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Comparison of Austrian and U.S. residential Net-Zero Energy Buildings: Result analysis from multiple building energy simulations of a case study

BACHELOR THESIS 2

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Technik
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Declaration of Authenticity

I hereby declare in lieu of oath that I have written the present bachelor thesis independently and without external help, and that I have not used any other sources and aids than those indicated. Furthermore, I hereby declare that I have marked the passages taken literally or in terms of content from the sources used as such.

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Abstract

This study utilizes a descriptive and exploratory case study to evaluate to examine the impact of specific measures on a case study. At the beginning of this thesis, the importance of reducing energy consumption in the building sector is pointed out and why the approach of Net-Zero Energy Buildings is considered to be the most promising. It is further shown that this approach is not yet uniformly and universally applicable and why the term Net-Zero Energy Building itself is not a binding indicator that such a building is sustainable or resource friendly. Afterwards, the background and relevance of this work is presented. Furthermore, fundamental theoretical basics are presented in order to evaluate the results of the work. In the practical part of this paper a reference project, which was provided to the author during his academic stay at the Virginia Polytechnical Institute and State University, is modeled and two further variations are simulated and analyzed. The results of the simulation of version 1 show that the simulated building performs within a reasonable range in terms of energy consumption as the real reference building. The change in the thermal properties of the building envelope in version 2 achieves a 38% consumption reduction for heating, but the total energy consumption is only reduced by 4.5%. The improvement of air tightness and heat recovery in version 3 achieves a further 50% reduction in heating energy consumption, but the total energy consumption is only reduced by 1.3%. The results of this study show that the measures taken are effective and have a positive impact on the overall energy balance. Therefore, the Austrian Version of the case study reference object achieved the Definition of a Net-Zero Energy Building by Pless & Torcellini (2010).

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1. Introduction

Buildings have a significant impact on the environment and the global energy use. The world-wide CO_2 emissions caused by the energy consumption of buildings accounts for about 33 % of total emissions. Furthermore, the global consumption of final energy in the building sector is about 40 % (Marszal et al., 2011). Statistics in the USA show that the total energy consumption of commercial and residential buildings accounts for about 40 % of total energy consumption (EIA, 2018). On a European level, some member states even exceed 45 % of total energy consumption, which makes the building sector the largest end-use sector in Europe (D'Agostino & Mazzarella, 2019). Statistics like these do not only indicate the necessity of the energetic development of buildings, but it shows how big the potential for energy reduction, mitigation of climate change and carbon footprint reduction in this sector is worldwide. (Feng et al., 2019)

One way to exploit this potential, which has been pursued and discussed internationally for a long time, is to achieve energy self-sufficiency in the building sector, from where the term Net-Zero Energy Building originates, and which, due to the current significance of climate change, should no longer represent a concept of a remote future. The principle here is that in the future, buildings will only consume as much energy as they are able to offset or generate within a specific time span. (Marszal et al., 2011)

1.1. Problem Statement

The need for suitable and robust calculation methods has gained interest with the growing number of Net-Zero Energy Building projects around the world. Some countries are already in the process of integrating framework conditions for Net-Zero Energy Buildings into their respective standards and codes, although no standardized procedure has yet been developed to evaluate and assess these buildings uniformly. The projects and concepts submitted so far, that are trying to fulfill this need, are on a voluntary basis and mostly represent the calculation method for special Net-Zero Energy Building case studies only. (Marszal et al., 2010)

Marszal et al. (2011) mention that at the current point in the development of sustainable and suitable buildings to fight the issue of climate change and the growing energy resource shortage, the international discussions mostly focus on the lack of a common understanding for this building concept. Furthermore, it is stated that before Net-Zero Energy Building strategies can be adopted towards international standards and national building codes, a commonly agreed energy calculation methodology and a robust definition have to be developed.

Feng et al. (2019) also imply that although many efforts have been made in order to establish an international understanding of Net-Zero Energy Buildings, there is no common agreement on how to cope with the situation regarding calculation methodologies and national building codes and that reaching a common agreement for a unified definition could be a challenging task. Furthermore, the impact of occupant behavior influence on Net-Zero energy performance is gaining increasing importance. Due to the load shift in residential housing from enclosure dominated towards miscellaneous electric loads, the role of the occupant in achieving performance goals in the Net-Zero Energy Building context becomes critical (Agee, 2016).

1.2. Motivation

The way the zero-energy goal is defined affects the choices designers make to achieve this goal and whether they can claim success. This finding shows that the success of a meaningful Net-Zero Energy Building definition depends on several stakeholders. Furthermore, a clear framework for the successful implementation of a Net-Zero Energy Building project must be provided in order to ensure qualitative implementation, as also shown in the report of Knotzer & Selvicka (2017).

In mathematical terms, a building without good energy performance can still be classified as a Net-Zero Energy Building. However, high energy efficiency in the building makes sense in any case, because: The higher the energy demand of the Net-Zero-Energy Building, the greater the proportion of usable renewable energy on site i.e. more photovoltaic surfaces, more thermal collectors, etc. (Knotzer & Selvicka, 2017). For this reason, the U.S. Department of Energy states, that a Net-Zero Energy Building is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies. (Torcellini, Pless, Deru & Crawley, 2006)

The findings of a meta-study by Feng et al. (2019), who analyzed 34 case study buildings in hot and humid climates, also show that the term Net-Zero Energy Building is not a binding indicator for an energy efficient building, because a building with a sufficient amount of renewable energy generation can still achieve Net-Zero Energy status even with high energy use intensity. Nevertheless, their review showed, that Net-Zero Energy Buildings have a tendency to adopt advanced energy efficiency technology and design.

1.3. Research question

The aim of this thesis is to examine how a Net Zero Energy Building according to specific Austrian standards performs in the US. The Austrian version of a Net-Zero Energy Building is based on a U.S. case study, which is considered a Net-Zero Energy Building according to the criteria of different certifications in the state of Virginia. Another key point of this thesis is to highlight the differences in the respective codes, standards and guidelines for Net Zero energy buildings in the U.S. and Austria. Furthermore, differences in the definition of terms and the respective legal situation will be pointed out, as there is still confusion in this subject area.

These issues lead the author to answer the following research question:
:

- *How does a residential building with specific Austrian standards perform in terms of total annual energy use in comparison to a case study from a certified Net-Zero Energy Building in the U.S.?*

1.4. Methods

In order to answer the research question, two methods will be applied. First, a literature review is carried out in order to get an overview of the origin and the current state of the art of Net-Zero Energy Buildings. Then, data from energetic simulations of multiple reference objects is analyzed. The literature review was conducted using “Google Scholar” and “ScienceDirect”, where the most recent and relevant literature was searched and cited afterwards. The limitation of this research is determined by referring to literature that corresponds to the present and essential state of science. In some cases, this work may also include earlier literature sources due to their distinctiveness and relevance to the research of others.
For the practical part of this thesis, the simulation program IDA ICE version 4.8 was used. This simulation program is used primarily to investigate the indoor climate of several zones within a building, but it is also used to predict the total energy consumption of buildings. The data needed for the investigation of the energy consumption of the reference objects were partly provided by the partner institution, but also characteristic values of the german “Passivhaus Institut” have been used, since it is in widely use in Austria in terms of classification systems.

In order to investigate the influence of different measures taken on the total annual energy consumption and the resulting energy balance in the Net-Zero Energy Building context, Version 1 was designed to represent the a single building of the actual reference project using the same building properties. Version 2 und 3 were designed with regard to the german “Passivhaus Institut” in order to investigate the affects of the measures taken on the annual energy consumption. The results of the simulations were then presented and discussed in section 5. The results of this work only refer to a single reference object for which assumptions have been made for the calculation of further versions and must therefore be viewed critically.

2. Net-Zero Energy Buildings

In the following section, the theoretical principles regarding Net-Zero Energy Buildings are explained in order to show the versatility of this topic and to explain why there is still no standardized, internationally recognized definition of this building concept. Furthermore, the definitions relevant for the evaluation of the case study are described.

The issue of Net-Zero Energy Buildings has gained increased recognition in recent years. The revised version of the EU Energy Performance of Buildings Directive (EPBD) requires that all buildings which are occupied by public authorities have to be Nearly Zero Energy Buildings (nZEB) after December 31, 2018 and all new buildings should be nZEB by the end of 2020 (Zhang, Zhou, Hinge, Feng & Zhang, 2016). As determined in accordance with Annex 1 of the EPBD, a nZEB is defined as a building with a very high energy performance. The “very low” amount of energy needed by the building should be covered by renewable energy supply strategies to a significant extent. The extent, however, has to be determined individually by each member state. (D'Agostino & Mazzarella, 2019)

The way a Net-Zero Energy Building is defined is crucial to understand the combination of applicable efficiency measures and renewable energy supply options, because design goals are important to achieve a high-performance building (Torcellini et al., 2006).
The Building Technologies Program of the US Department of Energy (DOE) has set their goal of achieving marketable zero-energy buildings in 2020 and commercial zero-energy buildings in 2025. These goals are based on the Energy Independence and Security Act of 2007 and Executive Order 13514. Even though there are similarities between the EU and U.S. regulations for Net-Zero Energy Buildings in several terms, differences in EU and U.S. policies and definitions are significant (Zhang et al., 2016).

2.1. Before Defining Net-Zero Energy Buildings

In the paper by Marszal et al. (2011), several proposals for reaching a common Net-Zero Energy Building definition framework are reviewed and analyzed. The authors indicate that there are several key aspects that should be considered before developing a common definition for a Net-Zero Energy Building. The suggested key aspects are:

- Metrics of the balance
- Balancing period
- Type of energy use included in the balance
- Type of energy balance
- Accepted renewable energy supply options
- Connection to the energy infrastructure
- Requirements for energy efficiency, indoor climate and building-grid interaction

The metrics of the balance can be influenced by several measures. Therefore, more than one unit can be applied i.e. primary energy, final energy, CO_2 equivalent emissions, the cost of energy, exergy or other parameters defined by a national energy policy. It is further indicated that there is more than one option for the balancing period i.e. annual, seasonal, monthly or even balancing over the life cycle of a building. The types of energy usages include various inputs and are very diverse in practice, nevertheless there should be a common agreement on what types of energy usages are included in the total energy use of the building for balancing the energy. The issue of choosing the appropriate type of balance addresses two possible balances: (i), the balance between the renewable energy use and the building's energy use is more applicable in the design process of the building or (ii), the balance between the energy delivered to the building and the exported energy is more applicable during the monitoring phase of a buildings energy use after the building process. There are also several renewable energy supply sources, but in principle there is either an on-site supply or off-site supply strategy. (Marszal et al., 2011)

As shown in Figure 1, Torcellini et al. (2006) indicate that there should be a hierarchy of energy supply options, whereas Marszal et al. (2010) propose possible supply options in different calculation methodologies as shown in Figure 1, and emphasize that this graph should not be seen as a hierarchy.

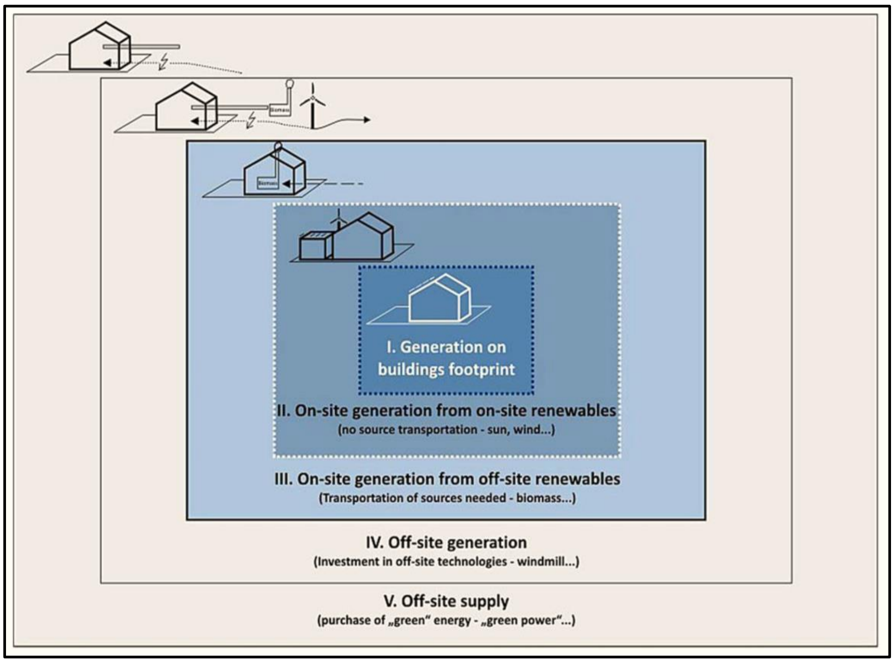

Figure 1: Overview of current renewable energy supply options linked to common international practice for energy calculation methodologies for Net ZEBs, source: Marszal et al. (2010)

Torcellini et al. (2006) state that a variety of supply-side renewable energy technologies can be used to supply energy to a Net-Zero Energy Building. Renewable energy sources are always preferable over fossil fuels and a distinction is also made between the different renewable energy sources. Therefore, a priority ranking in the Net-Zero Energy Building context has been established, according to which certain energy sources are preferable over others.

The principles they have applied to develop this ranking are based on technologies that:

- Reduce conversion and transportation losses.
- Can be used and will be available over the lifecycle of the building.
- Are widely applicable and available and have a high replication potential for Net-Zero Energy Buildings in the future.
- Minimize the overall impact on the environment by promoting energy-efficient building designs.

Table 1: Net-Zero Energy Building Renewable Energy Supply Option Hierarchy, source: Torcellini et al. (2006)

Option Number	Net-Zero Energy Building Supply-Side Options	Examples
0	Reduce site energy use through low-energy building technologies	Daylighting, high-efficiency HVAC equipment, natural ventilation, evaporative cooling, etc.

	On-Site Supply Options	
1	Use renewable energy sources available within the building's footprint	PV, solar hot water, and wind located on the building
2	Use renewable energy sources available at the site	PV, solar hot water, low-impact hydro, and wind located on-site, but not on the building
	Off-Site Supply Options	
3	Use renewable energy sources off-site to generate energy on site	Biomass, wood pellets, ethanol, or biodiesel that can be imported from off site, or waste streams from on-site processes that can be used on-site to generate electricity and heat.
4	Purchase off-site renewable energy sources	Utility-based wind, PV, emissions credits, or other "green" purchasing options. Hydroelectric is sometimes considered.

It is stated that this ranking is weighted towards those renewable technologies that are available within the building's footprint and at the site. Supply-side technologies for widespread application in Net-Zero Energy Buildings are rooftop photovoltaics and solar water heating. There are other supply-side technologies such as parking lot-based wind or PV systems that may be available for limited applications.

Another approach of supplying energy to the building is consuming energy from the outside of the building site, which can also achieve the goal of a Net-Zero balance, but it is not the same as one that generates energy on site and therefore it should not be classified as such.
Hence, the term "off-site Zero Energy Building" is used for buildings that draw energy form sources outside the boundaries of the building site (e.g. the energy grid). A Net-Zero Energy Building that is not considered to be "off-grid" uses available energy sources such as the electric or natural gas utilities when the on-site generation does not meet the demand loads and exports the amount of energy that cannot be used, when the energy production exceeds the building's load. Furthermore, it is stated that achieving a Net-Zero Energy Building without using the grid would be difficult, as the current generation of storage technologies is limited. They assume that excess on-site generation can always be sent to the grid except in high market penetration scenarios, where the grid will not need the excess energy from the building. In this case on-site energy storage would become necessary. (Torcellini et al., 2006)
(Zhang et al., 2016) indicate that approximately 75 methodologies for determining a balance system in practice are used internationally. This variety of metrics and boundary conditions shows the regional and international diversity in the concerns and motivation of Net-Zero Energy market stakeholders.

2.2. Definitions of Net-Zero Energy Buildings

Since it is an essential goal of this thesis to show the differences in terms of terminology and framework conditions for Net-Zero Energy Buildings between Austria and the U.S., an attempt to define these types of buildings, in which these two countries have contributed to the development, is presented in sections 2.2.1 & 2.2.2.

In their study Feng et al. (2019) concluded that a meaningful Net-Zero Energy Building definition should prioritize the energy efficiency of a building first, and then integrate renewable energy strategies properly.

The National Renewable Energy Laboratory (NREL) proposes a variety of Net-Zero Energy definitions in order to give architects, developers and other stakeholders the chance to choose the definition which best suits their project, since it is difficult to unify a single international common agreed standard (Torcellini et al., 2006). This shows that the approach to form a single definition is not the general goal to pursue in this topic, but it also indicates a direction for future systematic Net-Zero Energy Building definitions. The definition developed by Pless & Torcellini (2010) and the U.S. Department of Energy is similar to the definition discussed in the work of D’Agostino & Mazzarella (2019) as they both use the terms on-site and off-site energy generation as their major disparity to categorize different versions of Net-Zero Energy Buildings (Feng et al., 2019). The European Committee for Standardization (CEN) also developed a methodological proposal for the definition of Net-Zero Energy Buildings in their resulting standard that has being substituted by prEN ISO/DIS 52000-1:2015 in Annex H (D'Agostino & Mazzarella, 2019).

The literature review done by D’Agostino & Mazzarella (2019), which is limited to the main literature sources on Zero-Energy-, Nearly Zero Energy- and Net-Zero Energy Buildings, indicates two principle issues. The first issue deals with the different approaches implementing such buildings. It can be differentiated between the European “by law” and the market-oriented U.S. DOE approach. The second issue regard the differences in terminology of the “zero” balancing principle.

2.2.1. Definition of Net-Zero Energy Buildings in the U.S.

The idea that buildings can meet all their energy requirements from low-cost, nonpolluting, locally available and renewable sources is at the heart of the Net-Zero Energy Building concept in the US. At the strictest level, the building generates enough renewable energy on site to equal or exceed its annual energy use. Thus, the U.S. definition for Net-Zero Energy Buildings puts energy efficiency before the use of on-site, renewable energy sources. The background of this approach is that it is almost always easier to save energy than to produce energy. The U.S. definition also includes buildings that receive all their energy from off-site sources into their Net-Zero Energy Building concept. Even so these building have little incentive for reducing building loads, they are referred to as “off-site Zero Energy Buildings” as shown in Table 1. Therefore, in the U.S., a Net-Zero Energy Building can be defined in several ways, depending on the boundary and the metric. Furthermore, the project goals of the various stakeholders in the building process make different definitions necessary. Generally, four definitions are commonly used in the Net-Zero Energy Building context. Each definition uses the grid for net use balancing and considers different applicable renewable energy sources. (Torcellini et al., 2006)

In particular, the four commonly used terms are described by (Crawley, Pless & Torcellini, 2009) as following:

- **Net-Zero Site Energy:** A site balanced Net-Zero Energy Building produces as much renewable energy as it uses within a year, when it is accounted for at the site.
- **Net-Zero Source Energy:** A source balanced Net-Zero Energy Building produces (or purchases) as much renewable energy as it uses within a year, when it is accounted for at the source. The source energy or primary energy includes the energy used to extract, process, generate and deliver it to the site. In order to calculate the building’s total energy use by source, the energy flows between the boundaries are multiplied by the appropriate site-to-source conversion factors based on the source energy type.
- **Net-Zero Energy Costs:** In a cost based Net-Zero Energy Building, the amount of money the building owner pays the utility for the energy services and the energy used over the year is at least equal to the amount of money the utility pays the owner for the exported renewable energy from the building site.

- **Net-Zero Emissions:** The concept of a net-zero emissions building is that it produces (or purchases) enough emissions-free renewable energy to offset the emissions from all energy used in the building within a year. Nitrogen oxides, carbon and sulfur oxides are common emissions that Net-Zero Energy Buildings can offset. In order to calculate the building’s total emissions, the energy flows between the boundaries are multiplied by the appropriate emission conversion factors based on the utility’s emissions and possible on-site generation emissions.

Even though all attempts to achieve a Net-Zero Energy Building are valuable, the classification system applied needs to be based on the definitions met and the renewable energy sources used. Therefore, a building that offsets all its energy use from renewable energy sources within the buildings footprint is placed on top of the classification system and is classified as a NZEB:A building. When a building achieves the definition because of a combination of on-site renewable energy generation and off-site renewable energy purchases it is placed on the low end of the classification system and is therefore classified as a NZEB:D as shown in Table 2. The background for this type of classification system is to encourage building designers and owners to first exploit all possible cost-effective energy efficiency strategies and then use renewable energy sources and technologies that are located within the buildings footprint. Once these cost-effective and on-site renewable energy strategies are fully used, off-site options for energy supply can be used to meet the building's energy demand. (Pless & Torcellini, 2010)

Table 2: Applying a NZEB classification system, source: Pless & Torcellini (2010)

NZEB Classification	Option Number	Net-Zero Energy Building Supply-Side Options	NZEB Defintions Met
	0	Reduce site energy use through energy efficiency and demand-side renewable building technologies	**NA**
	On-Site Supply Options		
A	1	Use RE sources available within the building's footprint and connected to the building's electricity or hot/chilled water distribution system. Reach an NZEB position without needing NZEB:B, NZEB:C, or NZEB:D sources.	YES: Site, Source, Emissions Difficult: Cost Potential Issues: • Reaching a source or emissions NZEB position is difficult if multipliers are high when utility energy is used but low when exporting to the grid. • Qualifying as a cost NZEB may be difficult if net metering policies are unfavorable.

B	2	NZEB:A sources may also be used and Use RE sources that are outside the building footprint but still within the building site and connected to the building's electricity or hot/chilled water distribution system. Reach an NZEB position without needing NZEB:C or NZEB:D sources.	YES: Site, Source, Cost, Emissions Difficult: Cost Potential Issues: • Reaching a source or emissions NZEB position is difficult if multipliers are high when utility energy is used but low when exporting to the grid. • Qualifying as a cost NZEB may be difficult if net metering policies are unfavorable.
	Off-Site Supply Options		
C	3	NZEB:A and/or NZEB:B sources are used (to the extent feasible) and Use RE sources available off-site to generate energy through on-site processes connected to the building's electricity or hot/chilled water distribution system. Reach an NZEB position without needing NZEB:D sources.	YES: Site Difficult: Source, Cost, Emissions Potential Issues: • Reaching a source or emissions NZEB position is difficult if carbon-neutral renewables are used or if source and carbon multipliers are high when utility energy is used but low when exporting to the grid. • Qualifying as a cost NZEB is very difficult because of the cost to purchase and continually transport off-site renewable materials to the site
D	4	NZEB:A and/or NZEB:B sources are used (to the extent feasible), NZEB:C sources may also be used and Purchase recently added off-site RE sources, as certified from Green-E (2009) or other equivalent REC programs. Continue to purchase the generation from this new resource to maintain NZEB status.	YES: Source, Emissions NO: Site, Cost Potential Issues: • Reaching a source and emissions NZEB position is based on the type and quantity of the purchased RE. • Qualifying as a site and cost NZEB is not possible

These definitions and the resulting classification system of the U.S. Department of Energy (DOE) have been essential for the development of several other approaches to form a meaningful Net-Zero Energy Building definition on an international level, which are also cited in this thesis.

Nevertheless, the U.S. DOE together with the National Institute of Building Science came up with another definition framework and guidelines for Net-Zero Energy Buildings in 2014 (Peterson, Torcellini & Grant, 2015). In their latest definition, the term Net-Zero Energy Building (NZEB) was replaced by the term Zero-Energy Building (ZEB), as the "net" in the previous definition was confusing to customers. However, U.S. authorities recognize that the previous term is still in wide use in the industry. Furthermore, the new term is still based on the same methodological approach (D'Agostino & Mazzarella, 2019).

In the newer definition, the focus is to distinguish between different concepts of Net-Zero Energy Buildings on a larger scale. This led to the following terms and definitions based on Peterson et al. (2015):

- **Zero Energy Building (ZEB):**
  "An energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy." (Peterson et al., 2015)

- **Zero Energy Campus (ZEC):**
  "An energy-efficient campus where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy." (Peterson et al., 2015)

- **Zero Energy Portfolio (ZEP):**
  "An energy-efficient portfolio where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy." (Peterson et al., 2015)

- **Zero Energy Community (ZECo):**
  "An energy-efficient community where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy." (Peterson et al., 2015)

D'Agostino & Mazzarella (2019) further state that the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) came up with their own definition of this building concept in its vision for 2020, which is referred to as NZEB and not ZEB as in the definition of the DOE, that uses the site energy for their balance principle.

2.2.2. Definition of Net-Zero Energy Buildings Europe

In 1974, the International Energy Agency was established as an autonomous unit of the OECD with headquarters in Paris. The International Energy Agency (IEA) is a cooperation platform for research, market introduction, development and application of energy technologies. It was founded by 16 industrialized nations, including Austria and the United States, for joint action against the oil crisis at the time. (Knotzer & Selvicka, 2017)

Despite being a member of the IEA, the United States are not a participant in the Solar Heating & Cooling Technology Collaboration Programme (SHC) of the IEA and is therefore not considered to be actively participating in the development of the Net-Zero Energy Definition Framework in the context of the SHC program “Towards Net Zero Energy Solar Buildings”, but Austria is. (IEA SHC, 2015-2020)

(Zhang et al., 2016) states that while there is currently no universally accepted definition of a Net-Zero Energy Building, the IEA SHC TASK40/ECBCS Annex 52 set a goal to highlight and present different international definitions. The already existing definitions comply to regional or national political and other considerations that are linked with promoting Net-Zero Energy Buildings (Sartori, Napolitano & Voss, 2012).

At the beginning of this program, already existing proposals and different approaches of defining Net-Zero Energy Buildings were analyzed and evaluated. Based on these applications, a consistent definition framework was developed. (D'Agostino & Mazzarella, 2019)

From this definition framework, it becomes clear that in the European context, the mere achievement of an annual balance is not sufficient to evaluate a Net-Zero Energy Building in terms of minimizing the energy use related environmental impact. Furthermore, the interaction between the building and the grid should be regulated and discussed. In this definition framework the balance concept is an essential part, but a single balance concept is not sufficient to cover this interaction. For this reason, two terms have been introduced and described around this topic, namely the load/generation balance and the import/export balance. The basic principle consists of the balancing approach that the remaining demand from the previous energy efficiency gains is covered by renewable energy production (see Figure 2).
Therefore, in the European context, the term Net-Zero Energy Building refers to buildings that are connected to the energy grid, as the term "Net" indicates an interaction between the building and the energy infrastructure. The term Zero-Energy Building is considered to be more comprehensive and can therefore also refer to autonomous or off-grid buildings. The building concept of Net-Zero-Energy Buildings is designed for buildings that draw their energy from a

grid that is not covered by 100% renewable energy sources. It is further indicated that this concept can cause problems such as insufficient grid stability within the energy grid due to the large scattering of energy feeds. However, the aim of this feed-in is to create a synergy and not to stress the grid. For this reason, the demand for smart grid solutions in this context is crucial, as distributed renewable energy production contributes significantly to a reduction of primary energy, operation costs and carbon emission factors. It is further explained that each country needs to adapt its own framework for implementing a Net-Zero Energy Building definition in terms of conversion factors for primary energy and carbon emissions, prioritization of different sources of supply or energy efficiency requirements. (Sartori et al., 2012)

$$|weighted\ supply| - |weighted\ demand| = 0 \qquad \text{[Eq. 1][1]}$$

Figure 2 describes the principle of the balancing method regarding the associated Equation 1, which should be calculated in absolute figures to avoid general misunderstandings as to whether the value for demand or the value for supply is to be applied positively. Furthermore, the reference building in this case represents a building which complies with the minimum energy efficiency requirements of national building codes. From this point on, in order to achieve a balance, the first step is to increase efficiency and then to generate renewable energy from several possible sources. (Sartori et al., 2012)

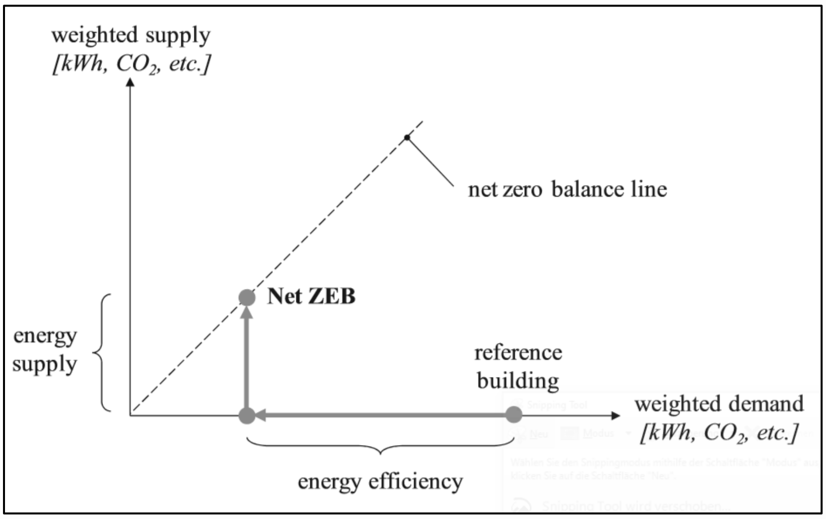

Figure 2: Net-Zero Energy Building balance concept, source: (Sartori et al., 2012)

[1] Equation 1: Net-Zero Energy Balance, source: Sartori et al. (2012)

In order to describe the relevant characteristics and to form future definitions of Net-Zero Energy Buildings, a framework consisting of five criteria and relevant sub criteria has been developed by Sartori et al. (2012) as shown below:

I. Building system boundaries
   - I Physical boundary
   - II Balance boundary
   - III Boundary conditions

II. Weighting systems
   - I Metrics
   - II Symmetry
   - III Time dependent accounting

III. Net-Zero Energy Building Balance
   - I Balancing period
   - II Type of balance
   - III Energy efficiency
   - IV Energy Supply

IV. Temporal energy match characteristic
   - I Load matching
   - II Grid interaction

V. Measurement and verifications

Furthermore, it is argued that building designers need information about the behavioral patterns of building users from normative data or simulation programs in order to cope more effectively with the problem of grid interaction. This stresses the importance of verifying energy consumption after having completed the construction phase as mentioned in section 2.4. Preferably all operative energies within the building boundary should be included in the balance calculation. (Sartori et al., 2012)

Within the Subtask A of the IEA task 40/annex 52, an evaluation tool for selected Net-Zero Energy Building definitions based on the definition framework of Sartori et al. (2012) and several other assumptions has been developed. This tool has the intention to show available options and to convert them into balance calculation methodologies which later result in supported design solutions. The tool can be applied for a wide range of stakeholders and is also intended to show how entered building data affects different definitions. In the context of building designers, different measures in the development of new building design can be evaluated for their impact on different definitions. Furthermore, for building managers the monitored data can be evaluated according to different definitions or support the implementation process of Net-Zero Energy strategies for policy makers. Through the combination of several options for each criterion and category defined in the work of Sartori et al. (2012), several definitions could possibly be generated.

The definitions presented below have been selected under the conditions that the definition is applicable for both design and monitored data. Furthermore, shared ideas had to be reflected by project partners as well as the calculation methodologies and factors had to be close to their finalization and identification before they resulted in several Net-Zero Energy Building types. (Belleri & Napolitano, 2012)

- **Net ZEB limited:**
  "A low energy building, fulfilling any national/local energy efficiency requirements, which offsets the yearly balance between its weighted energy demand for heating, DHW, cooling, ventilation, auxiliaries and built-in lighting (for non-residential buildings only), and the weighted energy supplied by on-site generation systems driven by on or off site sources and connected to the energy infrastructure. Static (or quasi-static) and symmetric primary energy factors are used as weights in the balance." (Belleri & Napolitano, 2012)

- **Net ZEB primary:**
  "A low energy building, fulfilling any national/local energy efficiency requirements, which offsets the yearly balance between its weighted loads for heating, DHW, cooling, ventilation, auxiliaries and lighting and every kind of plug loads (electrical mobility included), and the weighted energy supplied by only on site generation systems driven by on or off site sources and connected to the energy infrastructure. Static (or quasistatic) and symmetric primary energy factors are used as weights in the balance." (Belleri & Napolitano, 2012)

- **Net ZEB strategic:**
  "A building which offsets the yearly balance between its weighted energy demand for heating, DHW, cooling, ventilation, auxiliaries, built-in lighting and every kind of plug loads and the weighted energy supplied by on/off-site generation systems driven by on/off site sources and connected to the energy infrastructure. Weighting factors are static (or quasi-static) and asymmetric, varying on the basis of the energy carrier, the technology used as energy supply system and its location." (Belleri & Napolitano, 2012)

- **Net ZEB carbon:**
  "A building which offsets the yearly balance between its weighted energy demand for heating, DHW, cooling, ventilation, auxiliaries, embodied energy, built-in lighting and every kind of plug loads and the weighted energy supplied by on site generation systems driven by on or off site sources and connected to the energy infrastructure. Static (or quasi-static) carbon factors are used as weights in the balance. They can be symmetric or asymmetric, depending on the energy carrier, technologies used as energy supply systems and their location." (Belleri & Napolitano, 2012)

2.2.3. Post-Occupancy Performance

Housing projects have always been mainly focused on the energy efficiency of envelope and building systems. Due to the stricter requirements imposed by legislation on the maximal allowed total energy demand of buildings and specified standards for the energy efficiency of envelope systems and building systems technology, internal loads, hot water consumption and other energy consumption caused by the occupants are becoming increasingly important. Preliminary findings have found that the human factor in the operation of the building can have a major impact on its classification as a Net-Zero Energy Building and that in some cases energy simulation software does not properly include this factor in the calculation during the design phase of the building. For this reason, the process of post-occupancy feedback is essential for the qualitative evaluation of a Net-Zero Energy Building, where, after the completion of the construction, all energy consumption is monitored and later evaluated and compared to the originally predicted energy performance indicators. However, this evaluation and the subsequent comparison of the predicted and actual energy consumption could increase the consciousness for the later energy consumption. This will contribute to a positive development for the consideration of miscellaneous electric loads (MELs) in the design phase and thus ensure that this building concept can receive different classifications for Net-Zero Energy Buildings not only in theory but also in practice and in building operation. This margin between predicted and actual energy consumption currently contributes directly to the fact that the implementation of the Net-Zero Energy Building concept in the residential market is currently still impeded. (Agee, Reichard, McCoy, Kleiner & Hamm, 2017)

2.3. Building Regulations and Codes

The two main types of building energy performance codes are performance and prescriptive based. Currently a third type of code is being developed in the U.S. This new third type of building energy performance code is an outcome-based approach and requires post-occupancy energy metering. An advantage of this approach is that the actual energy demand is measured and not just predicted, which leads to a better consciousness of plug loads and occupant behaviors, that are currently neglected by most building regulations. There are only a few countries that already implemented Net-Zero Energy Building targets in their respective governance modes. Two regions leading in the development of Net-Zero Energy Building development are Denmark on a European level and the state of California in the United States. (Zhang et al., 2016)

Despite showing general interest and contributing to a definition framework in the context of Net-Zero Energy Buildings, the calculation methods presented by Austria in the paper by Marszal et al. (2010) are not directly related to the national building regulations. The Austrian building regulations only define the method of calculating the energy demand of a building, but do not consider possibilities for energy production on site and balancing, except solar hot water. The calculation methods presented therefore do not provide a legally valid basis for the calculation. Another aspect is that the proposed calculation methods use the energy demand of the building including the consumption of household appliances as a basis, whereas the building codes for residential buildings only use the demand for hot water, building heating and auxiliary energy, but not the demand for cooling and lighting. Furthermore, the building codes use the final energy as metric, whereas the calculation methods presented use the primary energy as the basis for balancing. (Marszal et al., 2010)

2.4. Outlook on NZEB

While Net-Zero Energy Building projects are facing problems and challenges in developing countries, they are growing rapidly in developed countries. Over 300 of these projects are already listed in the International Energy Agency (IEA) Solar Heating and Cooling Programme (SHC) Task 40 world map and more than 90% are located in the developed regions of the United Stated and the European Union. There are some countries that have initiated their guidance development process and standards to apply different types of Net-Zero Energy Building definitions. The American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) together with several U.S. stakeholders has been working on the development of a Net-Zero Energy Building guideline, that is based on the previous developed advanced energy guideline (AEDG). The intention of the new guideline is to provide building designers as well as building operators with information on operation parameters and Net-Zero Energy technology choices. It is also indicated that in order to evaluate the energy performance of this building concept, an energy use intensity-based criterion should be established for every Net-Zero Energy Building concept. An example for such a criteria is the net zero energy ready criteria of the New Building Institute in the U.S., that uses an Energy Utilization Index (EUI) equal or less than 56.8kWh/m²a and therefore forms a good reference to evaluate the energy performance of this building concept. (Feng et al., 2019)

The authors of the previous cited work also created policy recommendations based on their research outcome. Some of these suggestions are listed below in abbreviated form as they are:

- Setting up binding building standards and codes would help with the adoption of advanced building envelope technologies in the Net-Zero Energy Building context. This measure would also help to facilitate the social scale adoption of this building concept.
- Policies and incentives are needed to help building owners overcome the high initial cost barrier in order to enhance the wide adoption of Net-Zero Energy Buildings in the market.
- To ensure that experiences with the construction of Net-Zero Energy Buildings can be applied on an international scale, local and national governments should report successful experiences regarding these building concepts in order to inform potential stakeholders as well as future Net-Zero Energy Building owners and therefore support the development in this sector.

3. Case Study

This section covers the practical part of this thesis. First, the reference object and its properties are presented in order to compare it with two other versions of the building with the same footprint. The basis for the other two versions is the criteria catalogue of the German “Passivhaus Institut”, which is applied differently in each case. Section 3.1 presents the project idea and the background of the residential project completed in 2014. Afterwards the input of the building components and the corresponding boundary conditions, which are applied in the same way for all three versions, into the simulation software IDA ICE is described. Finally, the differences in properties of all three building versions are shown and explained in order to establish a reference to the later simulation results.

3.1. Grissom Lane Case Study

The case study is based on the Grissom Lane Apartments, an affordable, single-story senior housing Net-Zero Energy Building project as seen in Figure 3. The project design was carried out by a local non-profit housing organization from Virginia, USA, which has already gained nationwide recognition for its concept of affordable and sustainable housing. The site for the planned eight all-electric apartments, which are divided into four semi-detached houses, was donated by the town of Blacksburg to compensate for the growing demand for affordable housing in the university town. Due to the high-quality planning of the building, with regard to the thermal performance of the building envelope and the installed building systems, this showcase project was able to fulfill the criteria of a number of certification programs, e.g.: Energy Star, Department of Energy's Challenge Home (Now Zero Energy Ready Home) criteria, EarthCraft House and the EarthCraft Virginia (Now Viridiant) Net-Zero criteria. (Agee, 2016)

Figure 3: Building 1 & 2 of the Grissom Lane Apartments, Source: Agee, 2016

The background for the selection of building components such as the envelope, building systems technology and appliances is to demonstrate that this building concept can also be constructed with "off the shelf" technology and can therefore be used for widespread application as a cost-effective solution for energy-efficient housing. The four buildings are located on the east side of the city, but environmental factors such as shading only allow three of the four buildings to be equipped with a photovoltaic system (As seen in Figure 4). However, the total renewable energy output will be divided equally among all eight apartments and therefore the project is considered a community where both the energy production and the energy consumption of the entire eight apartments must be taken into account.

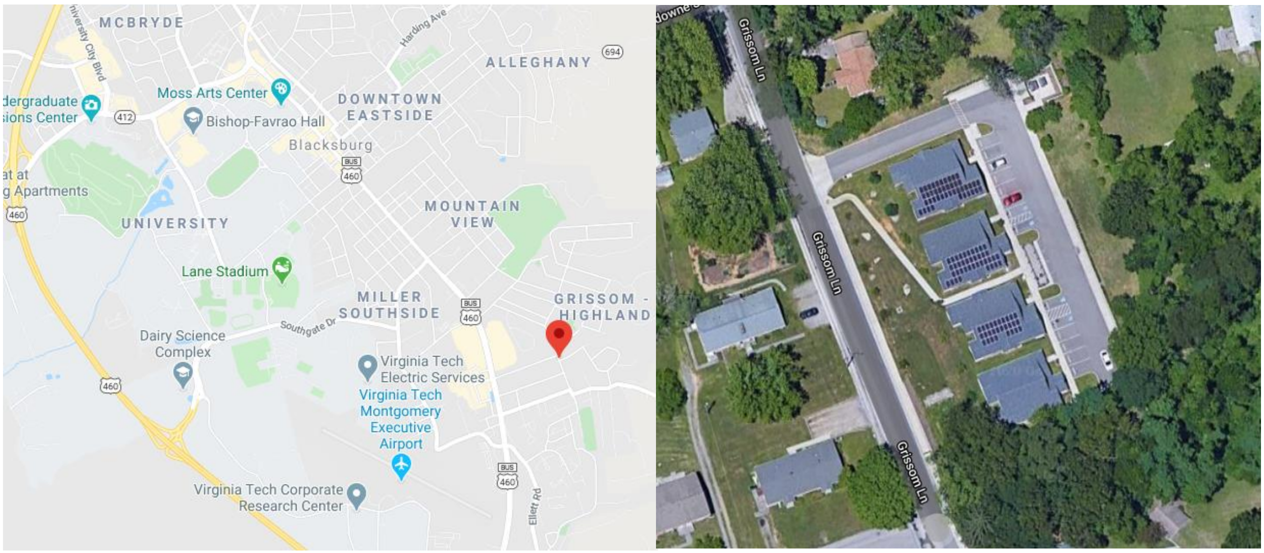

Figure 4: Location of the Grissom Lane Apartments, Source: Google Maps, Commonweatlh of Virginia, Maxar Technologies (2020)

In the design process of the building envelope, "state of the art" technology was avoided and instead high-quality, cost-efficient structures have been chosen. Therefore, the exterior wall construction has a U-value of 0.23 W/m²K, the insulating ceiling 0.09 W/m²K, the slab 0.28 W/m²K and the windows 1.42 W/m²K. An exhaust air-only system with a constant air flow rate of 67.96 m³/h was installed per unit and the supply air flow rate is provided by passive inlets in the bedrooms, which means there is no possibility of active heat recovery ventilation. Further technical data of the reference buildings can be seen in Table 3.

Table 3: Grissom Lane Apartments building properties: source: Author

Grissom Lane Apartments building properties			
Location	Blacksburg, VA, USA	**Number of Units**	8
Resident Population	Senior (+55 years), affordable	**Number of Buildings**	4
Climate Zone	4A (mixed-humid climate)	**Energy sources**	Electric grid fed, photo-voltaic (PV)
Heating Degree Days (HDD)	5466 HDD	**Conditioned Floor Area per Unit**	89,74 m²
Window to wall ratio	0,141	**Space heating**	2,64 kW, 18 SEER
Window U-Value	1,42 W/m²K	**Space cooling**	2,64 kW, 10 HSPF
Window SHGC	0,27	**Duct tightness**	1% of conditioned floor area
Slab U-Value	0,28 W/m²K	**Water heating**	2,75 EF, 190l, electric hy-brid
Exterior Wall U-Value	0,23 W/m²K	**Lights/Appliances**	100% LED lighting, 470 kWh/a refrigerator, En-ergy Star rated
Ceiling U-Value	0,09 W/m²K	**Ventilation**	Exhaust only ventilation with passive inlets, 67,96 m³/h constant air flow
Enclosure Tightness (n50)	2.0 h^{-1}	**Renewable energy sup-ply**	3,5 kWp PV per Unit

This residential project, which is unique in the town of Blacksburg, was put into operation in November 2014 and its total energy consumption is being monitored in order to assess the energy efficiency of those buildings and the influence of user behavior on the previously pre-dicted energy consumption.

The actual metered energy data of this building community has been evaluated in the study of Agee, Reichard, McCoy, Kleiner & Hamm (2017), where the aim of their research was to con-tribute to closing the post-occupancy performance gap in Net-Zero Energy Building projects. The authors utilized a descriptive and exploratory case study where they conducted research on the eight all-electric residential housing units in order to evaluate the following aspects:

- Predicted versus measured energy performance
- Impact of the actual weather versus a simulated standard climate
- Alternative simulation software programs, which contributes to a better assessment of the actual energy consumption caused by the occupants

The energy consumption of the respective residential units has been monitored from January 2015 to January 2017 and was then averaged and compared with the simulation results of selected simulation programs as seen in Figure 5. The simulation programs "BEopt", "Home Energy Saver" and "RemRate" have been used. From the graph it can be seen that each of the three simulation programs underestimated the energy consumption of the heating system and overestimated the energy consumption for air conditioning and the MELs (lighting, small and large appliances). (Agee et al., 2017)

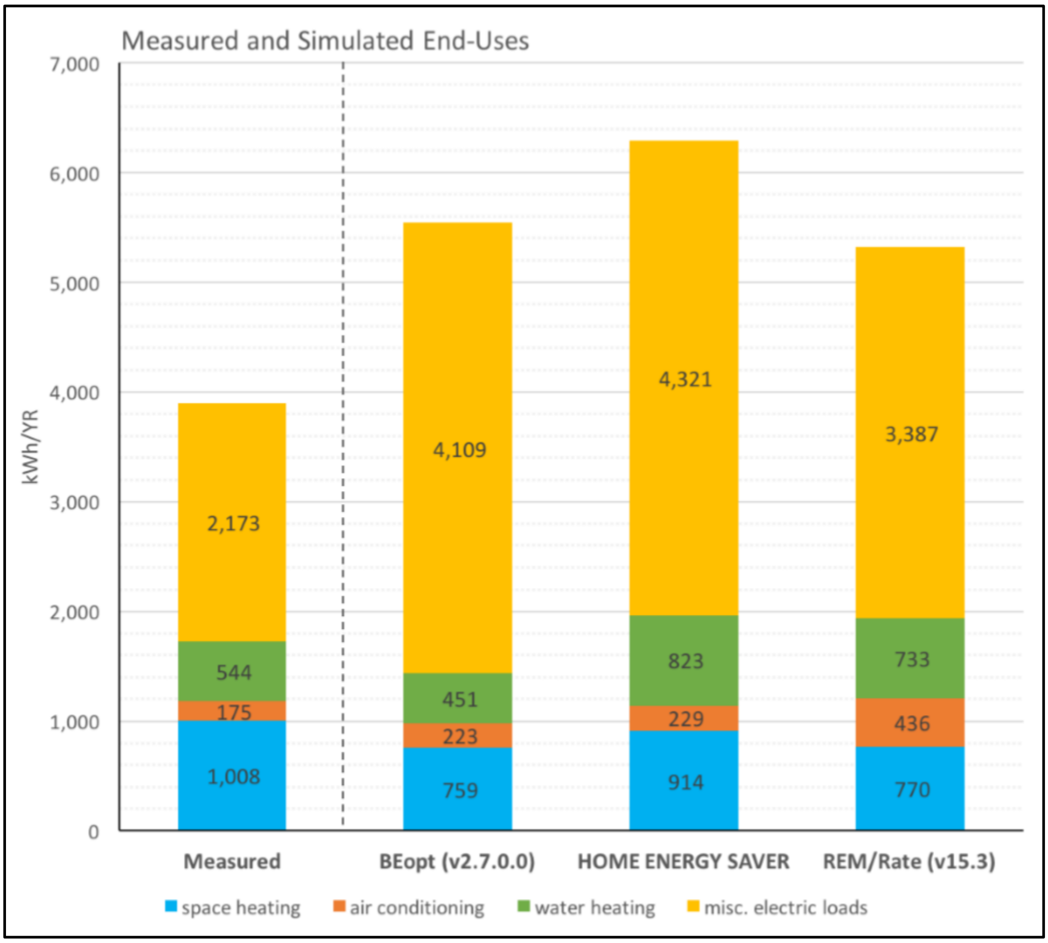

Figure 5: Measured and Simulated End-Uses, source: Agee et al., 2017

Out of the different simulation programs, "RemRate" provided the most accurate results, but still overestimated the energy consumption of MELs by 35%. In the study by Agee (2016), the residential units were simulated individually in "RemRate" and compared to the measured values as seen in Figure 6.

	Actual Use kWh/yr	Generated (solar) kWh/yr	Net-Measured kWh/yr	REM/Rate Simulation kWh/yr	REM/Rate Measure of Error kWh/yr
Unit A	6775	5617	1158	-15	1172
Unit B	2299	5480	-3181	-235	2946
Unit C	5467	4887	580	499	81
Unit D	4936	4793	143	587	444
Unit E	6152	5052	1100	147	953
Unit F	5734	4943	791	117	674
Unit G	4840	5216	-376	29	405
Unit H	4711	5282	-571	88	659
Total	40,914	41,270	-356	1,217	Diff. 1573
Sample Mean	5114	5158	-45	152	917
Sample Std Dev.	1338	292	1332	269	886

Figure 6: Actual versus simulated energy use, source: Agee, 2016

The characteristics of the envelope and the systems technologies are the same in every housing unit. Furthermore, the resident population in terms of age and income is the same for each unit. The results from the balance of actual energy consumption and solar energy generated indicate that this Net-Zero Energy Housing Community meets the criteria of Crawley, Pless and Torcellini (2009) and Marszal et al (2011) (see section 2), even during the operation phase of the building. The monitored energy consumption and the error rate of the simulation program show that the relationship between systems technologies and the behavior of the occupants has a significant influence on the ability to meet the Net-Zero Energy criteria. (Agee, 2016)

The energy perfomance and the definitions met will further be disussed in section 6.

3.2. General simulation parameters

In order to implement the building characteristics of the reference object, the author was provided with a number of design plans and data from Virginia Tech University. This section describes the implementation of general simulation parameters. The presented values and properties are generally applicable for the implementation scenarios described in section 3.3.

3.2.1. Building geometry

The building geometry was adapted to the metric system and converted into a plan format of the "AutoCad" program in order to simplify the implementation of the building geometry into the simulation program. The building body and the respective zones of the housing units were modeled from the adopted plan set. The author's investigations are limited to a single building of the housing community, which contains the units C and D as seen in Figure 6. Unit C is divided into four zones, while Unit D consists of five zones, as it contains a separate enclosed space for utilities as seen in Figure 7.

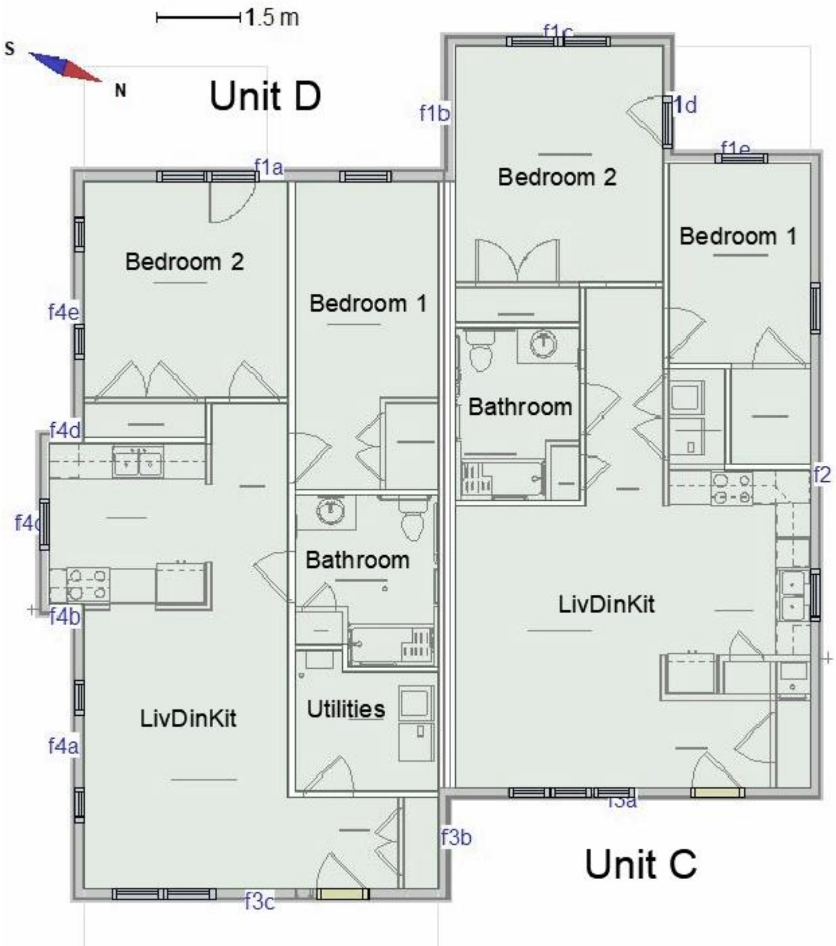

Figure 7: Building geometry and zones, source: Author

3.2.2. Building systems technologies

The calculation of the energy demand regarding heating and cooling was performed using ideal heating and cooling elements in IDA ICE. The program uses static energy efficiency factors to convert the calculated energy demand into an annual energy consumption. These factors were entered into the simulation program using the Coefficient of Performance (COP) for heating and the Energy Efficiency Ratio (EER) for cooling. However, since the manufacturer's data only represent the seasonal characteristics (see Table 3), they have been converted using a rule of thumb. Afterwards they were applied equally to all three versions. Thus, an EER of 4.46 and a COP of 2.94 were assumed for the calculation of the annual energy consumption.

The setpoints for the heating and cooling periods of systems technologies were selected based on a study by Parker (2013). The study evaluated numerous data sources showing measured data on heating and cooling temperatures in buildings and has the goal of describing appropriate heating and cooling thermostat set points in Building Energy Simulations for residential buildings in North America. However, they suggest an average 24-hour value of 18,89 °C for heating and 25 °C for cooling setpoints. This will further be discussed in section 6.

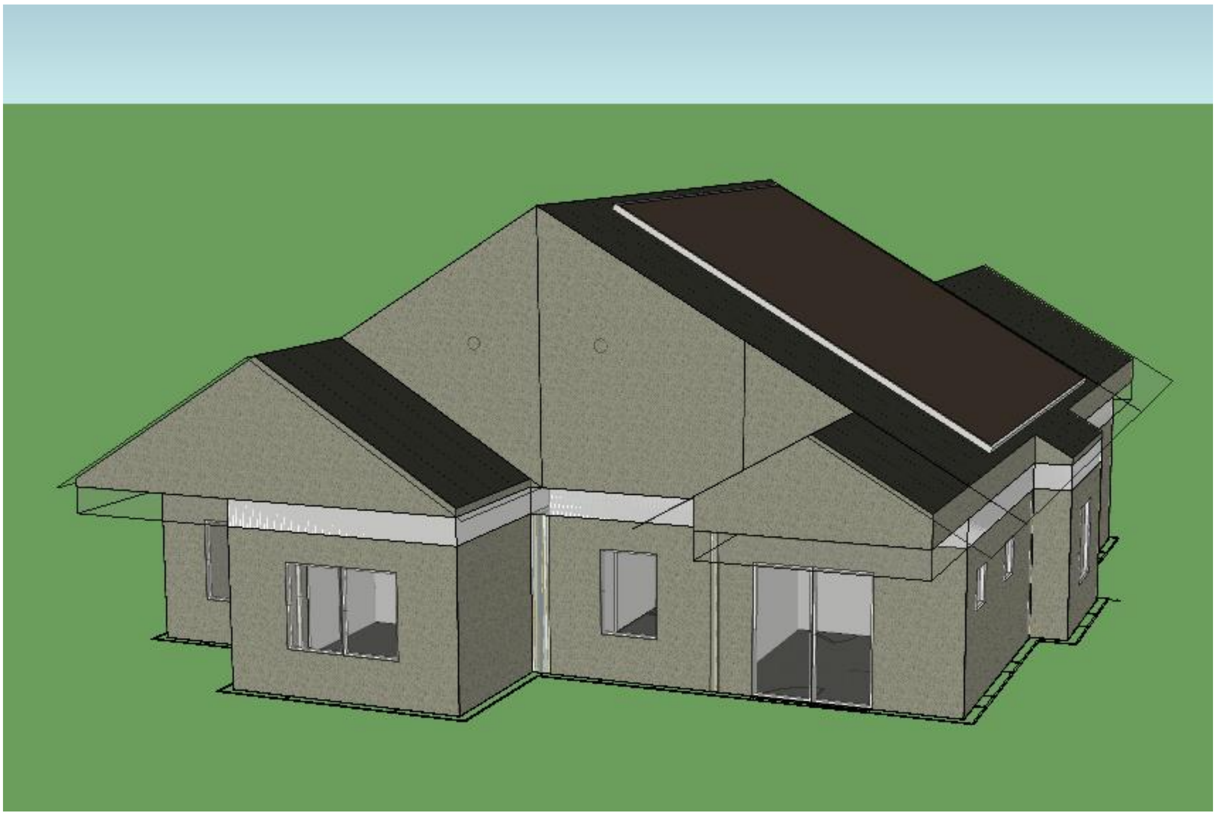

Figure 8: 3D model of the reference building, Source: Author

The photovoltaic system was added to the energy supply system in the simulation and partially adjusted until the values of the simulation results matched the monitoring data from Figure 6. The roof shape of the building allows the photovoltaic system to be oriented in a southeast direction with an azimuth angle of -20° and a vertical tilt of 30° (see Figure 8). All canopies were taken into account in the simulation to avoid distortion of the energy demand for both heating and cooling. However, one canopy on the north side had to be neglected, which has no significant influence on the calculation of demand because of its orientation. The ventilation rate for the attic space was estimated using a rule of thumb and was then included in the calculation through ventilation openings on the north and south sides of the attic space.

3.2.3. Internal gains

The basis for the input of internal gains is based on the AN-SI/RESNET/ICC 301-2019 standard. This standard is used for the calculation and labeling of the energy performance of dwelling and sleeping units using an Energy Rating Index and is approved by the American National Standard Institution (ANSI). The characteristics required for the calculation were adopted from this standard and adapted to the metric system (see Figure 9) and subsequently calculated using Equation 2.

$$Gains = a + b * CFA + c * NBr$$ [Eq. 2][2]

CFA Conditioned Floor Area in ft^2

NBr Number of Bedrooms

End Use Components	Sensible Gains in W			Latent Gains in W			Total in W
	a	b	c	a	b	c	
Residual MELs	0	0,089	0	0	0,005	0	**80,449**
Interior lighting	51,935	0,091	0	0	0	0	**130,596**
Refrigerator	72,718	0	2,051	0	0	0	**76,821**
TVs	47,148	0	7,876	0	0	0	**62,900**
Oven (elect.)	27,207	0	3,199	3,028	0	0,354	**37,342**
Clothes Dryer (electr.)	8,072	0	2,296	0,891	0	0,256	**14,067**
Dishwasher	2,674	0	1,062	2,674	0	1,062	**9,598**
Clothes Washer	1,160	0	0,317	0,134	0	0,037	**2,003**
General Water Use	-14,983	0	-4,994	15,203	0	5,068	**0,366**
Occupants	0	0	45,377	0	0	35,217	**161,189**

Figure 9: Internal gains converted calculation table, source: Author

[2] Equation 2: Calculation of internal gains, source: ANSI/RESNET/ICC 301-2019

The results were then adapted to the respective units and divided into their zones as seen in Figure 10 & 11. The use of schedules was avoided, because the internal loads were adjusted to a corresponding constant load.

Unit C				
Zone	**Area in m²**	**Lighting in W/m²**	**Equipment in W/m²**	**Occupants in W/m²**
Bedroom 1	15,87	1,632	1,005	2,014
Bedroom 2	14,31	1,632	1,005	2,014
Bathroom	7,51	1,632	1,054	2,014
LivDinKit	36,51	1,632	6,118	2,014
Utility	5,84	1,632	3,757	2,014

Figure 10: Internal gains for Unit C, source: Author

Unit D				
Zone	**Area in m²**	**Lighting in W/m²**	**Equipment in W/m²**	**Occupants in W/m²**
Bedroom 1	11,61	1,692	1,042	2,089
Bedroom 2	17,41	1,692	1,042	2,089
Bathroom	6,856	1,692	1,096	2,089
LivDinKit	41,3	1,692	5,951	2,089

Figure 11: Internal gains for Unit D, source: Author

Internal gains were subsequently accounted separately for each zone in the program. However, in this paper these are only used to calculate the heating and cooling energy demand and are not applied for the calculation of energy consumption by MELs.

3.2.4. Domestic hot water consumption

The hot water consumption was also calculated according to the ANSI/RESNET/ICC 301-2019 standard. According to the partner institution, one water heater for each building is used for both housing units. This water heater represents a heat pump water heater with an efficiency factor of 2.75. The possible impact on the energy balance using this technology was neglected. Equation 3 describes the composition of the individual hot water consumptions and Figure 12 shows both the total hot water consumption and the resulting annual energy use.

$$HWgpd = (refDWgpd + refCWgpd + Fmix * (refFgpd + refWgpd)) \qquad \text{[Eq. 3]}$$ [3]

HW_{gpd}	Hot water use in gallons per day
$refDW_{gpd}$	Reference dishwasher in gallons per day
$refCW_{gpd}$	Reference clothes washer in gallons per day
F_{mix}	Temperature mix factor
$refF_{gpd}$	Reference climate-normalized daily fixture water use in gallons per day
$refW_{gpd}$	Reference climate-normalized daily hot water waste through losses in gallons per day

Total hot water use per day		Hot water electr. energy use		
Description	**Value**	**Description**	**Unit**	**Value**
refdwgpd	3,54	**t_water_sup**	°C	10,00
refcwgpd	3,29	**t_water_out**	°C	52,00
fmix	0,73	**c_w**	kJ/kg*K	4,19
reffgdp	34,60	**ρ_w**	kg/dm³	1,00
fefwgd	13,20	**V° per Unit**	l/d	157,23
Total hot water use per Unit in gal per day	41,54	**Efficiency factor**	-	2,75
Total hot water use per Unit in l per day	**157,23**	**Total energy use**	kWh/y	**2040,26**

Figure 12: Domestic hot water consumption, source: Author

3.2.5. Miscellaneous electric loads

For the calculation of the MELs, the ANSI/RESNET/ICC 301-2019 standard was initially used. Figure 13 shows the calculation results for the annual energy consumption of MELs within the reference building and the respective factors of the end use components, which are required for the calculation using Equation 4.

$$kWh\ per\ year = a + b * CFA + c * NBr \qquad \text{[Eq. 4]}$$ [4]

CFA	Conditioned Floor Area in ft²
NBr	Number of Bedrooms

3 Equation 3: Hot water use, Source: ANSI/RESNET/ICC 301-2019
4 Equation 4: Calculation of MELs, Source: ANSI/RESNET/ICC 301-2019

End Use Components	Equation Coefficients			Total Use in kWh/y
	a	b	c	
Residual MELs	0	0,91	0	1539,44
Interior Lighting	455	0,8	0	2263,35
Exterior Lighting	100	0,05	0	284,58
Refrigerator	637	0	18	1346,00
Televisions	413	0	69	1102,00
Oven	331	0	39	818,00
Clothes Dryer	529	0	150	1658,00
Clothes Washer	78	0	31	280,00
Dishwasher	38	0	10	116,00
Total	-	-	-	9407,37
Total per Unit	-	-	-	4703,68

Figure 13: Energy use of MELs within the reference building, source: Author

The calculated total energy consumption by MELs of 9407.37 kWh/year applies to the entire building. Assuming that the energy consumption is distributed equally among the housing units, the energy consumption is 4703.68 kWh/year per unit. This consumption is disproportionately high when compared to the values in Figure 5 (chart AGEE). The measured consumption for MELs from the report by Agee et al. 2017 is an average value of all eight housing units of the Net-Zero Energy Building Community and results in a total consumption of 2173 kWh/year per unit. The calculation using the ANSI/RESNET/ICC 301-2019 standard overestimates the energy consumption by 116%. In order to keep a relation to the actual energy consumption of the reference building, the averaged value from the monitoring data is used in the further course of this thesis.

3.2.6. Additional specifications

The climate data required for the simulation are available in IDA ICE and reference is made to ASHRAE fundamentals 2013. This is the airport of Virginia Tech University, which is located in the close to the reference object and is also located in Blacksburg, VA.

The building ventilation is simulated in different versions in order to investigate the influence on energy consumption. However, the air flow volume of the ventilation system is the same for all three versions and was determined to be 67.96 m³/h according to the partner institution. This value is a constant air change rate and was applied equally among the three versions.

3.3. Case study implementations

This section describes the implementation of the reference building into the simulation program IDA ICE using three different design approaches. The properties and characteristics described in section 3.2 were applied to all three versions to ensure comparability equally. The individual requirements and characteristics of the versions are described in detail in the sections below.

3.3.1. Version 1: Reference Building

As a reference for the basic version, the reference building with the original construction details and thermal properties was used to enable a subsequent comparison with the other two versions. The individual layers of the wall constructions were integrated into the simulation program based on the plan sets in order to achieve the same U-values as seen in Figure 14. The building ventilation was included in the program according to the project information provided. The ventilation system is an exhaust air-only system with passive inlets in the two bedrooms. The exhaust air is removed in the bathrooms and the living rooms, and the passive supply air is distributed by overflowing zones in the respective units.

Construction characteristics	
External Walls:	
Construction type	Stud walls with blown-in cellulose insulation
U-Value	0,233 [W/m²K]
Foundation:	
Construction type	Insulated concrete slab, inside perimeter of foundation wall
U-Value	0,28 [W/m²K]
Insulated ceiling:	
Construction type	Pre-Engineered WD Roof with blown-in cellulose insulation, Truss with energy heel
U-Value	0,09 [W/m²K]
Fenestration:	
Construction type	Double-glazed vinyl window unit
Total U-Value	1,42 [W/m²K]
SHGC	0,27 [-]
Enclosure tightness:	
n50 (Air changes per hour)	2 [1/h]
Ventilation system:	Exhaust air only system with passive inlets in bedrooms; no heat recovery

Figure 14: Version 1 – characteristics, source: Author

3.3.2. Version 2: Passivhaus - thermal

The second version of the simulation is partly based on the criteria of the German “Passivhaus Institut”. Here, the minimum requirements for the performance of the exterior wall, foundation and fenestration were adopted. The value for the insulated ceiling was assumed to be 0.10 W/m²K as seen in Figure 15. The value for the Solar Heat Gain Coefficient (SHGC) is between 0.5 and 0.55 for the “Passivhaus” Standard. In this case, a SHGC of 0.55 was chosen to investigate the effects on the cooling energy demand. The air tightness and the ventilation system have been integrated into the simulation program in the same way as version 1. The air handling unit does not provide the possibility of heat recovery either. Any other criteria of the “Passivhaus Institut”, that are not mentioned in this context, were neglected.

Construction characteristics	
External Walls:	
Construction type	Insulated brick wall with EPS
U-Value	0,15 [W/m²K]
Foundation:	
Construction type	Insulated concrete slab, inside perimeter of foundation wall
U-Value	0,15 [W/m²K]
Insulated ceiling:	
Construction type	Insulated concrete ceiling with blown-in cellulose insulation
U-Value	0,10 [W/m²K]
Fenestration:	
Construction type	Triple-glazed window unit
Total U-Value	0,85 [W/m²K]
SHGC	0,55 [-]
Enclosure tightness:	
n50 (Air changes per hour)	2 [1/h]
Ventilation system:	Exhaust air only system with passive inlets in bedrooms; no heat recovery

Figure 15: Version 2 – characteristics, source: Author

3.3.3. Version 3: Passivhaus - thermal and ventilation

Version 3 of the simulations is also partly based on the criteria of the German “Passivhaus Institut”. The minimum requirements for the performance of the exterior wall, foundation, fenestration and insulated ceiling were adopted as in Version 2. In this version, further criteria of the “Passivhaus Institut” have been adopted. The air exchange rate for infiltration was assumed to be 0.6 h^{-1} in order to investigate the influence of air tightness on the total energy consumption (see Figure 16). Furthermore, a balanced supply and return air handling unit was added to the energy concept in order to investigate the influence of ventilation heat losses on the total energy consumption. The ventilation system includes a heat recovery system with a heat recovery ratio of 75%. Any other criteria of the “Passivhaus Institut”, that are not mentioned in this context, were neglected.

Construction characteristics	
External Walls:	
Construction type	Insulated brick wall with EPS
U-Value	0,15 [W/m²K]
Foundation:	
Construction type	Insulated concrete slab, inside perimeter of foundation wall
U-Value	0,15 [W/m²K]
Insulated ceiling:	
Construction type	Insulated concrete ceiling with blown-in cellulose insulation
U-Value	0,10 [W/m²K]
Fenestration:	
Construction type	Triple-glazed window unit
Total U-Value	0,85 [W/m²K]
SHGC	0,55 [-]
Enclosure tightness:	
n50 (Air changes per hour)	0,6 [1/h]
Ventilation system:	Balanced supply and return air system; heat recovery ventilation η=75%

Figure 16: Version 3 – characteristics, source: Author

4. Results

In the following sections, the influences of the different design characteristics on the total energy consumption are presented. The values for the total annual energy use are then compared to the energy production of the photovoltaic system. A balance between the two values is then established and presented.

4.1. Results Version 1

The values presented in Figure 17 represent the total energy used for space heating and -cooling, domestic hot water, HVAC auxiliary and appliances regarding Version 1. The values for space heating and -cooling have been calculated by the simulation program under the conditions described in section 3.3.1. Domestic hot water energy use has been calculated using the RESNET Standard described in section 3.2.4. The energy use for HVAC auxiliary also includes the energy use of fans used for the building ventilation. Appliances and MELs energy use have been applied using the values of the monitoring process of the building (see section 3.2.5). Figure 18 shows the annual energy consumptions by sector and the balance of renewable energy generation and energy consumption.

Version 1: Reference Building	
End Use Categories	**Energy Use in kWh**
Space heating	2298,0
Space cooling	260,0
Domestic hot water	2040,3
HVAC Aux	596,0
Appliances (MELs)	4346,0
Total Energy Use	9540,3
PV Production	-9680,0
Balance	-139,7

Figure 17: Annual energy use of Version 1 in kWh/year, source: Author

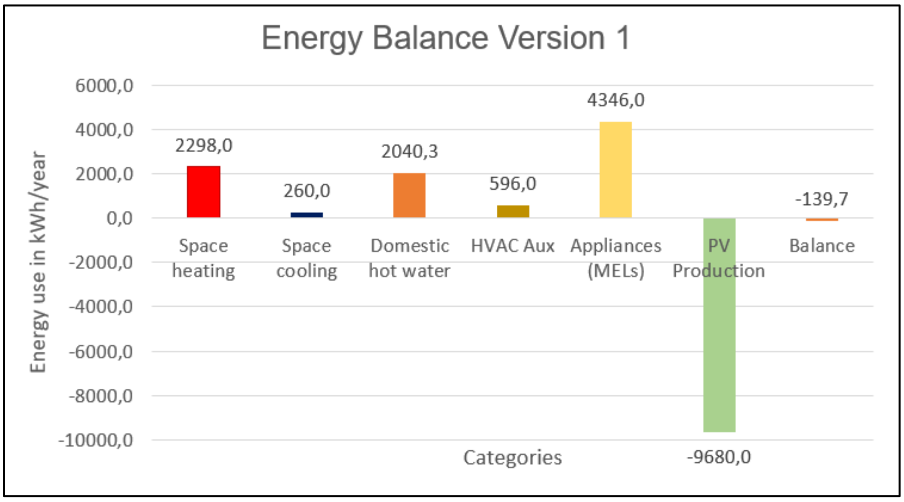

Figure 18: Energy Balance Version 1, source: Author

4.2. Results Version 2

The values presented in Figure 19 represent the total energy used for space heating and -cooling, domestic hot water, HVAC auxiliary and appliances regarding Version 2. The values for space heating and -cooling have been calculated by the simulation program under the conditions described in section 3.3.2. Domestic hot water energy use has been calculated using the RESNET Standard described in section 3.2.4. The energy use for HVAC auxiliary also includes the energy use of fans used for the building ventilation. Appliances and MELs energy use have been applied using the values of the monitoring process of the building (see section 3.2.5). Figure 20 shows the annual energy consumptions by sector and the balance of renewable energy generation and energy consumption. Figure 20 shows the annual energy consumptions by sector and the balance of renewable energy generation and total energy used.

Version 2: Passivhaus - thermal	
End Use Categories	**Energy Use in kWh**
Space heating	1426,0
Space cooling	704,0
Domestic hot water	2040,3
HVAC Aux	596,0
Appliances (MELs)	4346,0
Total Energy Use	9112,3
PV Production	-9680,0
Balance	-567,7

Figure 19: Annual energy use of Version 2 in kWh/year, source: Author

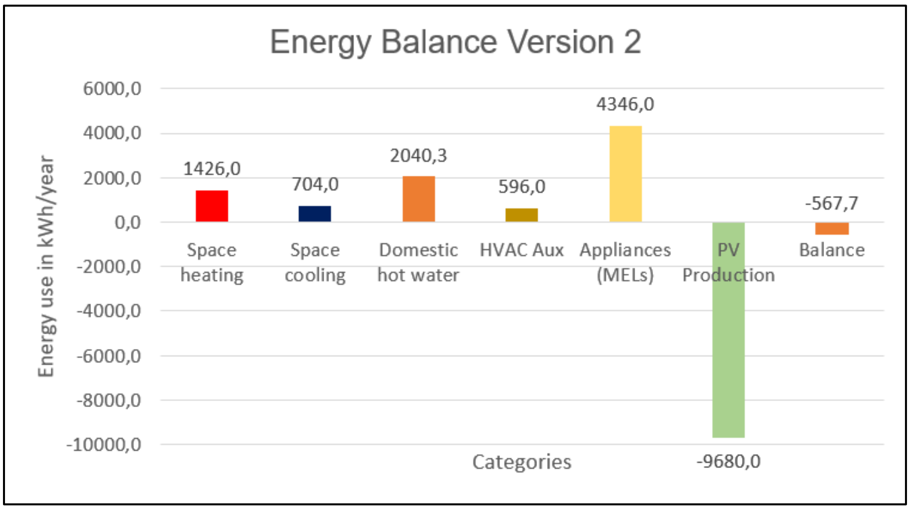

Figure 20: Energy Balance Version 2, source: Author

4.3. Results Version 3

The values presented in Figure 21 represent the total energy used for space heating and -cooling, domestic hot water, HVAC auxiliary and appliances regarding Version 3. The values for space heating and -cooling have been calculated by the simulation program under the conditions described in section 3.3.3. Domestic hot water energy use has been calculated using the RESNET Standard described in section 3.2.4. The energy use for HVAC auxiliary also includes the energy use of fans used for the building ventilation. Appliances and MELs energy use have been applied using the values of the monitoring process of the building (see section 3.2.5). Figure 22 shows the annual energy consumptions by sector and the balance of renewable energy generation and energy consumption.

Version 3: Passivhaus - thermal and ventilation	
End Use Categories	**Energy Use in kWh**
Space heating	710,0
Space cooling	734,0
Domestic hot water	2040,3
HVAC Aux	1170,0
Appliances (MELs)	4346,0
Total Energy Use	9000,3
PV Production	-9680,0
Balance	-679,7

Figure 21: Annual energy use of Version 3 in kWh/year, source: Author

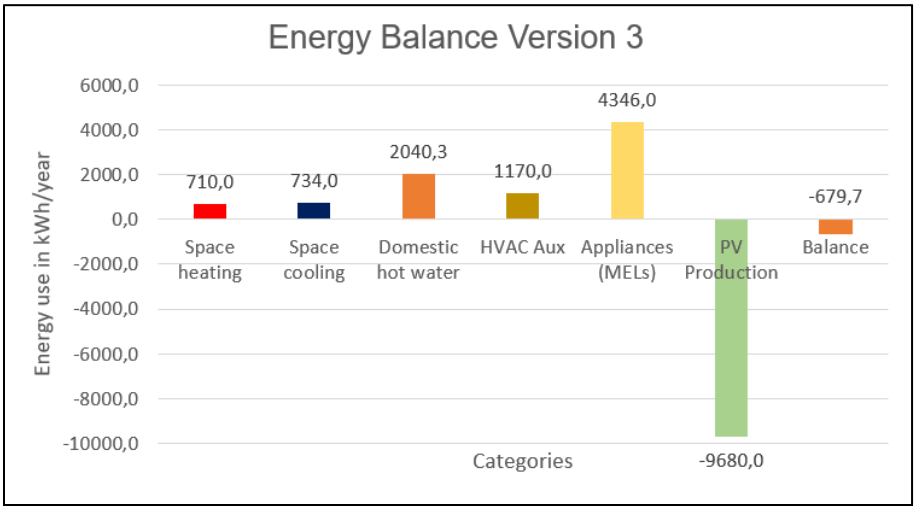

Figure 22: Energy Balance Version 3, source: Author

5. Findings

From the simulation results (see section 4) you can see a constant improvement of the total annual energy consumption by each measure taken. However, this finding cannot be applied to the individual sub-sectors.

The calculation of Version 1 results in a total energy consumption of 9540.9 kWh/year. The total of the recorded data for Unit C and Unit D of the study by Agee (2016) (see Figure 6), equals 10403 kWh/year. Comparing these values, the deviation is 8.3%. However, this deviation can be explained by the use of the averaged monitoring data for MELs from Figure 5, since the disproportionately low consumption of unit B was included. This finding suggests that the calculations of the heating and cooling energy demand and the resulting total energy consumption are very close to the actual values of the reference building. This statement is confirmed by the comparison of the respective energy consumption by heating and cooling. Version 1 consumes 2298 kWh/year for heating and 260 kWh/year for cooling (see Figure 17). The averaged values from Figure 5 are 2016 kWh/year for heating and 350 kWh/year for cooling, only slightly below or above the simulated version. Thus, version 1 is a good initial basis for the further evaluation of the energy reduction by the measures taken in version 2 and 3.

The comparison of the total annual energy consumption of versions 1 and 2 (see Figure 17 & 19) shows that the improvements in the thermal properties of the building envelope have a significant impact on the reduction of the total annual energy consumption for heating. By this measure, a 38% reduction in heating energy consumption has been achieved. However, the increase of the SHGC value leads to an increase in cooling energy consumption of 171%. The total annual energy consumption is reduced by 4.5% due to the measures taken.

The comparison of the total annual energy consumption of version 2 and 3 (see Figure 19 & 21) shows a reduction of 50% in heating energy consumption and only 1.3% of total reduction. This can be explained by the 96% increase in energy consumption for air handling units (HVAC auxiliary). This increase in consumption can be attributed to the use of a second fan in the selected system for version 3. In this case, the total energy consumption for cooling exceeds the heating energy consumption. The reduction of the air change rate by infiltration and the heat recovery measure have little effect on the total annual energy consumption of version 3.

6. Conclusions

A building with a high standard of energy efficiency, located in Blacksburg, Virginia, was simulated in this work according to different methods. Section 2 shows that this term is very comprehensive and without a uniform framework, it is not very meaningful in terms of comparability. In addition, the literature review also shows that a building that meets the NZEB criterion is not necessarily an indicator of a sustainable use of resources.

The residential development was designed to meet the Net-Zero Energy Building criterion in the combined operation. The findings of the energy monitoring (see Figure 6) show that this criterion was achieved not only theoretically in the simulations, but also practically according to the energy monitoring data. However, according to the definitions of Pless & Torcellini (2010), only the class of a site energy building of class NZEB:A could be achieved. However, it should be noted that this was only achieved by the very conservative power consumption of unit B (see Figure 6). However, if this exception were not included in the balance, the target would not be achieved. Furthermore, considering Figure 6 with regard to the energy balance of Building 2 (Unit C & Unit D), this definition is not achieved for the individual building. Furthermore, this classification is to be viewed critically, as the Department of Energy modified the key definition in 2015 and thus Net-Zero Site Energy Buildings no longer fall within the scope of the elaborated definition. Rather, they are now accounted for according to source energy.

For this reason, different versions of this building with the same footprint of the building were simulated and analyzed with different parameters. The two other building variants were also examined to investigate the influence of the building envelope on the annual energy balance for the same amount of energy produced and the resulting impact on different definitions of zero-energy buildings. The results from version 1 show that the simulated version of the reference building meets the definition of Pless & Torcellini (2010) in this case.

The results of the study also show that a reduction in consumption from version 1 to version 2 of 4.5% and a reduction of 1.3% from version 2 to version 3 is achieved. These results show that the Austrian version also meets the definition of Pless & Torcellini (2010).

The results of this work confirm the statement of Agee (2016) that by reducing the energy demand for heating and cooling of buildings through ever improving building envelopes, the energy consumption influenced by the occupants becomes more and more important. This fact underlines the need for energy metering in relation to NZEBs. Not only to ensure the classification during operation, but also for the implementation of renewable energy sources in public networks with regard to smart grids and variable electricity rates.

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