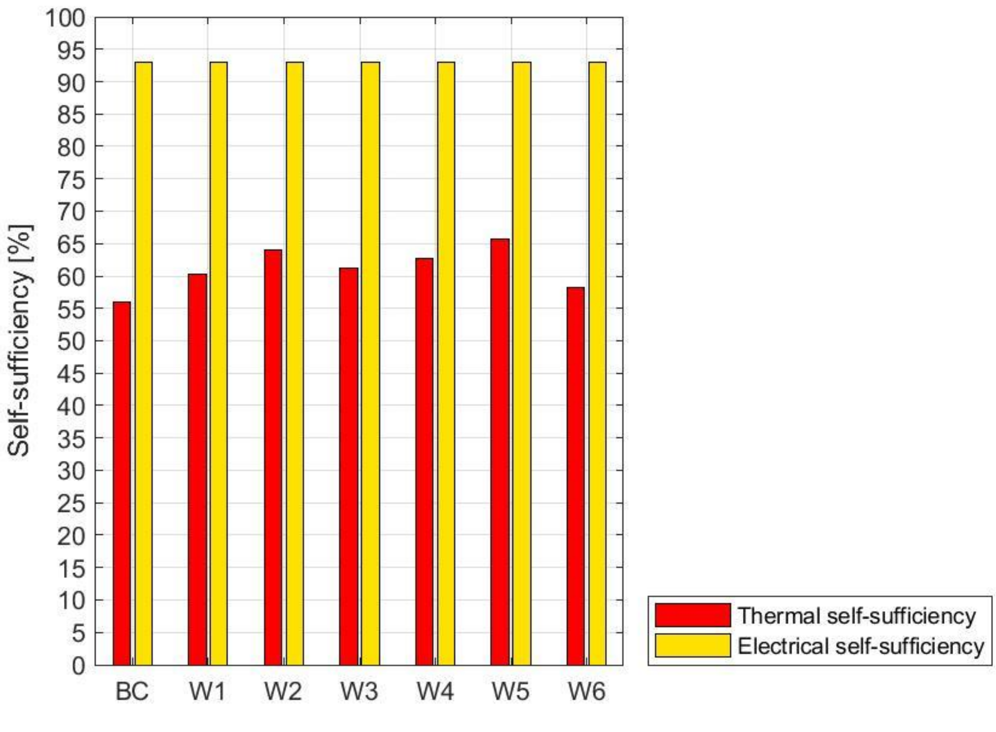


Figure 18: Thermal and electrical self-sufficiency as a function of different constructions

Still, 34% of the time – meaning nearly 4 months of the year – the comfort requirements are not met, and this is far beyond acceptable. However, the question arises, why such innovative materials have nearly no impact on the system's self-sufficiency. The reason for this is the fact, that if no active heating is present and the gains are not high enough to cover the demand, eventually the indoor temperature will fall in correspondence to the outside temperature. Also, in the case of a good thermal envelope, a cooling-out will take place, even if this occurs at a much slower rate.

Table 11: Overview of the simulated constructions

Construction name	**BC**	**W1**	**W2**	**W3**	**W4**	**W5**	**W6**
Thermal self-sufficiency [%]	56%	60%	63%	61%	63%	66%	58%
Description (only layers used for thermal simulation)	Mix of different wall types (W1, W2, W3, etc.)	wood-stud construction with sheep wool insulation, cladding on outside and inside	CLT with sheep wool insulation and larch cladding	wood stud construction with sheep wool insulation, cladding on outside and inside and clay plaster	wood stud construction with vacuum insulation, cladding on outside and inside	CLT with vacuum insulation and larch cladding	CLT only
Thickness [cm]	13.6 - 20	13.6	20	14.1	13.6	20	20
U-value [$Wm^{-2}K^{-1}$]	0.38 - 0.43	0.43	0.38	0.43	0.35	0.33	0.59

One construction is especially worth mentioning, namely the massive wood construction. Although the U-value is significantly higher than in other constructions, the performance is better than in the base case. As pointed out by Kouba et al. (2002), the U-value alone does not determine the thermal performance of the construction. Still, for the Case 3, the W5 construction is chosen, as it provides the highest self-sufficiency rates.

4.3 Case 2: ventilation and infiltration

With the implementation of a controlled ventilation system with heat recovery in the Base Case set-up, the thermal self-sufficiency can be improved to 59%. Despite the additional energy demand for a compact single room ventilation system, the electrical self-sufficiency degree did not change. This can be explained due to the fact that small ventilation devices consume very little energy; the fan consumes only 7 W for the required ventilation rate (Glen Dimplex Deutschland GmbH 2011), which has no impact on the self-sufficiency rate.

Additionally, the thermal self-sufficiency can only be improved by 3%. The reason is identical to the case of the improved building envelope. If the gains are not high enough to cover the losses, the system will cool down in correspondence to the outside boundary conditions. The temperature distribution over the year is shown in Figure 19, where it can be seen that the controlled ventilation has an especially positive impact in the summer months.

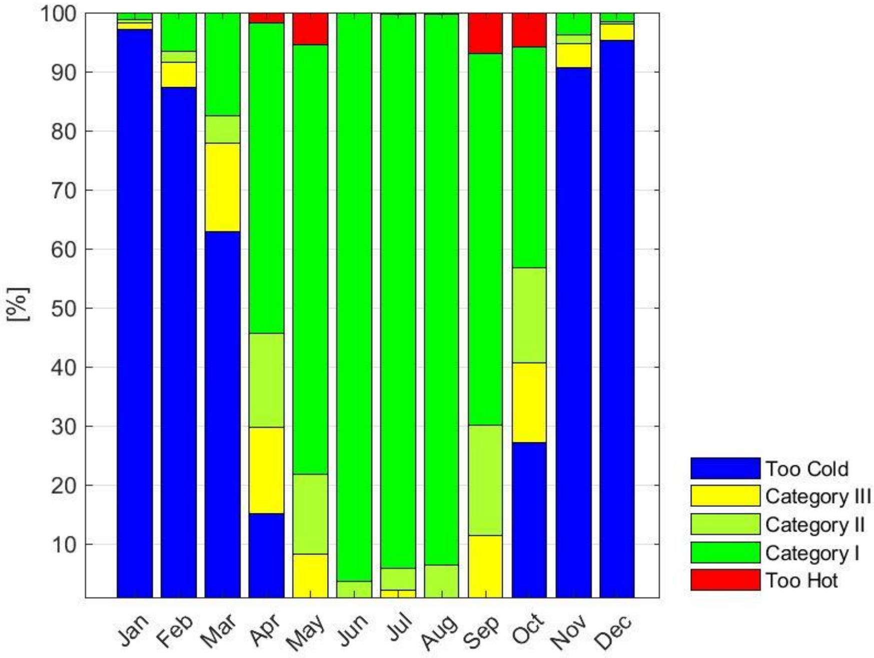


Figure 19: Evaluation of indoor temperatures according to thermal categories, C2, thermal self-sufficiency 59%

Figure 20 shows that the impact of implementing a ventilation system with heat recovery as well as improved air-tightness (see BC improved) does increase the self-sufficiency by 3%.

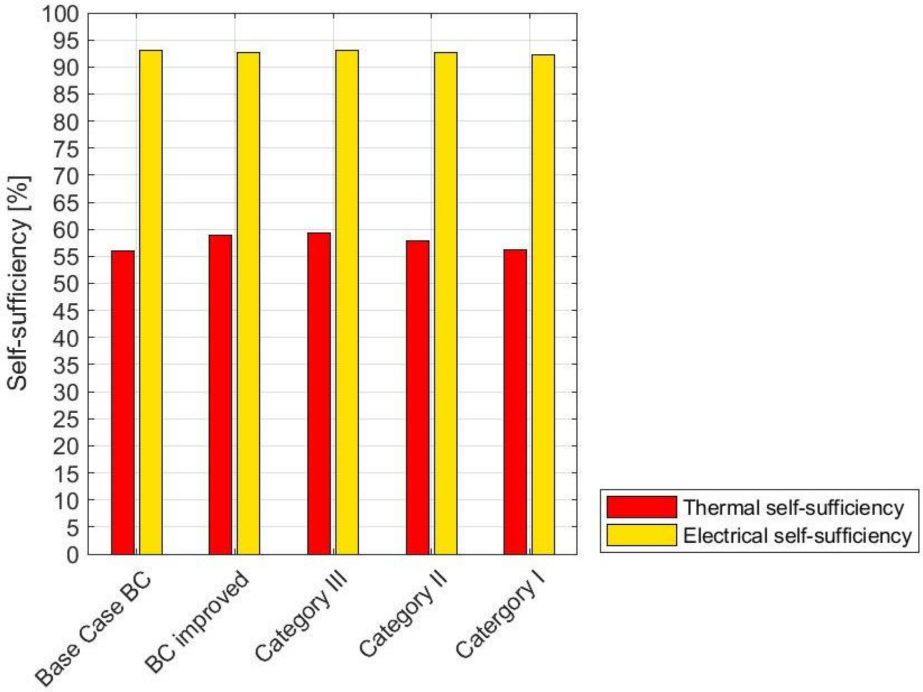


Figure 20: Self-sufficiency depending on air-tightness and ventilation rates

4.4 Case 3: heating system

In the case of using an air-to-air heat pump with a Coefficient of Performance (COP) of 4 (Zimmermann Lüftungs- und Wärmesysteme 2018) for heating and cooling, a system was sized with a heating load of 1.7 kW and a cooling load of 1 kW. The advantage of using a heat pump can be explained by the fact that with the use of little electrical energy, ambient heat can be transformed to a much higher temperature level and “more” thermal energy can be introduced to the room than with a direct electrical heating. Comparing the sized system to existent air-to-air heat pumps, systems with similar heating and cooling loads exist. However, the volume flow is higher than in the simulated example, i.e. 60 m^3h^{-1} to 15 m^3h^{-1} (Glen Dimplex Deutschland GmbH 2011; Zimmermann Lüftungs- und Wärmesysteme 2018). A thermal self-sufficiency of 100% was attained, however the electrical self-sufficiency was reduced to 49%. Figure 21 shows that the demand in December is four times as high as the produced electricity. Additionally, Figure 22 shows that all the temperatures are within the accepted comfort classes.

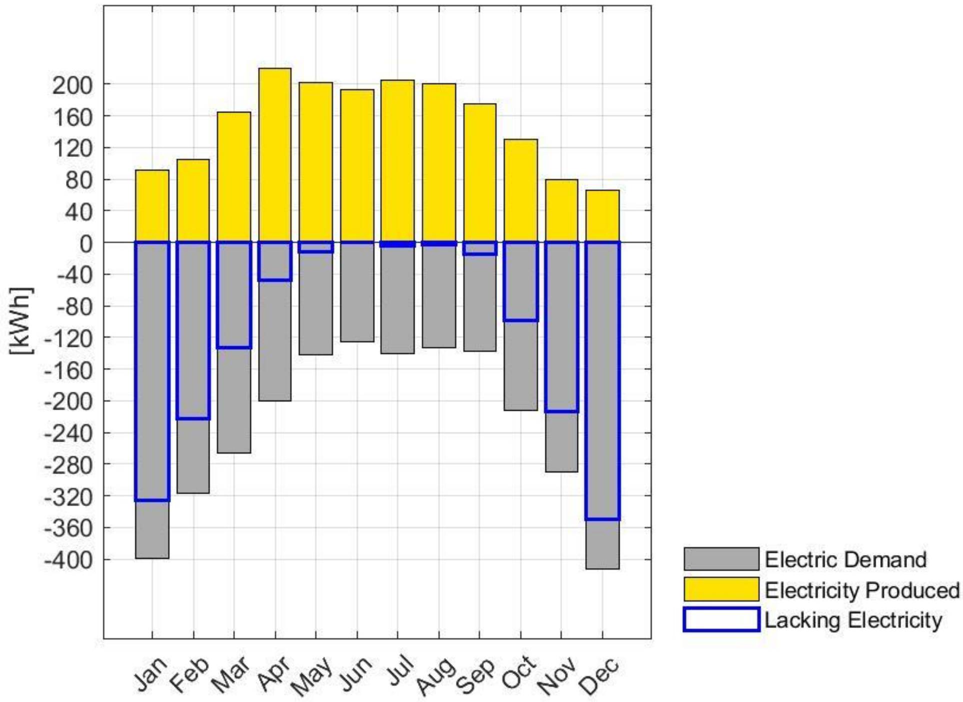


Figure 21: Electric demand, production, and shortage of electricity per month, C3, electrical self-sufficiency 49%

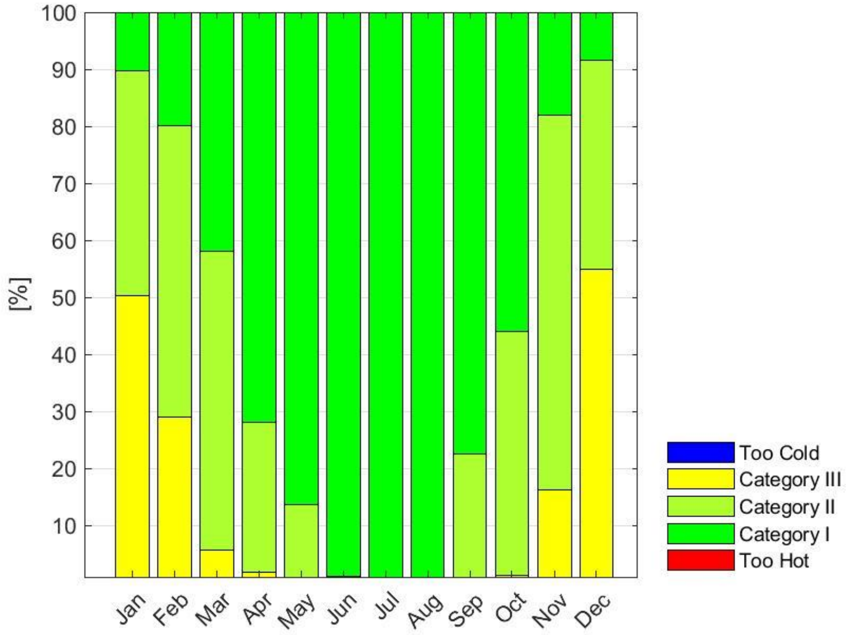


Figure 22: Evaluation of indoor temperatures according to thermal categories, C3, thermal self-sufficiency 100%

Through these results we can see that the thermal and electrical self-sufficiency have to be brought into a certain balance. Especially, in the case of a system based solely on self-produced electricity, a very high thermal self-sufficiency makes it difficult to accomplish high values of electrical self-sufficiency. Therefore, the heating set-point was variated, as can be seen in Figure 23.

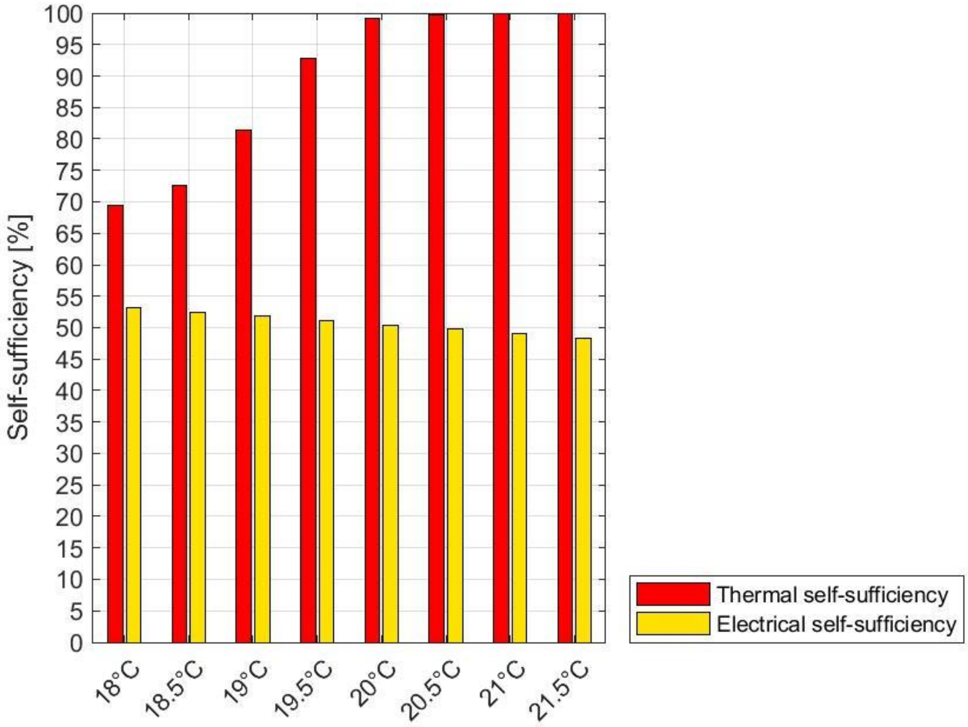


Figure 23: Self-sufficiency as a function of the heating setpoint

As can be derived from Figure 23, even if the thermal self-sufficiency is decreased to 99%, by choosing a setpoint of 20°C room temperature, the electrical self-sufficiency is still as low as 51%. It is remarking that by increasing the setpoint by 2 Kelvin, the thermal self-sufficiency increases dramatically from 69% to 99%, however the electrical self-sufficiency decreases only by 3%, from 53% to 51%. These results show that the setpoint has a significant positive impact on the thermal self-sufficiency without diminishing the electrical self-sufficiency considerably.

4.5 Case 4: energy supply

As it was already evident in the previous Chapter 4.4, the photovoltaic system is far from producing enough electricity to provide the energy required for the heat pump. The production would need to be 4.4 times higher, leading to an increase of photovoltaic surface to at least 43 m². This would require double the space available, which is contradictory to the boundary conditions set in the beginning. Therefore, it is focused on how 99% electrical self-sufficiency for the electrical equipment and hot water can be obtained.

As discussed in Chapter 4.1, enough electricity is produced over the months in winter, however, electricity demand cannot be met due to the fact that storage capacities are exhausted. Because of this, in a first attempt, different battery sizes are analyzed (Figure 24). The same batteries were used as in the Base Case, varying the capacities to analyze the effects (BMZ GmbH 2018).

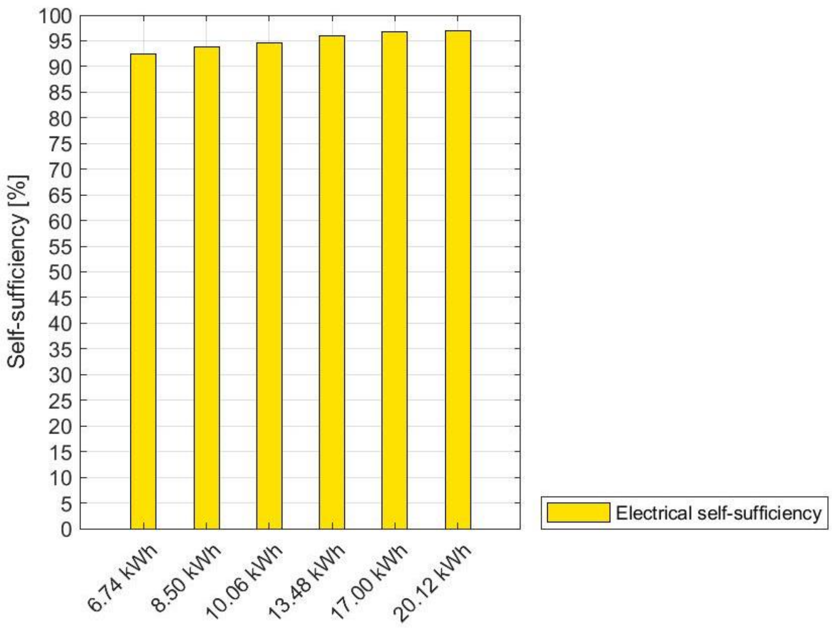


Figure 24: Electrical self-sufficiency dependent on electrical storage size

It can be seen that even increasing the battery size nearly threefold has hardly any impact on the overall self-sufficiency of the system. This can be further explained through Figure 25, showing that the discharging takes place at a much faster rate than the battery can be recharged.

For example, between the 18th and the 25th of December, not sufficient energy can be produced as the solar radiation is very low. Between the 23rd and the 25th of December, no electricity at all is produced and as the battery is already empty as there was not enough insolation in the previous days to fully fill up the batteries. It can be followed that a bigger photovoltaic system is needed.

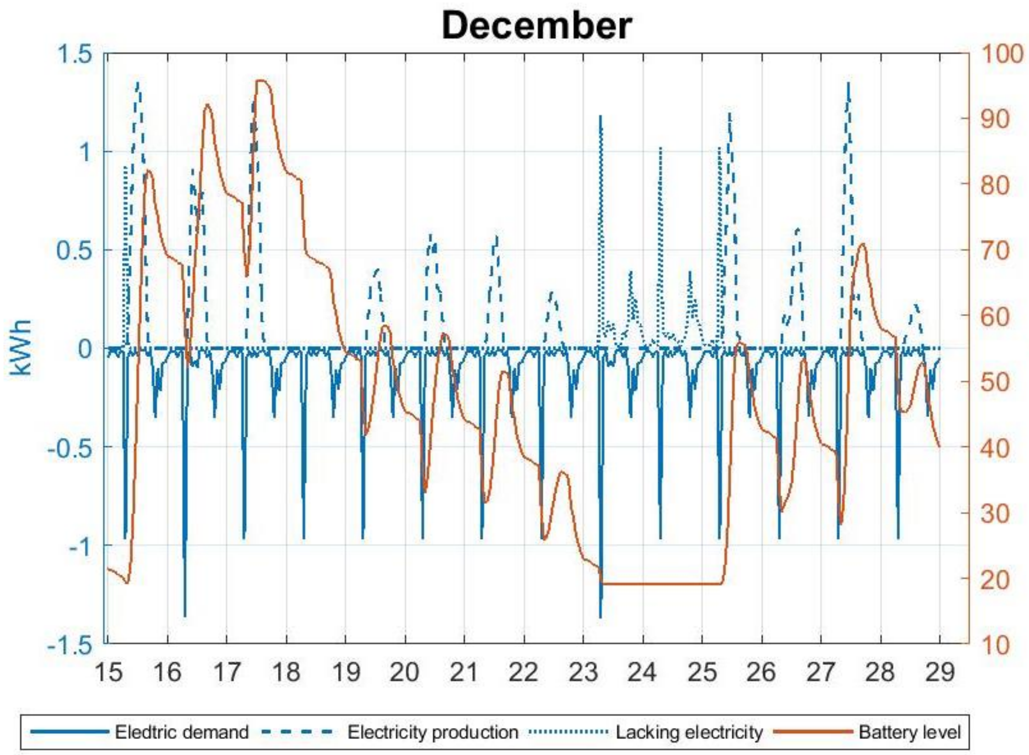


Figure 25: Charging and discharging of the battery in December

The impact of the size variations of the PV system are shown in Figure 26. Through the increase of the PV to double the area – which would cover the maximum surface available – an electrical self-sufficiency of 99% can be achieved with a battery capacity of 10.06 kWh.

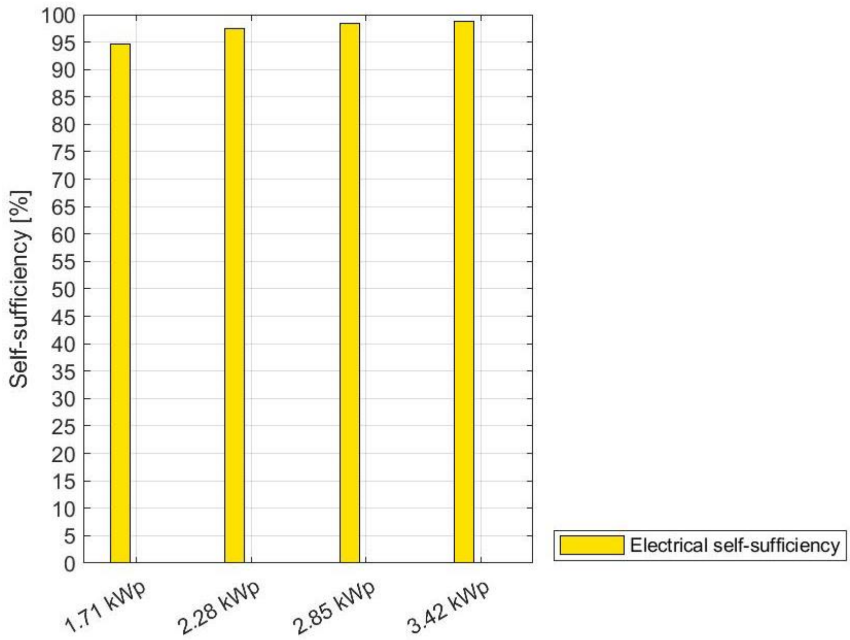


Figure 26: Electrical self-sufficiency dependent on photovoltaic size with a battery storage of 10.06 kWh

4.6 Summary

The obtained results show that a solely electrical set-up according to the state-of-the-art technologies does not allow for a self-sufficient off-grid unit. As an optimum, a solution of 99% electrical and 66% thermal self-sufficiency can be achieved, or alternatively 99 % thermal and 51% electrical self-sufficiency. This means, however, that the defined and already rather loose comfort requirements are not met for a significant part of the year. Figure 27 shows an overview of the optimum results achieved in each case. An overview of the considered components in each case is shown in Table 12.

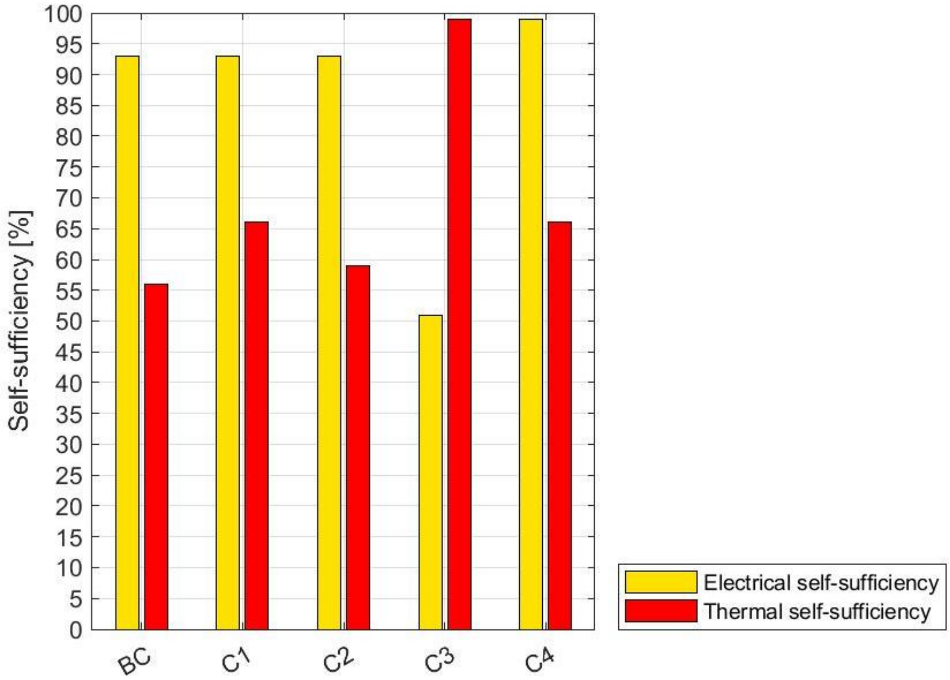


Figure 27: Simulation summary

Table 12: Simulation cases and component overview

		Base Case	**C1 Envelope**	**C2 Ventilation and infiltration**	**C3 Heating system**	**C4 Energy supply and storage**
Thermal envelope improvements	Opaque		X		X	X
	Transparent		X		X	X
Air exchange	Natural	X	X	X	X	X
	Controlled ventilation with heat recovery			X	X	X
	Improved air-tightness			X	X	X
Energy supply and storage system	Increased photovoltaic					X
	Increased battery					X
Heating	Air- to-air heat pump				X	

Furthermore, the results indicate that the improvement of the envelope and the application of a ventilation with heat recovery can improve the thermal self-sufficiency. Whereas the improvement of the envelope had a stronger impact than the application of controlled ventilation and increased air-tightness, however, self-sufficiency based on self-produced electricity was not achieved due to the limited available space. Double the area would be necessary to produce enough electricity for the heat pump in winter. This shows that significant aspects of the model are the electricity production system as well as the thermal storage.

5 CONCLUSION

This thesis highlights the current state of research on self-sufficient buildings. Under these aspects, a case study model, namely “wohnwagon”, was analyzed. Although only minimum requirements were agreed upon, this set-up was not able to achieve full self-sufficiency based on self-produced electricity with limited space. Also by setting the sufficiency level to 99% percent, full autarky was not achieved. When 99% electrical self-sufficiency were obtained, only 66% thermal self-sufficiency were reached. And 99% thermal self-sufficiency resulted in maximum 51% electrical self-sufficiency under the set boundary conditions.

The simulation depicted that the variation of the construction in this case study has a more significant impact on self-sufficiency than the application of controlled ventilation with heat recovery. Autarky in this case study was not achieved due to the fact that the energy demand is the highest when the electricity production of the photovoltaic is the lowest. These contradictory aspects do not allow full self-sufficiency here. This shows that the determining factors of self-sufficiency are available energy production possibilities and storage capacities. Furthermore, a large surface-area-to-volume-ratio leads to high losses which additionally aggravates the achievement of the goal self-sufficiency. However, other solutions like the application of solar thermal panels, which would use solar energy more efficiently, or the application of a biomass back-up system, like it is applied in the original set-up of the underlying case study, would be possible.

Future research topics instrumental to the further development of the topic lie in the fields of grey energy, life cycle analysis, user behavior in a self-sufficient unit, among others.

In this present work, an approach using a solely electrical set-up has been analyzed. It would be interesting to implement thermal energy production components, like solar thermal panels, as their efficiency is significantly higher than photovoltaic panels, to examine whether the self-sufficiency degree can be improved.

As several studies show the importance of grey energy in modern buildings (Chastas et al. 2016), it is recommended for further research to analyze the grey energy connected to different components like energy production and storage systems and to analyze these aspects in a life cycle assessment.

The user behavior in a self-sufficient system is an interesting topic itself. The occupant is directly confronted with the consequences of the malfunctioning of the system, and therefore is obliged to adapt his/her behavior to the availability of energy in the interest of maintaining comfortable conditions. The findings about the interaction between the user and the system (e.g. battery level) might deliver interesting results concerning the question in how far users can be encouraged to a more energy saving behavior.

In order to put the results of the self-sufficient unit into a context of more conventional living possibilities, it is further recommended to analyze the energy demand, including transportation, comparing average housing in urban and rural areas with the self-sufficient unit.

Additionally, the impact of the implementation of smart control methods on self-sufficiency buildings (e.g. implementation of a protocol which devices should not operate when the battery level is low) or even predictive control could be further researched.

6 INDEX

6.1 List of Figures

6.2 List of Tables

7 APPENDIX

A. Constructions and materials

Constructions	Layers: from outside to inside
Exterior wall light weight	2 cm larch cladding wind barrier (s_d=5) 10 cm wood-stud construction with sheep wool insulation vapor barrier 1.6 cm spruce cladding / 1 cm clay plaster / 0.8 cm flexible gypsum boards/ 40% stoneware tiles 1 – 1.5cm (in the bathroom)
Exterior wall massive wood	2 cm larch cladding wind barrier 8 cm sheep wool 10 cm CLT massive wood
Roof	4 cm pumice stones / water treatment plant with plants – water soaked 0.5 cm root protection layer 500g/m^2 PE vapor barrier Sarnavap 500 10 cm XPS vapor barrier 10 cm CLT massive wood
Floor – main area	2.5 cm massive wood 1.6 cm OSB
Floor – bay	10 cm XPS 10 cm CLT massive wood (3 layers – glued – each layer has an additional diffusion resistance of 2 cm wood)
Floor – equipment room	0.3 cm galvanized steel 3 cm XPS 10 cm varioPUR panels aluminum coated 1.6 cm OSB

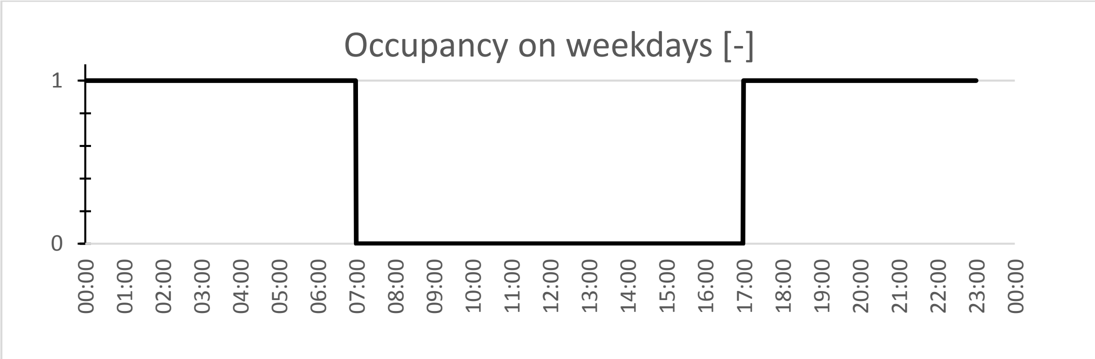
Layers below 0.003 m are not modelled as described as described in the EnergyPlus documentation (U.S. Department of Energy's Building Technologies Office 2017).

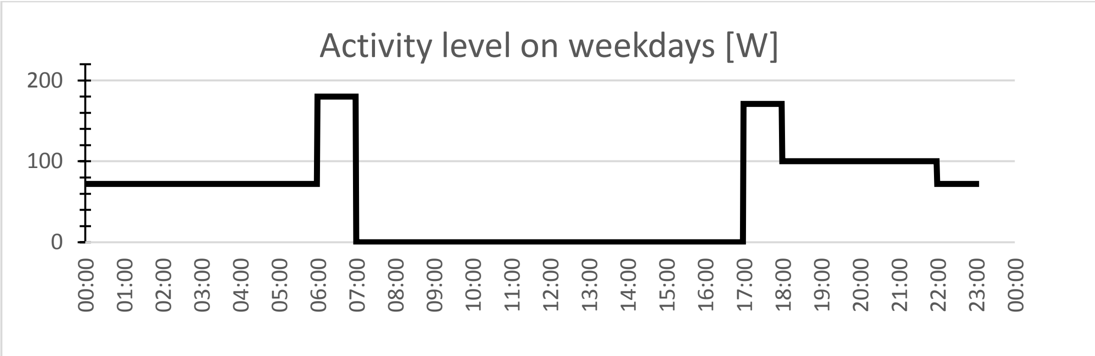
Material names	Roughness [-]	Conductivity [Wm^{-1}K^{-1}]	Density [kgm^{-3}]	Specific heat [Jkg^{-1}K^{-1}]	Thermal [6] absorptance [-]	Solar [6] absorptance [-]	Visible [6] absorptance [-]
larch cladding[7]	medium smooth	0.13	500	1600	0.9	0.7	0.7
wooden studs[7]	medium smooth	0.12	450	1600	0.9	0.7	0.7
sheep wool[8]	medium rough	0.04	19.5	1730	0.9	0.7	0.7
spruce cladding[7]	medium smooth	0.12	450	1600	0.9	0.7	0.7
clay plaster[9]	medium rough	0,81	1700	936	0.9	0.7	0.7
gypsum boards[7]	very smooth	0.56	1500	1000	0.9	0.7	0.7
stoneware tiles[7]	very rough	3.5	2800	1000	0.9	0.7	0.7
CLT massive wood[7]	medium smooth	0.13	500	1600	0.9	0.7	0.7
pumice stones[7]	very rough	0.12	400	100	0.9	0.7	0.7
water treatment plant[10]	medium rough	2.42	3204	840	0.9	0.7	0.7
root protection layer[9]	medium smooth	0.22	300	792	0.9	0.7	0.7
XPS[7]	medium smooth	0.04	30	1450	0.9	0.7	0.7
polyurethane (PUR) panels aluminum coated[7,11, 12]	very smooth	0.22	32	1800	0.05	0.2	0.2
OSB[7]	very smooth	0.13	600	1700	0.9	0.7	0.7
galvanized steel[7]	medium smooth	50	7800	450	0.9	0.7	0.7
vacuum panel aluminum coated[13], [14]	very smooth	0.02	35	800	0.05	0.2	0.2
sheep wool insulation with 14.3% wood[15]	rough	0.053	81	1711	0.9	0.7	0.7

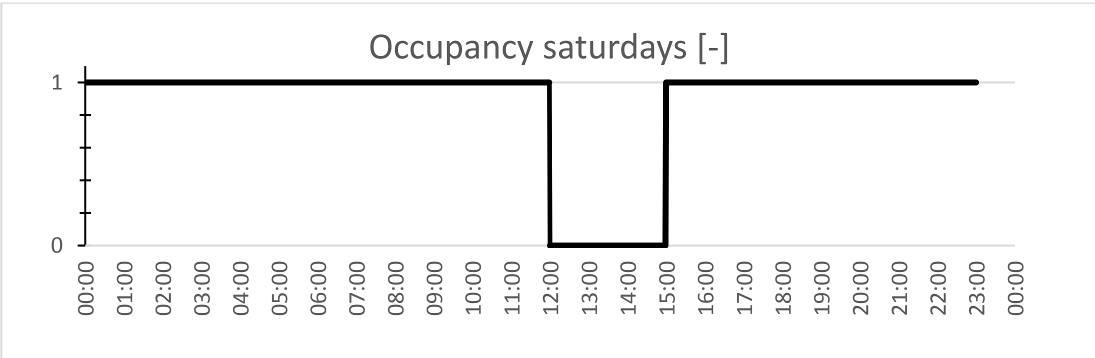
[6] For most cases default values according to the EnergyPlus manual (U.S. Department of Energy's Building Technologies Office, 2017)
[7] Austrian Standards Institute, 2010
[8] DAEMWOOL - Naturdämmstoffe GmbH & Co KG, 2017
[9] baubook GmbH, 2017
[10] Langbein, 2003
[11] Stürze, 2016
[12] Mahdavi, 2016
[13] Kingspan Group, 2017
[14] HiPTI - High Performance Thermal Insulation, 2005
[15] Ragonesi, 2018

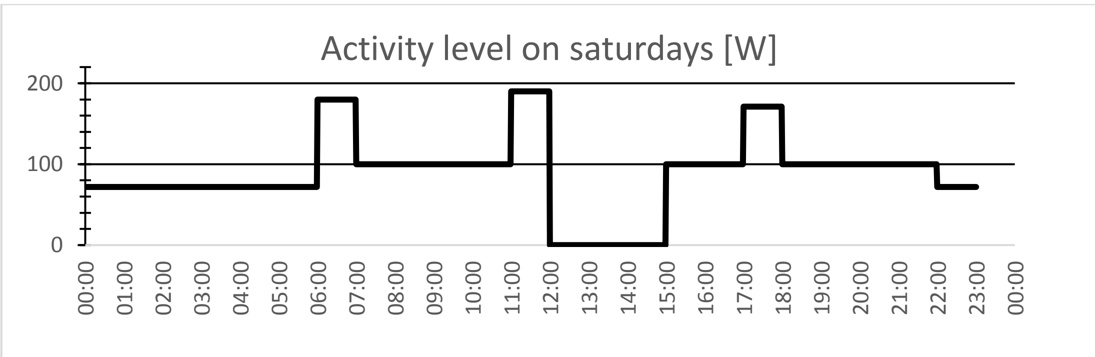
vacuum panels with 14.3% wood[15]	very smooth	0.041	94	914	0.005	0.2	0.2

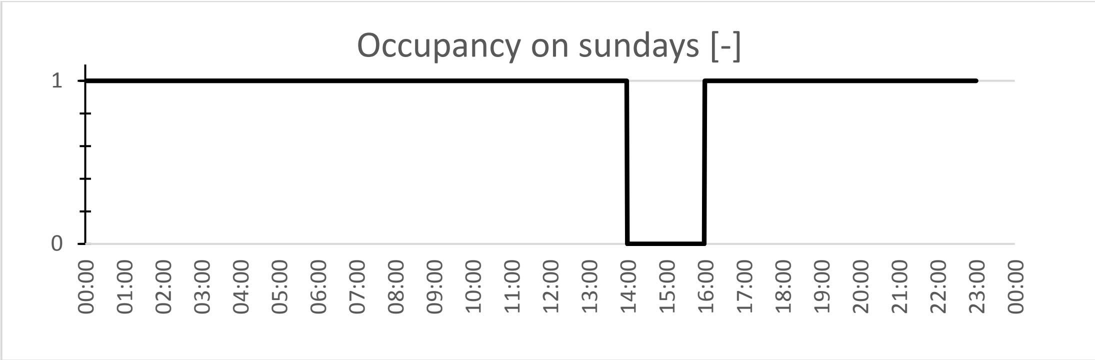
B. Schedules and load profiles

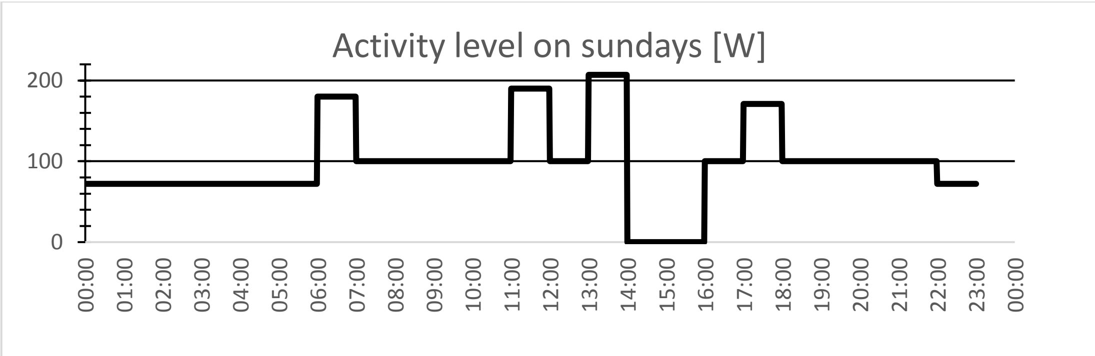


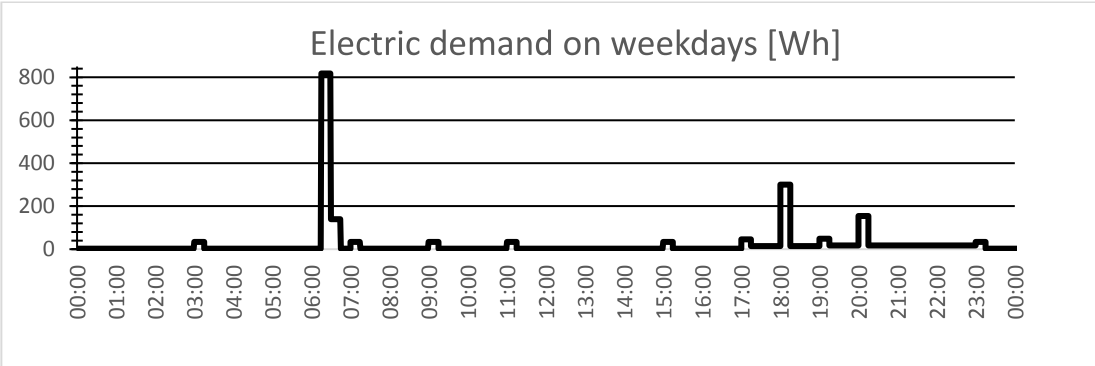












This graph includes all electrical equipment including lighting, hot water equipment but no heating equipment.

8 BIBLIOGRAPHY

ArchDaily (Ed.), 2016. *Monte Rosa Hut: Bearth & Deplazes Architekten.* https://www.archdaily.com/802453/monte-rosa-hut-bearth-and-deplazes-architekten. Accessed 20.04.2018.

arendo (Ed.), 2018. *Datasheet WDP 302803: Arende Steinless Stell Kettle and Thermal Jug.* https://downloads.ganzeinfach.de/storage/downloads/datasheet/302803/Datasheet-Arendo-Wasserkocher_1_2l_1850_2200W_anthrazit-302803.pdf. Accessed 20.04.2018.

Austrian Institute of Construction Engineering, 2015. *OIB-Richtlinie 6 Energieeinsparung und Wärmeschutz*.

Austrian National Council, 2012. *Bundesgesetz über die Pflicht zur Vorlage eines Energieausweises beim Verkauf und bei der In-Bestand-Gabe von Gebäuden und Nutzungsobjekten: Energieausweis-Vorlage-Gesetz*.

Austrian Standards Institute (Ed.), 2007. *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, ÖNORM EN 15251.* Vienna: Austrian Standards Institute.

Austrian Standards Institute (Ed.), 2008. *Energy performance of buildings – overall energy use and definition of energy ratings, ÖNORM EN 15603.* Vienna: Austrian Standards Institute.

Austrian Standards Institute (Ed.), 2010. *Baustoffe und Bauprodukte - Wärme- und feuchtetechnische Eigenschaften - Tabellierte Bemessungswerte und Verfahren zur Bestimmung der wärmeschutztechnischen Nenn- und Bemessungswerte, EN ISO 10456.* Vienna: Austrian Standards Institute.

Austrian Standards Institute (Ed.), 2011. *Thermal insulation in building construction — Part 5: Model of climate and user profiles, ÖNORM B 8110-5.* Vienna: Austrian Standards Institute.

Austrian Standards Institute (Ed.), 2014. *Wärmeschutz im Hochbau Teil 6: Grundlagen und Nachweisverfahren — Heizwärmebedarf und Kühlbedarf, ÖNORM B 8110-6.* Vienna: Austrian Standards Institute.

baubook GmbH (Ed.), 2017. *Baubook: Info/Produkt/Richtwert auswählen.* https://www.baubook.info/m/PHP/EinreichungI/Infoauswahl/index.php?Minibox=I_PRW_S&iSS=0&SI=&Balken=n&SW=5&LU=1823777493&qJ=7&LP=HngAo&SBT_open=134796. Accessed 13.12.2017.

Baumgartner, M., Ambrosetti, T. (Eds.), 2010. *Neue Monte Rosa-Hütte SAC: Ein autarkes Bauwerk im hochalpinen Raum. Ausstellung Neue Monte-Rosa-Hütte SAC.* Zurich: gta-Verl.

BenQ Group (Ed.), 2017. *SunVivo PM060MW2/PM060MB2: Monokristallines Photovoltaik-Modul.* http://solarenergysystems.baywa-re.com/media/filer_public/8e/14/8e149a18-a772-4678-8709-6239f7b8e638/pm060mw2_pm060mb2_de_20150915.pdf. Accessed 19.12.2017.

BMZ GmbH (Ed.), 2018. *Produktdatenblatt - ESS 7.0/9.0/X.* http://www.bmz-group.com/dokumente/Sonstiges/Datenblatt_Energy-Storage_DE.pdf. Accessed 19.12.2017.

Braun (Ed.), 2018. *Satin Hair Style&Go: Reisehaartrockner.* https://www.braun.de/de-de/hair-care/dryers/satin-hair-style-go-dryer. Accessed 06.01.2018.

Byrne, A., Byrne, G. and Robinson, A., 2017. *Compact facility for testing steady and transient thermal performance of building walls.* Energy and Buildings (152), pp. 602–614. DOI: 10.1016/j.enbuild.2017.07.086.

Cao, S., Hasan, A. and Sirén, K., 2013. *On-site energy matching indices for buildings with energy conversion, storage and hybrid grid connections.* Energy and Buildings (64), pp. 423–438. DOI: 10.1016/j.enbuild.2013.05.030.

Chastas, P., Theodosiou, T. and Bikas, D., 2016. *Embodied energy in residential buildings-towards the nearly zero energy building: A literature review.* Building and Environment (105), pp. 267–282. DOI: 10.1016/j.buildenv.2016.05.040.

CollinsDictionary.com (Ed.), 2017. *Collins Dictionary.* Glasgow. https://www.collinsdictionary.com/. Accessed 30.10.2017.

DAEMWOOL - Naturdämmstoffe GmbH & Co KG (Ed.), 2017. *Technische Daten - Schafwolle als Dämmstoff.* http://www.daemwool.at/de/daemstoff/technische-daten.html. Accessed 13.12.2017.

European Parliament, Council of the European Union, 2010. *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings: EPBD*.

Galvin, R. and Sunikka-Blank, M., 2014. *Disaggregating the causes of falling consumption of domestic heating energy in Germany.* Energy Efficiency (7), pp. 851–864. DOI: 10.1007/s12053-014-9259-5.

Glen Dimplex Deutschland GmbH (Ed.), 2011. *Lüftungsgeräte mit Wärmepumpe Serie LWP.* http://www.dimplex.de/fileadmin/dimplex/downloads/produktgruppendatenblatt/de/504-173_de_produktgruppe.pdf. Accessed 23.04.2018.

Glen Dimplex Deutschland GmbH (Ed.), 2018. *DL 50 WH2: Lüftungsgerät Version H mit Innenwandblende.* http://www.dimplex.de/lueftung/dezentrale-wohnungslueftung/dl-50-wh2.html. Accessed 21.04.2018.

Hansson, S. O., 2010. *Technology and the notion of sustainability.* Technology in Society (32), pp. 274–279. DOI: 10.1016/j.techsoc.2010.10.003.

HiPTI - High Performance Thermal Insulation (Ed.), 2005. *Vacuum Insulation Panels: Study on VIP-components and Panels for Service Liefe Prediction of VIP in Building Application.* http://www.vip-bau.de/pdf/literatur/Annex39_A.pdf. Accessed 22.04.2018.

Ipser, C., Bointer, R. and Stieldorf, K., 2012. *Planungsleitfaden Plusenergie: Energieeffizienz und gebäudeintegrierte regenerative Energieträgertechnologien in Vorentwurf und Entwurf. Teil 1 – Einleitung, Grundlagen und Projektbeispiele*.

Irulegi, O., Torres, L., Serra, A., Mendizabal, I. and Hernández, R., 2014. *The Ekihouse: An energy self-sufficient house based on passive design strategies.* Energy and Buildings (83), pp. 57–69. DOI: 10.1016/j.enbuild.2014.03.077.

Kingspan Group, 2017. *Kooltherm K15 Cladding Board.* https://www.kingspan.com/meati/en-in/product-groups/insulation/insulation-boards/kooltherm/kooltherm-k15-cladding-board. Accessed 21.04.2018.

Knotzer, A. and Weiss, T., 2014. *Ein internationales Spotlight auf die Bilanzierung von Null- und Plusenergiegebäuden.* http://www.aee.at/aee/

index.php?option=com_content&view=article&id=799&Itemid=113. Accessed 17.04.2017.

Kouba, R., Mach, T., Streicher, W. and Hemrath, R., 2002. *Simulation der instationären Wärmeausbreitung in Wandelementen des Holz 100 Bausystems der Firma Ing. Erwin Thoma GmbH*.

Langbein, S., 2003. *Erdwärmetauscher (EWT) - Systeme und Systemanbieter (Marktübersicht) Zubehör Erdwärmetauscher / Abdichtsysteme / Mauerdurchführungen Energiebrunnen, Erdenergietauscher.* http://www.bauweise.net/grundlagen/technik/lueftung/ewt/ewt-systeme.htm. Accessed 13.12.2017.

Lawrence Berkeley National Laboratory (Ed.), 2018. *IEA-EBC Annex 66: Introduction.* https://annex66.org/. Accessed 20.04.2018.

Leukefeld, T., 2015. *Zwei Energieautarke Häuser in Freiberg: Intelligente Eigenversorgung mit Wärme, Strom und Mobilität.* http://www.timoleukefeld.de/fileadmin/files/Projektskizze_zwei_EAHs_in_Freiberg.pdf. Accessed 15.11.2017.

Leukefeld, T., 2016. *Energieausweis Wohnwagon: Einschätzen und Hinweise zu dem energieautarken Wohnwagon*.

lib.znate.ru (Ed.), 2012. *Final Report on "Hydrogen Storage Technologies".* http://lib.znate.ru/docs/index-36506.html?page=9. Accessed 20.04.2018.

Liebherr Hausgeräte GmbH (Ed.), 2018. *Liebherr Hausgeräte: Datenblatt für elektrische Haushaltskühl- und gefriergeräte sowie ensprechende Kombinationsgeräte. Nach Verordnung (EU) Nr. 1060/2010.* https://home.liebherr.com/external/products/products-assets/HAU_EUProductDataSheet_999056651_de_DE_05-01-2018_05-26-59/UIK%201620-23_999056651_de_DE.pdf. Accessed 07.01.2018.

Mahdavi, A., 2016. *Thermal aspects of building performance*.

Märtel, C., 2017. *Wie weit kann man sich autark mit Solarstrom versorgen?* https://www.photovoltaik-web.de/photovoltaik/batteriesysteme-akkusysteme-pv/autarkie-pv-berechnung-autarkiegrad. Accessed 29.09.2017.

McKenna, R., Herbes, C. and Fichtner, W., 2015. *Energieautarkie: Definitionen, Für- bzw. Gegenargumente, und entstehende Forschungsbedarfe. Working Paper,* Karlsruhe.

McKenna, R., Jäger, T. and Fichtner, W., 2014. *Energieautarkie – ausgewählte Ansätze und Praxiserfahrungen im deutschsprachigen Raum.* uwf UmweltWirtschaftsForum (22), pp. 241–247. DOI: 10.1007/s00550-014-0339-y.

Menconi, M. E., dell'Anna, S., Scarlato, A. and Grohmann, D., 2016. *Energy sovereignty in Italian inner areas: Off-grid renewable solutions for isolated systems and rural buildings.* Renewable Energy (93), pp. 14–26. DOI: 10.1016/j.renene.2016.02.034.

Meteotest AG (Ed.), 2018. *meteonorm.* http://www.meteonorm.com/. Accessed 19.04.2018.

Müller, M. O., Stämpfli, A., Dold, U. and Hammer, T., 2011. *Energy autarky: A conceptual framework for sustainable regional development.* Energy Policy (39), pp. 5800–5810. DOI: 10.1016/j.enpol.2011.04.019.

nbi new buildings institute (Ed.), 2018. *Daylighting Pattern Guide: Daylight Autonomy.* http://patternguide.advancedbuildings.net/using-this-guide/analysis-methods/daylight-autonomy. Accessed 21.04.2018.

NÖN.at (Ed.). *Wer zieht ins Strohhaus?: Gruppe für angepasste Technologien plant als Vorzeigeprojekt eine neue Öko-Siedlung neben dem „S-House“. Böheimkirchen.* http://www.noen.at/st-poelten/boeheimkirchen-wer-zieht-ins-strohhaus-strohhaus-oeko-siedlung-vorzeigeprojekt-projekt-26868869. Accessed 18.05.2018.

Oxford University Press (Ed.), 2017. *Oxford Dictionaries.* https://en.oxforddictionaries.com/. Accessed 30.10.2017.

POS Architecture (Ed.), 2018. *Schiestlhaus.* http://www.pos-architecture.com/projects/schiestlhaus/. Accessed 20.04.2018.

Rae, C. and Bradley, F., 2012. *Energy autonomy in sustainable communities: A review of key issues.* Renewable and Sustainable Energy Reviews (16), pp. 6497–6506. DOI: 10.1016/j.rser.2012.08.002.

Ragonesi, M., 2018. *U-Wert Berechnung bei inhomogenen Holzbaukonstruktionen.* https://www.lignum.ch/editor/_migrated/content_uploads/U-Wert-Berechnung_bei_inhomogenen_Holzbaukonstruktionen_01.pdf. Accessed 22.04.2018.

Salom, J., Marszal, A. J., Widén, J., Candanedo, J. and Lindberg, K. B., 2014. *Analysis of load match and grid interaction indicators in net zero energy buildings with simulated and monitored data.* Applied Energy (136), pp. 119–131. DOI: 10.1016/j.apenergy.2014.09.018.

Salom, J., Widen, J., Candanedo, J. A., Sartori, I., Voss, K. and Marszal, A., 2011. *Understanding net zero energy buildings: Evaluation of load matching and grid interaction indicators.* In: Proceedings of Building Simulation 2011, 12th Conference of International Building Performance Simulation Association, Sydney, 14. - 16. 11, IBPSA International Building Performance Simulation Association (Ed.).

Sartori, I., Napolitano, A., Marszal, A. J., Pless, S., Torcellini, P. and Voss, K., 2010. *Criteria for Definition of Net Zero Energy Buildings.* In: Conference proceedings / EuroSun 2010, International Conference on Solar Heating, Cooling and Buildings. 28 September - 1 October 2010, Graz, Austria, EuroSun 2010, Graz, Austria, D. Chwieduk, W. Streicher, W. Weiss (Eds.), Graz: International Solar Energy Society.

Schneider, B. (Ed.), 2018. *BINE Information Service Energy Expertise: Vacuum glazing. When inert gas is replaced by vacuum.* http://www.bine.info/fileadmin/content/Publikationen/Englische_Infos/projekt_0108_engl_internetx.pdf. Accessed 21.04.2018.

Solar Heating and Cooling Program (Ed.), 2017. *Net ZEB Evaluation Tool.* http://task40.iea-shc.org/net-zeb.

Sorrell, S., 2015. *Reducing energy demand: A review of issues, challenges and approaches.* Renewable and Sustainable Energy Reviews (47), pp. 74–82. DOI: 10.1016/j.rser.2015.03.002.

Statistik Austria (Ed.), 2017. *Wohnungsgröße von Hauptwohnsitzwohnungen nach Bundesland: Zeitreihe.* http://www.statistik.at/web_de/statistiken/menschen_und_gesellschaft/wohnen/wohnsituation/index.html. Accessed 06.07.2017.

Stürze, O., 2016. *BACHL PUR Dachboden – Dämmelemente VP-ALU: Leistungserklärung Nr. LE-DE-16.1-DEO-dh-023-VPALU. nach Artikel 4 der Bauproduktenverordnung (EU-BauPVO) 305/2011.* http://www.bachl.de/index.php/component/easyfolderlistingpro/?view=download&format=raw&data=eNpNUEtPwzAM_i-5hzadNMA7IW23SXAZ18o0bhstjypJt0mI_477Epxif_4ejhGUgu8EexBtsJqiOHBTgTAOO0qFDndvA-qGfKZYaCTnMjW9N9fCkkl59F2ieLVIkUvyxTDGWk8ubCxGni2-aYZAlNuoGynlv8xnEHU9Y1P3skg9OpraEsS814IatjdQLqJIdsDc_2OxtjWWNm3FpPNJHk9S7Z8Uv-9S97KsdvLz4-18mSg7EPTIazXodt2HHoOJlLYwxf6YMza942OIw9eMvrJcItLN0H29Hf8shM5y9s8vw39vbA,,. Accessed 13.12.2017.

Talis Berufsstart Architekten | Bauingenieure (Ed.), 2013. *Energieautarkes Haus: Intelligent verschwenden.* https://www.talisonline.de/wp-content/uploads/2013/01/energieautark2.jpg. Accessed 20.04.2018.

The MathWorks, I. (Ed.), 2017. *MATLAB.* https://de.mathworks.com/products/matlab.html?s_tid=hp_ff_p_matlab. Accessed 23.04.2018.

Tjaden, T., Weniger, J. and Quaschning, V., 2014. *Individuelle Autarkie.* pv magazine (2014), pp. 58–61. DOI: 10.1007/978-3-658-01206-9_1.

Tjaden, T., Weniger, J., Schnorr, F. and Quaschning, V., 2014. *Einfluss des Standorts und des Nutzerverhaltens auf die energetische Bewertung von PV-Speichersystemen.* In: 29. Symposium photovoltaische Solarenergie, 29. Symposium photovoltaische Solarenergie, Bad Staffelstein, 12. - 14. 03. 2014, Symposium photovoltaische Solarenergie (Ed.).

U.S. Department of Energy’s Building Technologies Office, 2017. *EnergyPlus: Documentation: Input Output Reference.* U.S. Department of Energy’s Building Technologies Office.

Verbruggen, B., Coninck, R. de, Baetens, R., Saelens, D., Helsen, L. and Driesen, J., 2011. *Grid impact indicators for active building simulation.* In: IEEE PES innovative smart grid technologies. ISGT, 2011 IEEE PES Innovative Smart Grid Technologies (ISGT), Anaheim, CA, USA, 17.-19.01.2011, Piscataway, NJ: IEEE, pp. 1–6.

Victron Energy B.V. (Ed.), 2018. *Datasheet Quattro Inverter Charger: 3kVA - 15kVA.* https://www.victronenergy.com/upload/documents/Datasheet-Quattro-3kVA-15kVA-EN.pdf. Accessed 20.04.2018.

Voss, K. (Ed.), 1997. *Konzeption und Bau eines energieautarken Solarhauses: Schlußbericht zum Forschungsvorhaben im Auftrag des Bundesministeriums für Bildung, Wissenschaft, Forschung und Technologie. BMBF 0338973A.* Stuttgart: Fraunhofer-IRB-Verl.

Voss, K. and Musall, E., 2013. *Net zero energy buildings: International projects of carbon neutrality in buildings: International project of carbon neutrality in buildings.* Munich: DETAIL.

Voss, K., Sartori, I., Napolitano, A., Geier, S., Gonçalves, H., Hall, M., Heiselberg, P., Widén, J., Candanedo, J. A., Musall, E., Karlsson, B. and Torcellini, P., 2010. *Load Matching and Grid Interaction of Net Zero Energy Buildings.* In: Conference proceedings / EuroSun 2010, International Conference on Solar Heating, Cooling and Buildings. 28 September - 1 October 2010, Graz, Austria, EuroSun 2010, Graz, Austria, D. Chwieduk, W. Streicher, W. Weiss (Eds.), Graz: International Solar Energy Society, pp. 1–8.

Wimmer, R. and Eikemeier, S., 2014. *Life Cycle Habitation: Zero Carbon Building Concepts.* In: Zero Carbon Buildings Today and in the Future. Proceedings of a Conference held at Birmingham City University, 1st International Zero Carbon Building Conference, Birmingham, 11.-12.09.2014, L. Jankovic (Ed.), Birmingham: Birmingham City University.

Wolfert, C. and Rezac, M., 2006. *Schiestlhaus am Hochschwab 2154 m: Das weltweit erste Passivhaus-Schutzhaus.* https://nachhaltigwirtschaften.at/resources/nw_pdf/0655_schiestlhaus.pdf?m=1469659221. Accessed 26.04.2018.

ww wohnwagon GmbH (Ed.), 2017. *Deine Einschulung: Wohnwagon "Max",* Vienna.

ww wohnwagon GmbH (Ed.), 2018a. *wohnwagon.* https://www.wohnwagon.at/. Accessed 19.04.2018.

ww wohnwagon GmbH (Ed.), 2018b. *Wohnwagon Grundrisse: Einige Beispiele.* https://www.wohnwagon.at/wp-content/uploads/2016/11/Grundrisse-Wohnwagon-Beispiele.pdf. Accessed 26.04.2018.

www.gps-coordinates.net (Ed.), 2017. *GPS Coordinates with Google Maps.* https://www.gps-coordinates.net/gps-coordinates-converter.

Zeller, J., 2013. *Abschätzung der Infiltration nach DIN 1946-6 „Lüftung von Wohnungen": – Vergleich mit anderen Verfahren und Würdigung der Ergebnisse.* In: 8. Internationales BUILDAIR-Symposium, 8. Internationales BUILDAIR-Symposium, Hannover, euz energie + umwelt zentrum (Ed.), Hannover, pp. 1–10.

Ziegler, M., 2016. *Method for Establishing Scalable Load Profiles for Residential and Office Buildings to run an Urban Simulation Environment considering Construction and Mechanical Engineering Technologies as well as the Impact of Social Differentiation. Doctoral Thesis,* Vienna: TU Wien.

Zimmermann Lüftungs- und Wärmesysteme (Ed.), 2018. *Datenblatt: Lüftungsgerät. Proxon FWT-S1.* http://www.zimmermann-lueftung.de/fileadmin/download_datenblaetter/FWT-S/DEU/Datenblatt%20Proxon%20FWT-S1.pdf. Accessed 23.04.2018.

Zumtobel Lighting GmbH (Ed.), 2016. *Licht-Handbuch für den Praktiker.* https://www.zumtobel.com/PDB/teaser/DE/Lichthandbuch.pdf. Accessed 06.01.2018.