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Analysis of energy use and greenhouse gas emissions at the future building stock at the NTNU campus Gløshaugen

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Master in Industrial Ecology

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MASTER THESIS

for

Student Aleksandra Woszczek

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Analysis of energy use and greenhouse gas emissions at the future building stock at the NTNU campus Gløshaugen

Analyse av energibruk og klimagassutslipp for fremtidig bygningsmasse på NTNU campus Gløshaugen

Background and objective

The building stock represents a large share of the national energy demand, and is subject to ambitious policies on energy efficiency and shifts towards less carbon-intensive energy carriers. Current trends and recent analyses show that there is a large potential for energy improvements in the stock of existing buildings. With an ageing building stock, such efforts become increasingly important. Parallel to the refurbishment process of ageing buildings, new and better-performing buildings (TEK10, Passive house standard and NZEB standard) are added to the stock.

Previous building stock studies have mainly investigated the characteristics and dynamics of the dwelling stocks on a national or municipality scale. In parallel, much research has been done on energy efficiency solutions for individual buildings. The Zero Emission Neighbourhood Research Centre (ZEN Research Centre) studies the energy demand on a neighbourhood scale and investigates the combination of building-specific measures and local solutions on the neighbourhood scale. This Master thesis is related to the ongoing work at the ZEN Research Centre.

The objective of this MSc thesis is to carry out a systematic study of the current and possible future energy use in the building stock at the NTNU campus Gløshaugen. A neighbourhood building stock energy model is developed through the ZEN Research Centre and will be applied to the NTNU campus in this Master thesis. The model will be used to investigate possible future development paths for the energy use on the NTNU campus towards 2050, as well as the related greenhouse gas emissions. A scenario analysis will be used to identify the most critical factors for the future development and to evaluate to what extent it is possible for the NTNU campus to develop towards a zero energy or zero emission neighbourhood.

The following tasks are to be considered:

1. Carry out a literature review relevant to the work of the Master thesis.
2. Describe the current and possible future building stock at NTNU campus Gløshaugen, including information on functions and construction year, as well as current and possible future energy use for all buildings.
3. Develop a building typology description that is suitable for segmenting the current and future NTNU campus building stock.
4. Describe possible solutions for local energy generation and storage in this neighbourhood.
5. Provide an overview of the current monthly greenhouse gas emissions from the energy carriers used at Gløshaugen and estimate how they may change in the future.
6. Develop scenarios that are relevant to study the critical factors for future development in energy use and related greenhouse gas emissions in this system.
7. Run the neighbourhood building stock energy model for selected scenarios, with use of relevant IDA ICE energy profiles for existing and future buildings, and present results showing possible future development paths.
8. Discuss what factors will be the most important for future energy demand and greenhouse gas emission mitigation at NTNU campus.
9. Discuss strengths and weaknesses of your work, and recommendations for future research.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to “Regulations concerning the supplementary provisions to the technology study program/Master of Science” at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student’s name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 15. January 2018

Professor Helge Brattebø
Academic Supervisor

Research Advisor: Postdoc Nina Holck Sandberg

Abstract

The building sector plays an important role in a reduction in energy demand and greenhouse gas emissions. Recently, Zero Energy/Emission Neighbourhoods have aroused a lot of interest both in policies and in scientific research. The main objective of the study is to determine whether the building stock at NTNU Gløshaugen is able to become a Zero Energy/Emission Neighborhood towards 2050. A neighbourhood energy model is applied to the NTNU campus Gløshaugen in order to study the development of the building stock, energy demand and greenhouse gas emissions towards 2050.

The study shows that the building stock at NTNU Gløshaugen is expected to increase as a result of the relocation of campuses from other parts of Trondheim to NTNU Gløshaugen and in 2050 the heated floor area of the building stock is estimated to total 310 714 m^2. In spite of the stock growth, the estimated energy demand is considered to decrease from 2017 to 2050 by 10% (in Baseline scenario) and by 26% (in the most optimistic scenario) thanks to renovation activity and demolition of less energy-efficient buildings. The greenhouse gas emissions are estimated to decline by 40% (in Baseline scenario) and by 57% (in the most optimistic scenario), mainly due to a significant decrease in heat demand and a substitution of district heating with low carbon heat technologies (heat pumps and NH3).

Finally, the study demonstrates that NTNU Gløshaugen is far from reaching a Zero Energy/Emission balance in 2050. High electricity demand and limited local energy generation from photovoltaics and a biogas-based CHP result in a heavy reliance on imports of electricity. The findings suggest that advanced renovation including extensive use of heat pumps is the most promising strategy for reduction in energy demand and greenhouse gas emissions.

Preface

This dissertation is submitted for the degree of Master of Science in Industrial Ecology. The thesis was written in the spring semester 2018 at the Department of Energy and Process Engineering, Norwegian University of Science and Technology in Trondheim.

Due to a late handover of IDA ICE energy use profiles, which are key components of the scenario analysis, the scope of this thesis had to be limited. The tasks of the thesis were modified in agreement with the supervisors. Energy storage possibilities at NTNU Gløshaugen were not investigated. In addition, the sensitivity analysis of parameters was not performed.

Acknowledgments

I would like to thank my supervisor Helge Brattebø and my co-supervisor Nina Holck Sandberg for their scientific guidance, valuable inputs and support. Furthermore, I would like to express my thanks to Jan Sandstad Næss for his help with Matlab and the model. I would also like to thank Emil Dæhlin, Eirik Nesgård, Huy Ngo, Karoline B. Halvorsen Johansen, Ingrid M. Rennan and Andrea E. Holltrø Sørras for providing inputs into the thesis.

This work would have been impossible to complete without receiving support and help. I wish to express my gratitude to my parents and my little brother Filip who never stop believing in me. Last but not least, I want to express my sincerest thanks to my friends, particularly to my flatmates. I really appreciate all the love and support you gave me during our two years together in Trondheim.

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1. Introduction

1.1. Background

The Paris Agreement aims to maintain a global temperature increase below 2°C above preindustrial levels and even further to limit the temperature rise to 1,5°C. To reach this ambitious goal, appropriate measures mitigating climate change need to be taken (Vandyck, Keramidas, Saveyn, Kitous, & Vrontisi, 2016).

Buildings consume 40% of energy in the European Union, accounting for 36% of the CO_2 emissions (EPBD, 2010). Similarly, in Norway buildings are responsible for 40% of energy consumption, of which 22% is used by the residential building stock and 18% by the commercial buildings (Sartori, Wachenfeldt, & Hestnes, 2009).

According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, the energy use in buildings may double or even triple by mid-century. A major contributor is the increased standard of living in developing countries. More and more people are gaining access to adequate housing and cooking facilities. Other trends, which are related to increasing energy use in buildings, are population growth, migration from rural areas to cities, lifestyle changes as well as an increase in affluence (Lucon et al., 2014).

Buildings, due to the very long lifespan, have an impact on long-term energy consumption and have a significant potential to reduce energy demand and related emissions. The reduction of the energy consumption and the use of energy from renewable sources in buildings would allow to keep the global temperature increase below 2°C and reduce by 2050 greenhouse gas emissions by 80-95% below 1990 levels (EPBD, 2010).

The European Union issued two directives: the Energy Performance of Buildings Directive and the Energy Efficiency Directive, which are addressed to reduce energy use in buildings. The first introduces obligatory energy performance certificates in advertisements for the sale and rental of buildings and requires that all new buildings must be nearly zero energy buildings by 2020 and public buildings by 2018 (EPBD, 2010). The latter includes renovations at least 3% of buildings owned by central government (EED, 2012).

During the last few years, Zero Energy Buildings have received international attention both in policies and in the scientific literature. Nowadays, they are perceived as the target for the future design of buildings in order to reduce energy use and CO_2 emissions in the building sector.

In a period of 2009 - 2017 the Research Centre on Zero Emission Buildings was functioning in Norway. In 2017 the Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN Centre) was established as a follow-up to the Research Centre on Zero Emission Buildings. The main aim of the ZEN Centre is to develop competitive products and solutions for future buildings and neighbourhoods that will result in zero greenhouse gas emissions related to construction, operation and demolition of buildings (ZEN Research Centre).

One of the ZEN Centre's pilot projects is Knowledge Axis Trondheim, a north-south bound route in Trondheim with a high concentration of knowledge institutions. NTNU Gløshaugen is situated within the Knowledge Axis and NTNU is one of the primary actor along the axis. The planned relocation of campuses from other parts of Trondheim to NTNU Gløshaugen included in the Campus Development Project involves substantial construction activities. New buildings should be nearly zero emission buildings and energy efficiency in already existing buildings should be improved. Furthermore, in a long-term perspective NTNU has a vision of the zero energy building stock at NTNU Gløshaugen in 2060 (*NTNU 2016 Visjoner for Campusutvikling*, 2014).

The above-mentioned arguments make NTNU Gløshaugen an interesting case of research.

1.2. Main objectives

The objective of this Master thesis is to perform a study of possible future energy demand and related greenhouse gas emissions of the building stock at NTNU Gløshaugen towards 2050. In order to investigate possible future development paths for energy demand of NTNU Gløshaugen as well as associated greenhouse gas emissions a neighbourhood building stock energy model developed by the ZEN Centre is used. The following research questions are formulated:

1. To what extent is the building stock at NTNU Gløshaugen able to become a Zero Energy/Emission Neighbourhood towards 2050?
2. Which factors are the most important and which strategies are the most promising for reduction in energy demand and greenhouse gas emissions at NTNU Gløshaugen towards 2050?

1.3. Structure

Chapter 2 presents theory relevant for the case study and chapter 3 includes literature review. Chapter 4 explains methods used in the thesis and contains a detailed description of the case study and inputs into the Zero Emission Neighbourhood model. The results from modelling are demonstrated in chapter 5. The discussion of the results as well as strengths and weaknesses of the work are presented in Chapter 6. The last chapter contains the conclusion of the findings.

2. Theory

The theory chapter refers to and briefly outlines principles of the Zero Energy/Emission Building and Neighbourhood concepts.

2.1. Zero Energy Building concept

Zero Energy Building is a complex concept and thus several approaches co-exist which highlight various aspects of ZEB. Generally speaking, the Zero Energy Building is an energy efficient building capable of producing energy from renewable sources in order to offset its energy demand. The Zero Energy Building concept includes both autonomous buildings (off-grid ZEB) and buildings connected to the grid (net ZEB). The European Directive on the energy performance of buildings defines a 'nearly Zero Energy Building' as a high energy performance building which nearly zero or very low energy demand is covered to a large extent by energy from renewable sources generated on-site or nearby (EPBD, 2010).

Sartori, Napolitano & Voss (2012) develop a consistent framework which analyses all the significant aspects of net ZEB. The net ZEB balance is achieved when weighted supply is equal to or exceeds weighted demand. Figure 1 illustrates the interaction between a building and the grid in the net ZEB.

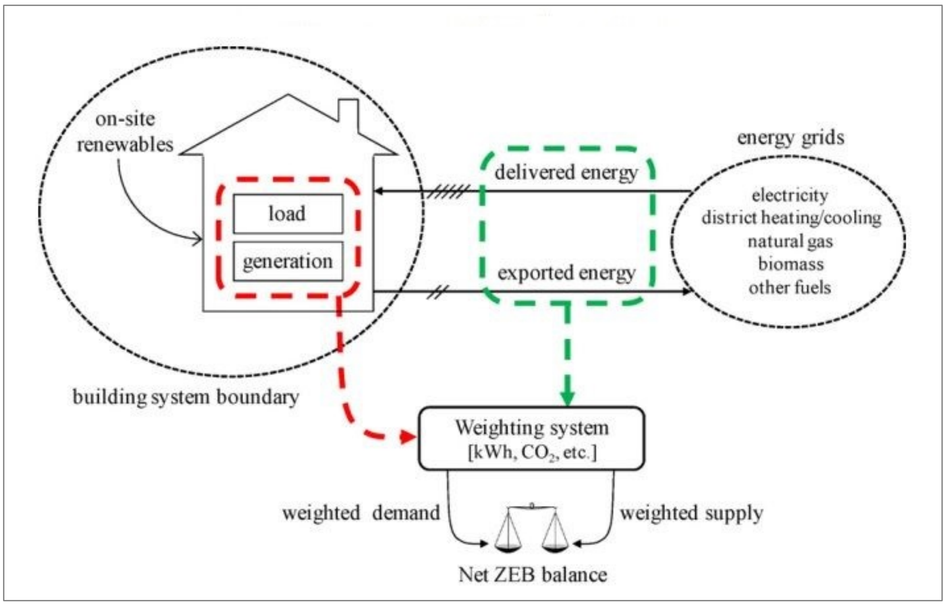


Figure 1. *Net ZEB. The interaction between a building and the grid (Sartori et al., 2012)*

A weighting system converts physical units into homogenous metrics. The weighting factor is unique for each energy carrier and varies over time and space. Therefore, the evaluation of weighting factors is a challenging task, particularly for electricity and thermal networks as it is dependent on several factors such as energy mix within specific geographical boundaries, present and expected future values, etc. In order to assess a Zero Energy Building, primary energy factors (PE) are used, while the evaluation of a Zero Emission Building requires CO_2 factors (Lindberg, 2017).

Figure 2 is a graphical representation of the net ZEB balance with the weighted demand on the x-axis and the weighted supply on the y-axis. In order to reach the net ZEB balance, energy demand of the reference building should be reduced by adopting energy efficiency measures. In addition, energy production from on-site renewable sources should be sufficient for compensating for the building's energy demand. In most cases, major energy efficiency measures are required since on-site energy production options are limited (Sartori et al., 2012).

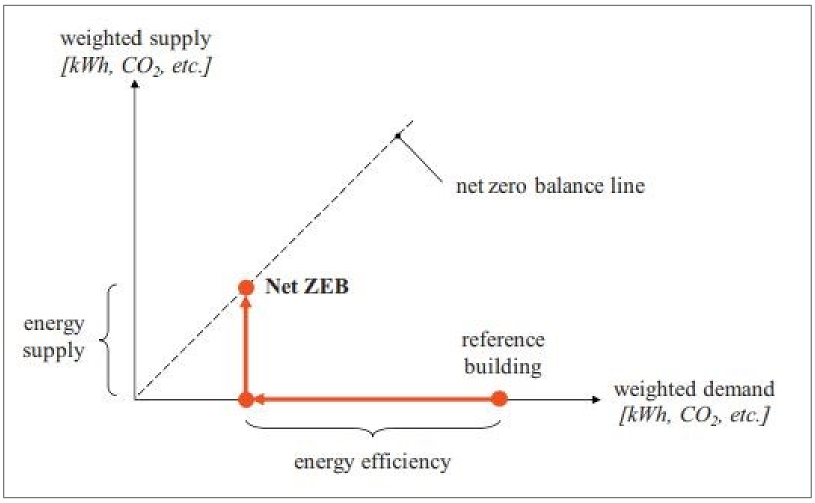


Figure 2. *Net ZEB balance concept (Sartori et al., 2012)*

The net ZEB balance can be calculated in terms of either delivered and exported energy or load and generation. In the first case, the balance can be calculated from the measurements of delivered and exported energy quantities, or alternatively based on estimated delivered and exported energy values during a design stage. Equation 1 shows the calculation for assessing an import/ export balance. The parameters e and d correspond to exported and delivered energy, respectively, w represents the weighting factor and i expresses energy carrier. E and D describe the weighted exported and delivered energy, respectively (Sartori et al., 2012).

$$\sum_i e_i \times w_{e,i} - \sum_i d_i \times w_{d,i} = E - D \geq 0 \quad (1)$$

Nevertheless, most building codes do not involve estimating self-consumption of energy generated on-site and thus data on delivered and exported energy quantities are lacking. Load and generation values are commonly available and a load/generation balance is presented in Equation 2 where g and l relate to generation and load, respectively, w corresponds to the weighting factor and i stands for energy carrier. G and L describe the weighted generation and load, respectively (Sartori et al., 2012).

$$\sum_i g_i \times w_{e,i} - \sum_i l_i \times w_{d,i} = G - L \geq 0 \tag{2}$$

The study of Satori et al. (2012) assumes that per each carrier the load is entirely met by delivered energy and the generation is entirely supplied to the grid. Figure 3 shows two types of the ZEB balance on the weighted demand and supply axes. The weighted demand and supply is expected to be lower in the import/export balance due to self-consumption. In the load/generation balance the building and energy generated are perceived separately, whereas in the import/export balance there is an interaction between the building and the grid and in this case the self-consumption is considered as an efficiency measure since it reduces the amount of exchanged energy (Sartori et al., 2012).

In the study, Sartori et al. (2012) concentrate on a single building. However, the framework can be applied for a cluster of buildings (Sartori et al., 2012)

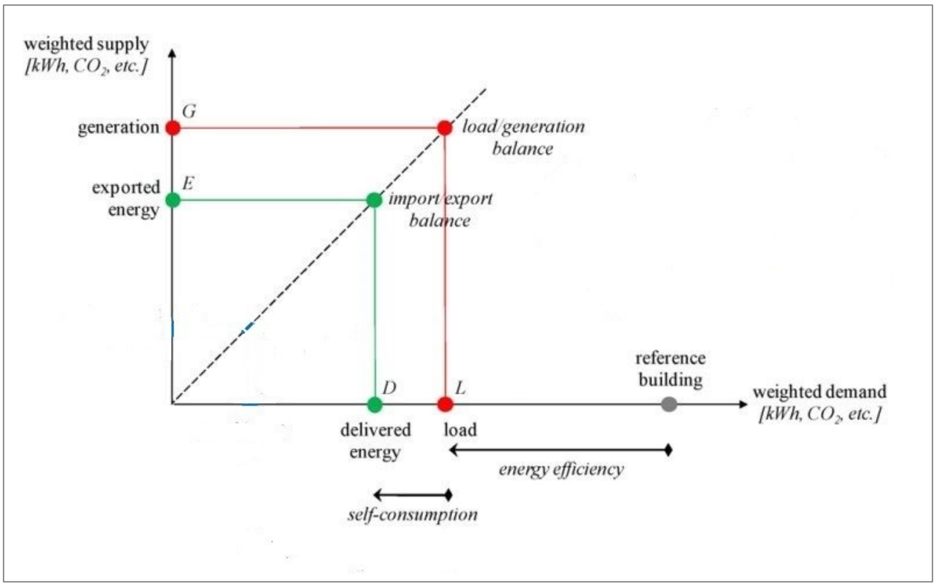


Figure 3. *Graphical representation of the two types of balance: import/export and load/generation balance (Sartori et al., 2012)*

2.2. Norwegian definition of Zero Emission Building

The Norwegian Research Centre on Zero Emission Buildings defines a Zero Emission Building based on the balance of associated greenhouse gas emissions during the lifetime of a building. Furthermore, the ZEB Research Centre determines five different ambition levels as presented in Figure 4 (Fufa, Schlanbusch, Sørnes, Inman & Andresen, 2016).

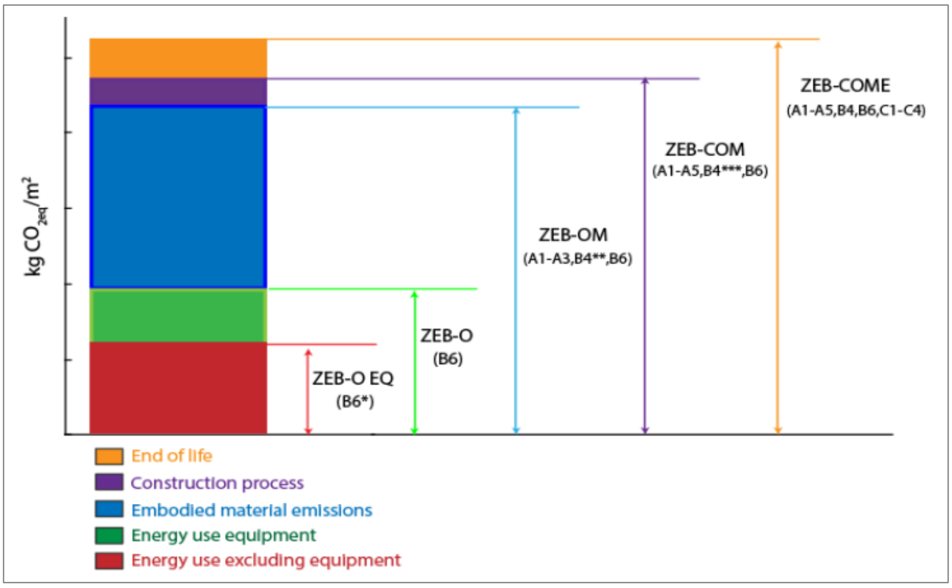


Figure 4. *ZEB ambition levels (Fufa et al., 2016)*

The lowest ambition level is ZEB-O EQ and it takes into account emissions related to all energy use for operation (O) excluding energy use for equipment and appliances (EQ). ZEB-O includes emissions from all operational energy, whereas ZEB-OM considers emissions both from all operational energy and emissions embodied in materials (M). ZEB-COM besides emissions included in ZEB-OM takes into account emissions related to construction process of a building. The highest ambition level is ZEB-COME and it considers emissions associated with construction, operation, materials and the end of life phase of a building (E). The two lowest level (ZEB-O EQ and ZEB-O) do not include emissions from materials and therefore such buildings may have relatively low greenhouse gas emissions during operation phase. Emissions embodied in materials account for a significant part of the total emissions over the lifetime of a building (Dokka, Sartori, Thyholt, Lien & Lindberg, 2013; Fufa et al., 2016).

2.3. System boundaries

Marszal et al. (2010) suggest five possible renewable energy supply options depending on the location of the energy supply option with regard to the building as shown in Figure 5. Marszal et al. (2010) point out that none of the options is preferable and Figure 5 does not represent a hierarchy of energy supply options.

The ZEB Research Centre agrees to use option I, II and III in Figure 5 regarding local renewable electricity generation. This includes on-site electricity production. In addition, off-site renewables such as biomass can also be used in on-site electricity production. When it comes to heat generation, the ZEB Research Centre decides to use option I, II, III and IV. Thermal energy can be produced either on-site or off-site. However, emissions from the actual energy mix and system losses from the production site to the building should be considered (Dokka et al., 2013).

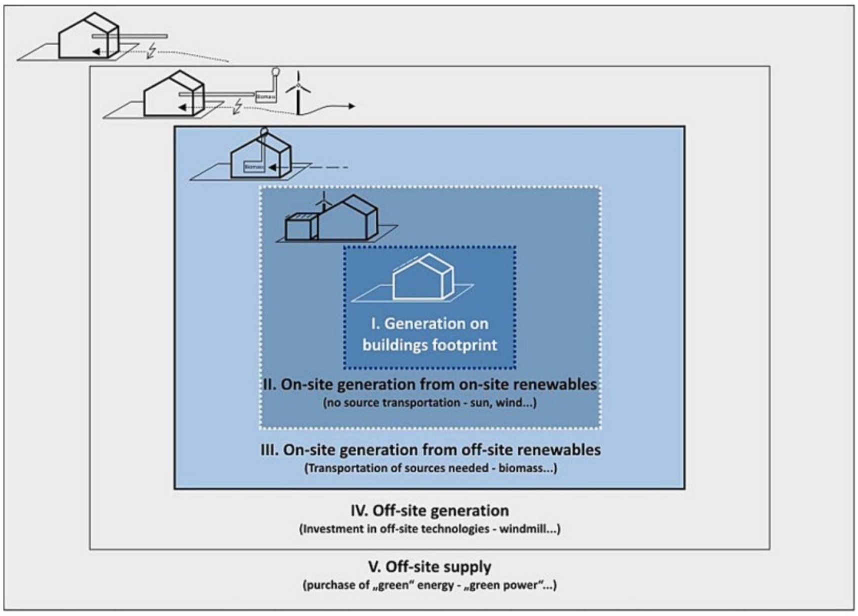


Figure 5. *Renewable energy supply options (Marszal et al., 2010)*

2.4. Zero Emission Neighbourhood concept

The ZEN Research Centre describes 'a neighbourhood' as a group of buildings (new, refurbished or a mix of both) and infrastructure (energy, water, sewage systems, roads, communication lines) situated within a specified geographical area and with a defined boundary of the electrical and thermal grid. The goal of a Zero Emission Neighbourhood is to reduce GHG emissions toward zero within its life cycle (Wiik et al., 2018).

In order to achieve this target, the neighbourhood should be highly energy efficient and smartly powered by local renewable energy sources. In addition, design and construction of buildings in the neighbourhood should contribute to zero or low GHG emissions during life cycle, from extraction of raw materials, through production, transport, installation, use, maintenance, deconstruction, waste treatment, reuse to final disposal. Moreover, during the planning, design and operation stages there should be focus on economic sustainability and diminishing life cycle costs. The design of the neighbourhood should allow to develop sustainable transport patterns as well as implement a sustainable mobility system both for local and regional use (Wiik et al., 2018).

2.4.1. From Zero Energy Building to Zero Energy Neighbourhood

Marique & Reiter (2014) develop a framework and a calculation method in order to assess zero-energy neighborhoods. Marique & Reiter (2014) analyse solely residential neighbourhoods. Nevertheless, the framework according to Marique & Reiter (2014) could be applied in non-residential neighbourhoods or a combination of residential and non-residential neighbourhoods.

A Zero Energy Neighbourhood concept is analogous to a 'Zero Energy Building' and is defined as a neighbourhood in which annual energy consumption of buildings as well as transportation of inhabitants is compensated for on-site renewable energy. The balance considers exclusively the operation phase of the neighbourhood and is calculated in terms of primary energy. In the study, the net Zero Energy Neighbourhood assumes interaction within the buildings and between the building and transportation energy consumption. Therefore, not every building in the neighbourhood is necessarily a zero energy building and the total annual energy balance is considered at the neighbourhood scale. Three types of energy uses are regarded: building energy consumption, on-site renewable energy generation and transportation energy consumption (Marique & Reiter, 2014).

Building energy consumption takes into account energy consumption for space heating (E_{SH}), space cooling (E_{CO}), ventilation (E_V), appliances (E_A), cooking (E_C) and domestic hot water (E_{HV}) as presented in Equation 3 (Marique & Reiter, 2014).

$$E_B = E_{SH} + E_{CO} + E_V + E_A + E_C + E_{HV} \tag{3}$$

The annual energy consumption for space heating, cooling and ventilation is obtained from thermal energy simulations for each type of a building. The energy consumption for appliances, cooking and domestic hot water is assumed to be independent on the building type, but related to the number of residents. Therefore, the values can be based on regional statistics or in situ surveys (Marique & Reiter, 2014).

The annual energy consumption for daily mobility (E_{DM}) is determined by a performance index (Boussauw & Witlox, 2009). The index represents the average energy consumption for travelling for a person within a specific neighbourhood (Equation 4).

$$Energy\ performance\ index\ (i) = \sum_m \frac{D_{mi} f_m}{T_i} \quad (4)$$

In the Equation 4 i corresponds to a territorial unit, m describes means of transportation (car, train, bus, bike, walking), D_{mi} represents the total distance travelled by the means of transportation m in the territorial unit i, f_m expresses the consumption factor assigned to the means of transportation m and T_i relates to the number of people in the territorial unit i.

Finally, the energy consumption for daily mobility is a multiplication of the performance index, the number of people N and the number of trips T in the neighbourhood as presented in Equation 5 (Marique & Reiter, 2014).

$$E_{DM} = Energy\ performance\ index\ \times NT \quad (5)$$

Regarding on-site energy generation, photovoltaic panels (E_{PV}), thermal panels (E_{TH}) and small wind turbines (E_{WT}) are analysed as potential renewable energy sources and thus the annual on-site energy production is a sum of energy produced by these sources (Equation 6).

$$E_{RP} = E_{PV} + E_{TH} + E_{WT} \quad (6)$$

The annual energy consumption of the neighbourhood (E_N) is calculated by summing up the building energy consumption (E_B) and transportation energy consumption (E_{DM}) and subtracting the on-site energy generation (E_{RP}) as presented in Equation 7 (Marique & Reiter, 2014).

$$E_N = E_B + E_{DM} - E_{RP} \quad (7)$$

2.5. On-site energy generation

The building is not able to achieve the 'strictly' Zero Energy/Emission target without producing and exporting energy. Figure 6 presents the net Zero Energy/Emission balance line including the weighting factors: PE and CO_2 factors. The metric values come from the draft of the European standard (PREN 15603:2013). The grey dot in Figure 6 illustrates a reference building without on-site energy generation. The nearly Zero Energy/Emission building is found in the blue shaded area. In order to maximally reduce the weighted energy imports, bio heating is a preferable heating technology as bio usually has the lowest weighting factor (Lindberg, 2017).

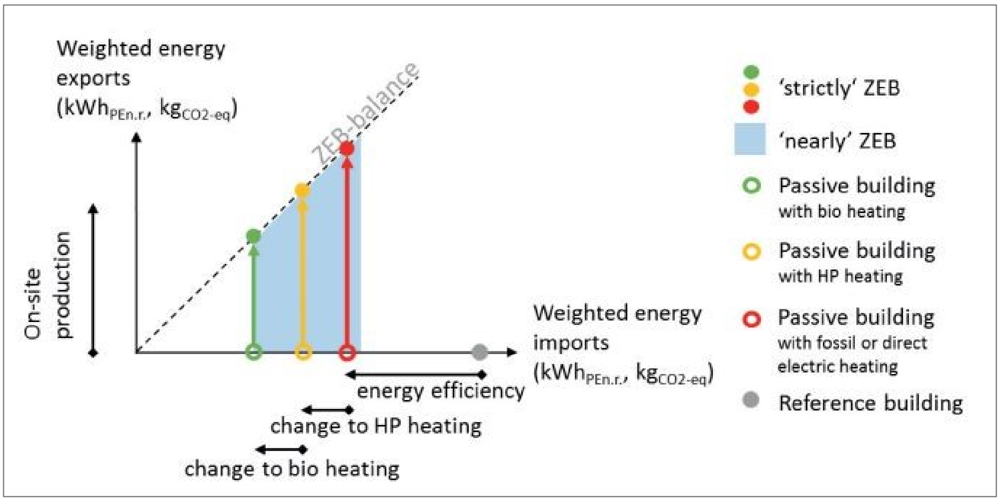


Figure 6. *Application of PE and CO_2 factors to a Zero Energy/Emission balance (Lindberg, 2017)*

Nevertheless, if all ZEBs used bio heating, there would not be enough bioenergy available. Therefore, Switzerland and Denmark have increased the weighting factor for bioenergy to make alternative heating technologies, such as heat pumps, attractive. On the other hand, by increasing weighting factor for bioenergy, the ZEB balance is more difficult to reach (Lindberg, 2017). According Norris et al. (2014), the politically influenced weighting factors often have a decisive effect upon the choice of technology used in ZEBs.

The most commonly used renewable source of energy in ZEB are photovoltaic modules and solar thermal panels (Marszal et al., 2011). The feasibility to reach the ZEB balance with PV modules installed on the roof is dependent on several factors, such as building load, shape of a building, technical solutions, etc. For tall buildings, it is difficult to achieve the balance because of the disadvantageous roof-to-floor-area ratio and supplementary renewable energy sources should be regarded. However, for low-rise buildings, it is possible to reach the balance with PV modules installed on the roof using current technologies and weighting factors. Installation of solar thermal panels have an insignificant impact on the feasibility of achieving the balance, particularly for office buildings where the demand for domestic hot water is low. On the one hand solar thermal panels reduce the load to be compensated for, but on the other hand they diminish the available area for PV (Noris et al., 2014).

2.6. Load matching and grid interaction indicators

Although in the net Zero Energy balance the building's energy demand and on-site energy generation match at the annual level, large differences between the two quantities can occur on an hourly, daily or monthly basis. In order to show the mismatch between the building's energy demand and on-site energy production, load matching and grid interaction indicators can be used. Load matching and grid interaction calculation should be made separately for each energy carrier.

The load matching refers to the degree of the utilization of on-site energy generation with the building load (Salom et al., 2014). If there is a low correlation between load and generation, for instance, load occurs mostly in winter and generation mostly in summer, the building is greatly dependent on the grid. In the case of a strong correlation, the building is most likely to finely adjust self-consumption, storage and energy exports (Sartori et al., 2012).

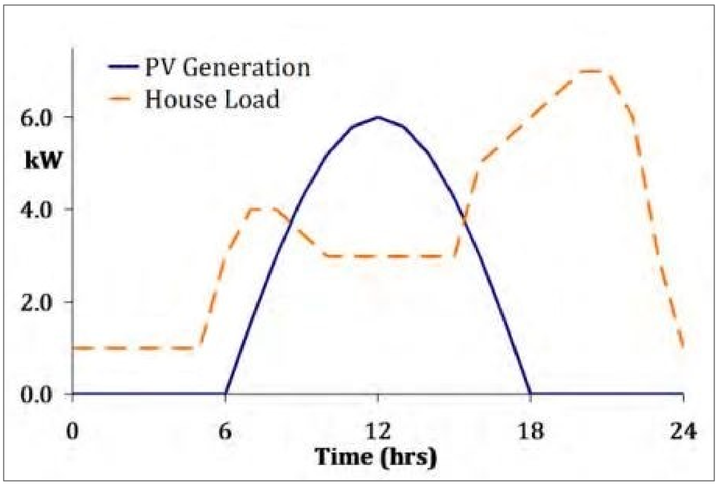


Figure 7. *Load matching (Salom et al., 2014)*

Increasing the match brings about a decrease in a demand for transportation and storage of energy. In order to enhance the match, one can adapt demand to generation, also known as

Demand Side Management (DSM) and/or adjust generation to demand. Additionally, a well-controlled on-site energy storage allows to cover an increased part of the load by utilizing the stored energy (Voss et al., 2010).

The grid interaction represents the energy exchange between the building and the grid as shown in Figure 8. The grid interaction index from the building perspective is described a variability (standard deviation) of the net export within a year, normalised by the highest absolute value. The net export is the difference between exported and delivered energy within a specified time interval.

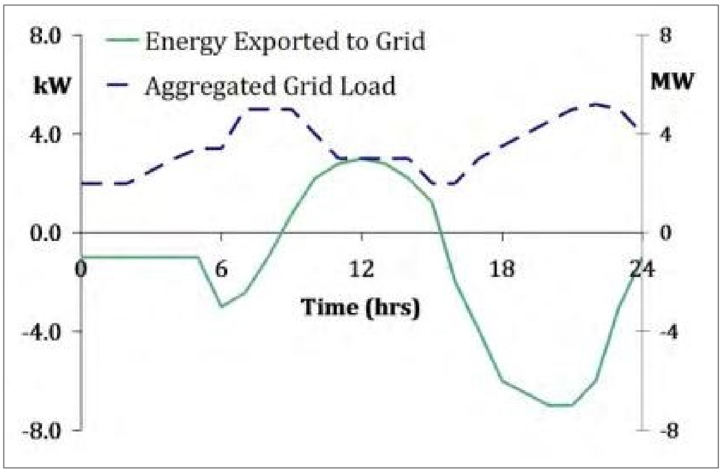


Figure 8. *Grid interaction (Salom et al., 2014)*

It is crucial to distinguish between load matching and grid interaction. Load matching is primarily important for determining the quantity of on-site generation and can be used by building designers and owners (e.g. sizing energy storage, adjusting orientation and slope of solar energy systems, in particular), whereas grid interaction is chiefly significant for the capacity of the distribution grid and the operation of a building with regard to time-of-use or feed-in tariffs (Salom et al., 2011).

3. Literature review

3.1. Modelling of building stock and future energy demand

Sandberg, Sartori, Vestrum & Brattebø (2017) develop a new approach to dwelling stock energy analysis. Sandberg et al. (2017) adopt a dynamic, segmented, stock-driven dwelling stock model based on mass balance in scenario analysis of future energy demand for residential buildings in Norway.

The dwelling stock energy model is based on dynamic material flow analysis and allows to examine the long term development of dwelling stock and its future energy demand. The driving force in the model is a need for housing determined by population and a lifestyle parameter - the number of persons per dwelling. The lifetime of buildings is modelled by means of a probability function. In contrast with other studies on modelling future energy use in building stocks which use exogenous renovation rates, the renovation activity is assessed using a renovation probability function and is case-specific. The dwelling stock is categorized into segments in line with dwelling types and construction periods (cohorts). The building stock energy model is linked to the dwelling stock model. The segment-specific average heated floor area and archetype-specific (defined by dwelling type, cohort and renovation state) parameters are applied in order to estimate energy need and delivered energy (Sandberg et al., 2017). The outline of the building stock and energy model is shown in Figure 9.

Firstly, Sandberg, Sartori, Vestrum & Brattebø (2016) implement the dwelling stock model together with segment-specific energy intensities in order to study the historical development of the energy use in Norwegian dwelling stock (1960-2015). The study of future energy demand for residential buildings in Norway is a follow-up to the historical analysis. Sandberg et al. (2017) use scenario analysis for appraising the effects of various possible strategies for energy savings in the dwelling stock.

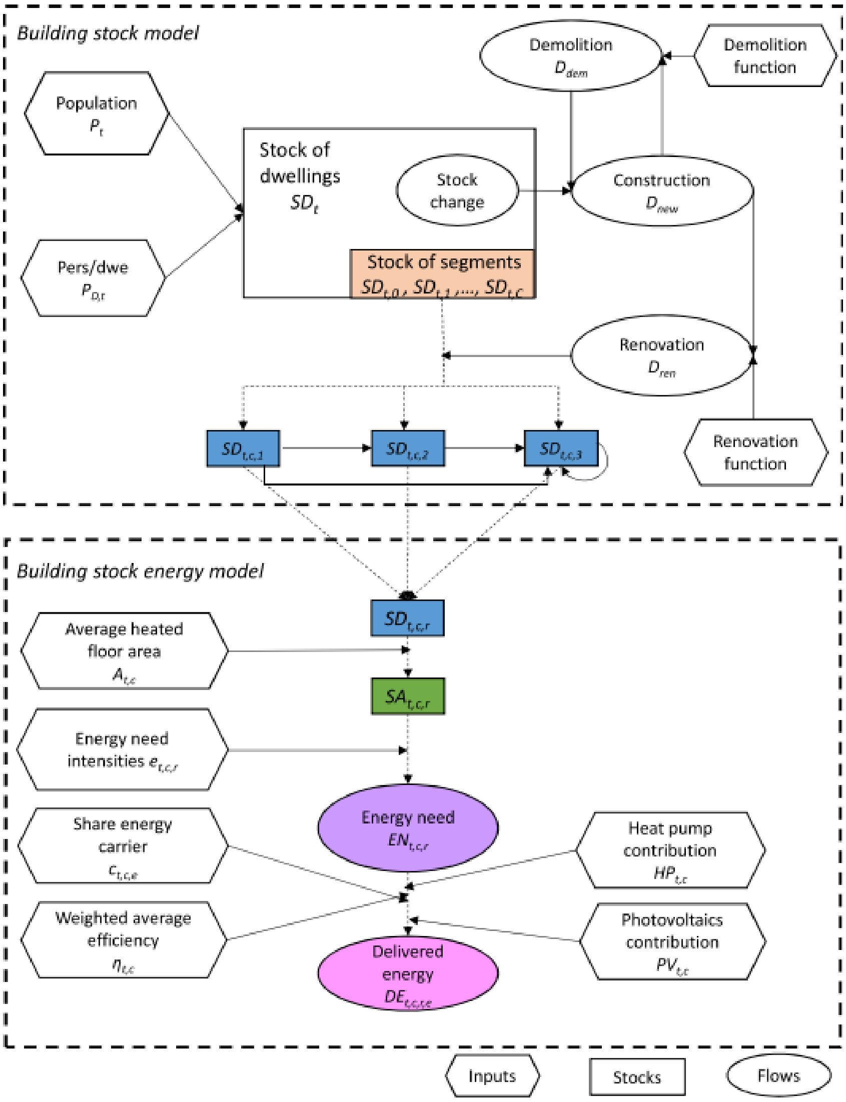


Figure 9. *Outline of the building stock model and the building stock energy model (Sandberg et al., 2017)*

3.2. Case studies

Two study cases are described in this section. The first one presents the experience of one of the University of California campuses in pursuit of net zero energy, whereas the second study illustrates the ZEB Research Centre's pilot project of Heimdal high school.

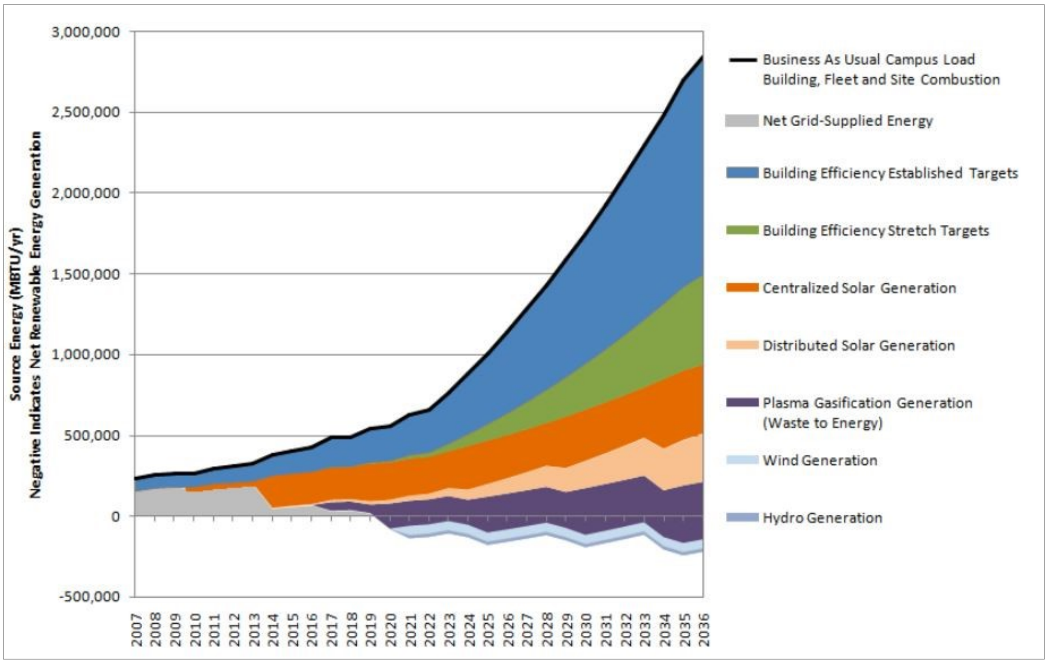
3.2.1. University of California, Merced

Merced, the newest of the University of California campuses in the USA, has set a goal to achieve net zero energy through conservation and renewable energy generation by 2020. This is a part of a Triple Zero Commitment along with elimination of landfill waste and attaining Net Zero GHG emissions impact in the same timeframe (UCMerced Sustainability, 2016).

Furthermore, the campus has been recognized as the only university in the USA that has earned LEED (Leadership in Energy and Environmental Design) status for every building (Diaz, Elliott & Coimbra, 2011). The study of Elliott & Brown (2010) demonstrates that development of net zero energy campus is feasible.

In order to fulfil the net zero energy ambition, the campus uses a strategy of achieving progressive targets of deep efficiency. The campus established an initial goal of using 50% less energy than a benchmark representing the energy performance of the existing building stock across the University of California and the California State University campuses. The initial success with deep efficiency has brought the campus to consider even more challenging target for buildings using barely 25% of benchmark energy use (compared to the 1999 level), and consequently requiring less renewable energy to meet the zero net energy objective. In 2009 the University of California at Merced installed a 1 MW photovoltaic plant. The solar installation consists of high-efficiency solar panels with a tracking system and produces approximately 17% of the campus electricity load (Elliott & Brown, 2010).

Figure 10 shows an example path to net zero energy campus through several efficiency objectives and renewable energy projects. The black trend line represents business as usual loads involved in the net zero energy commitment. The colourful areas demonstrate options to reduce grid-supplied energy through energy efficiency or renewable energy production. As shown in Figure 10 the building efficiency accounts for a significant part required to meet net zero energy. Regarding renewable energy sources, the most critical is the deployment of centralized solar (solar arrays) and distributed solar generation (photovoltaic panels on rooftops) as well as plasma gasification (conversion of campus solid and sewage waste to steam, syngas or electricity). The latter system not only produces energy with low levels of pollution but also contributes to zero waste target. Thanks to its dispatchable character, plasma gasification allows to plan and optimize the production of power and/or heat. Hydro and wind generation are considered to be less important systems in the path to net zero energy. Although this model allows to define a possible path to net zero energy, it is not able to identify whether such a path is cost-effective. The cost-effectiveness of renewable sources is dependent on various factors, for instance, seasonal and hourly production and load profiles, the costs for grid power used to meet loads in case the loads exceed generation capacity (Elliott & Brown, 2010).



*The data for 2007, 2008 and 2009 are measured values

Figure 10. *An example path to net zero energy campus (Elliott & Brown, 2010)*

Based on the experience at the Merced campus, Elliott & Brown (2010) suggest that other campuses pursuing similar targets should consider the following aspects. Firstly, Elliott & Brown (2010) underline that the improvement of energy efficiency is essential in order to make the net zero energy ambition feasible and will be the cheapest measures in the near future. In addition, Elliott & Brown (2010) point out that collecting and analysing operational data offers a deep insight into campus energy use and can enable the identification of energy saving possibilities.

3.2.2. Heimdal high school

Heimdal high school, located in Trondheim, is a pilot project within the Norwegian Research Centre on Zero Emission Buildings. The complex comprises a school building with 18 675 m^2 and a sports hall with 7 681 m^2 of heated floor area and will be open in 2018. The ambition is to achieve ZEB-O20%M balance which states that all GHG emissions connected with operational energy and 20% of material emissions should be offset by renewable energy generation. Regarding energy efficiency, the goal is set to cut down on building net energy need by approximately 70% compared to the Norwegian building code TEK10 (135 $kWh/m^2/yr$). This can be achieved by a well-insulated and air tight building envelope, a ventilation system with high efficiency heat recovery and electrochromic windows for shading to lower the cooling demand. The energy demand of Heimdal high school was calculated by means of a dynamic energy simulation tool SIMIEN. The estimated annual energy demand for the school building is equal to 38,7 kWh/m^2/yr (15,4 and 23,3 kWh/m^2/yr of heat and electricity, respectively) and for the sports hall 42,4 kWh/m^2/yr (24,8 and 17,6 kWh/m^2/yr of heat and electricity, respectively) (Schlanbusch, Fufa, Andresen, Wigenstad & Mjønes, 2017).

Energy generation from on-site renewable sources (biogas, solar and geothermal) is taken into account. A biogas-based combined heat and power (CHP) with an efficiency of 85% and power output of 50 kW electricity and 80 kW heat is considered for producing both electricity and heat. Heat produced by the CHP is expected to cover 4% of space heating and ventilation demand. Another renewable source of electricity in the Heimdal high school project will be a PV system installed on the rooftop of the school building. The designed PV system consists of 1088 Si monocrystalline modules with an efficiency of 21,15% and the total peak power of 375,4 kWp. Furthermore, a ground-source heat pump with a seasonal coefficient of performance (SCOP) of 4,05 is expected to satisfy up to 92% of space heating and ventilation demand. Besides the ground-source heat pump, a domestic hot water heat pump with SCOP of 3,5 is predicted to meet about 99% of domestic hot water demand. It is assumed that electricity produced by CHP and PV will be used for the operation of the heat pumps (Schlanbusch et al., 2017).

The Heimdal high school and the sports hall will be connected to district heating and electricity grid and thus heat and electricity peak loads will be covered by the grid. The excess energy production is considered to be exported to the local district heating grid and a nearby building. For ZEB balance calculation, the maximum amount of exported thermal energy is restricted to the maximum amount of imported thermal energy (Schlanbusch et al., 2017).

The GHG emissions from operational energy are calculated based on delivered and exported energy and associated CO_2-eq factors for each energy carrier. In the calculations, the CO_2-eq factors for grid electricity (130 g/kWh) and biogas (25 g/kWh) developed by Dokka et al. (2013) are used. The CO_2-eq factor for district heating is estimated to be 130 g/kWh. The ZEB balance for 3 different ambition levels (ZEB-O, ZEB-O20%M and ZEB-O20%M including transport of materials to the building site) is calculated for the Heimdal project. The results show that at the design stage, the Heimdal project is close to fulfilling the ZEB-O ambition level thanks to generating enough renewable energy for internal use and export in order to compensate for emissions associated with the operation of the school building and the sports hall. Regarding

ZEB-O20%M and ZEB-O20%M, the Heimdal project is able to fulfil neither of the two ambition levels (Schlanbusch et al., 2017).

3.3. Studies on NTNU Gløshaugen

This section presents studies on NTNU Gløshaugen describing future development of the buildings stock and energy demand, current energy use characteristics as well as the feasibility of implementation renewable energy sources at NTNU Gløshaugen.

3.3.1. Long-term analysis of the building stock and energy demand of NTNU Gløshaugen

Næss et al. (2018) apply NTNU Gløshaugen to the Zero Emission Neighbourhood model described in section 4.2. in order to demonstrate how the model can be used for a long-term, dynamic analysis of a complex building stock with several floor area types representing different functions. The simulated development of the heated floor area of the Gløshaugen building stock is shown in Figure 11. Næss et al. (2018) point out that the results of the development of the building stock are heavily dependent on assumptions about future construction.

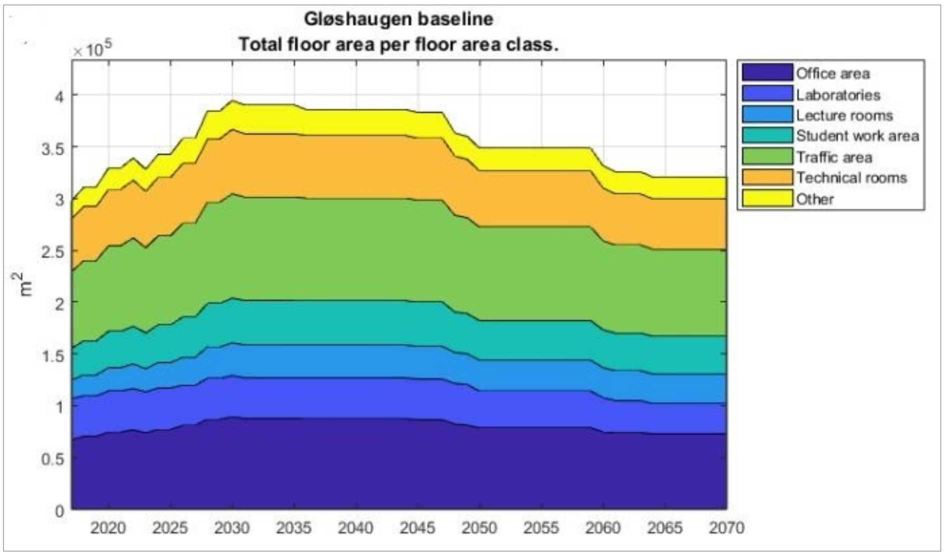


Figure 11. *Estimated heated floor area per floor area class (Næss et al., 2018)*

Moreover, in order to estimate energy demand towards 2070, Næss et al. (2018) make use of an IDA ICE energy use profile which represents an average building at NTNU Gløshaugen. The energy use profile includes hourly energy profiles of each class.

Næss et al. (2018) conclude that because of using the same energy use profile for all the cohort groups, the estimated annual delivered energy to NTNU Gløshaugen (Figure 12) follows the development trend of the building stock heated floor area.

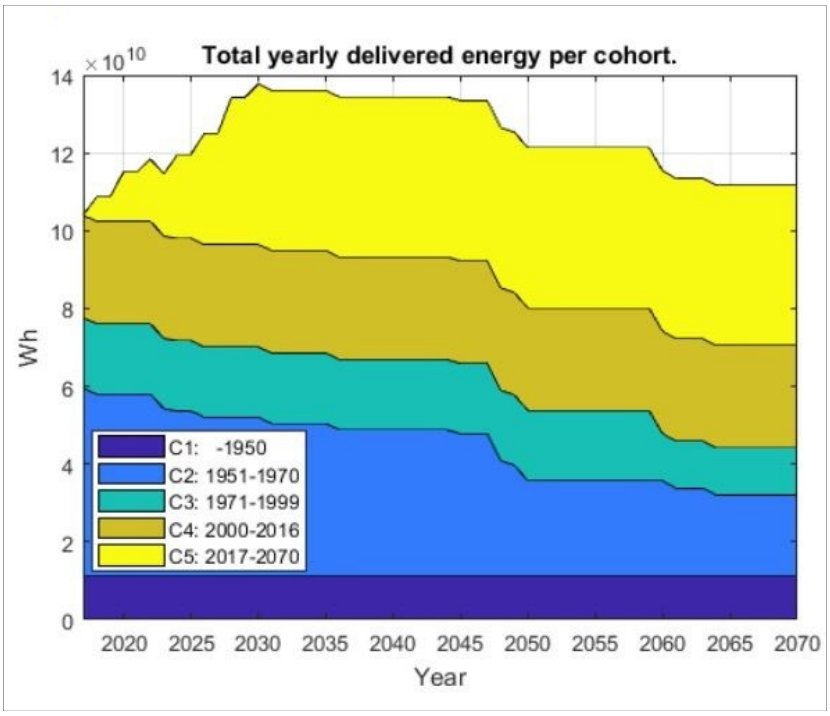


Figure 12. *Estimated yearly delivered energy to NTNU Gløshaugen per cohort (Næss et al., 2018)*

3.3.2. Energy use characteristics of NTNU Gløshaugen building stock

(Guan, Nord & Chen, 2016) analyse 24 buildings located on NTNU Gløshaugen with regard to energy planning of university building stock. Guan et al. (2016) use descriptive statistics in order to show energy use characteristics of the entire campus and individual buildings. Hourly data on electricity and heating from the period 2011-2013 is taken into account. The buildings are classified into 2 groups according to subject: Engineering & Technology (E&T) buildings and Art & Science buildings (A&S). Figure 13 presents the frequency contribution to electricity and heating use for all 24 buildings and Figure 14 illustrates the specific energy use of the individual buildings. The most common electricity use varied between 100 and 150 kWh/(m^2a), whereas the most frequent heating use was in the 50-100 kWh/(m^2a) range. The majority of the building with floor area lower than 20 000 m^2 have the specific electricity and heating use under 300 kWh/(m^2a), with the exception of few buildings with laboratories. Furthermore, the energy use in a building with exceptionally large floor area (Realfagbygg) is not significantly higher from the rest of the buildings. Guan et al. (2016) explain that large floor area did not substantially contribute to higher energy use. Instead, the study of Guan et al. (2016) suggest that high energy use may be associated with specific demands, particularly for laboratory facilities.

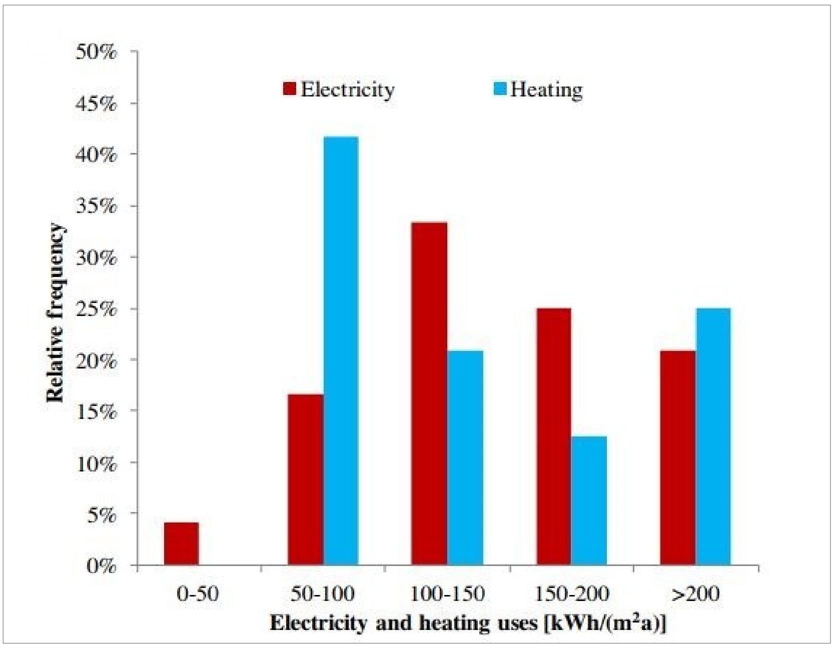


Figure 13. *Frequency contribution to energy use for all the buildings (Guan et al., 2016)*

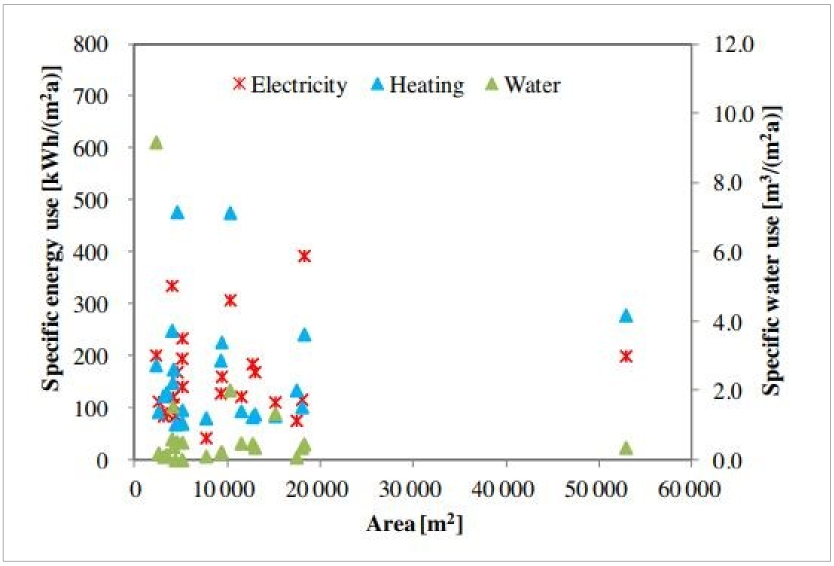


Figure 14. *Specific energy use of all the buildings (Guan et al., 2016)*

Moreover, Guan et al. (2016) investigate the impact of building function on the energy use. 4 buildings are chosen as typical buildings: 1# representing an office and educational building, 8# representing an E&T office building with laboratories, 16# representing an A&S office building with laboratories and 19# representing a sports building. Figure 15 illustrates monthly electricity use and Figure 16 heating use of these 4 buildings in the period 2011-2013. The highest electricity and heating use characterised the office building with laboratories (8#), whereas the lowest electricity and heating use described the sports building (19#). As shown in Figure 15 and Figure 16, the difference in energy use between individual buildings is significant.

In addition, Guan et al. (2016) develop coincidence factor for the entire campus in order to explore the campus load characteristics in the context of energy planning. The indicator is calculated based on hourly energy data for all the buildings in the period 2011-2013. The maximums of annual coincidence factors are averaged to be 78,8% for electricity and 79,4% for heating. The high coincidence factors of electricity and heating use indicate that the buildings are quite similar regarding energy use.

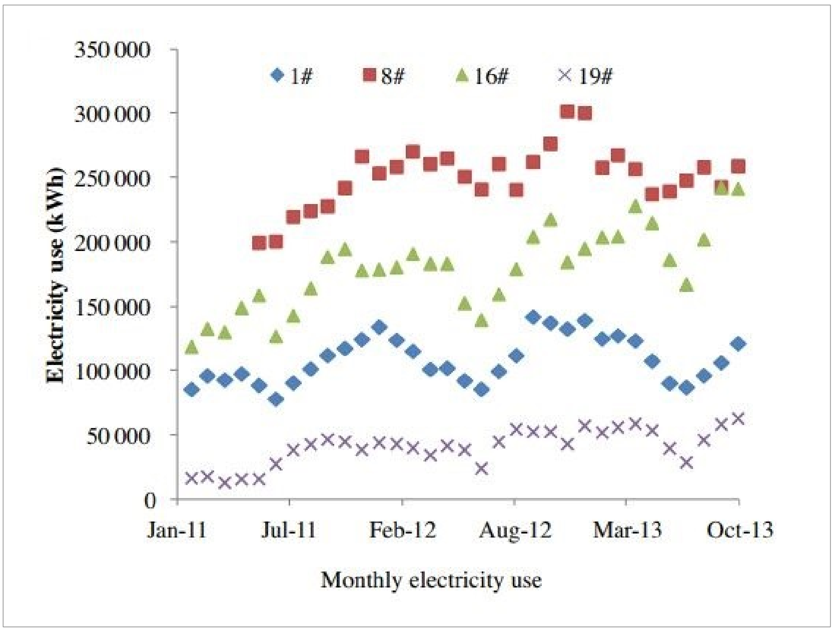


Figure 15. *Monthly electricity use of 4 individual buildings of different types in the period 2011-2013 (Guan et al., 2016)*

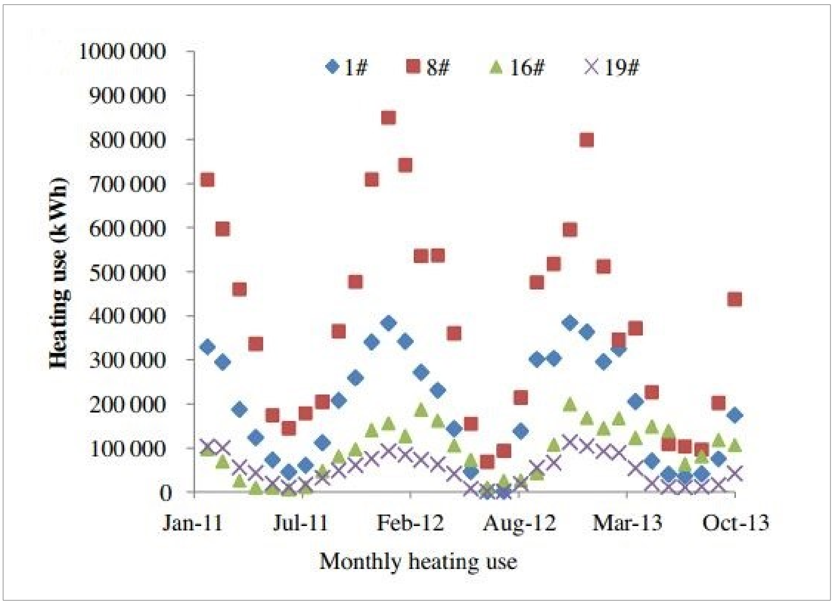


Figure 16. *Monthly heating use of 4 individual buildings of different types in the period 2011-2013 (Guan et al., 2016)*

3.3.3. Wind potential

Lopez Pareja (2016) carries out an assessment of wind conditions on NTNU Gløshaugen in his Master thesis. A wind turbine Primus Air-40 with a maximum power output of 250W at a wind speed of 11 m/s is installed on one of the Gløshaugen building's roof at 120 m above ground (170 m above sea level). The analysis shows that an annual average of the wind speed was 6,2 m/s in the period 2010-2015 and the highest wind speed occurred during winter months, particularly in February and March. It is estimated that the wind turbine generates 562 kWh/year. The study demonstrates that in order to compensate for the annual energy demand of Gløshaugen 11 000 of these wind turbines would have to be placed. Due to a high investment cost, the deployment of the wind turbines on NTNU Gløshaugen is considered as economically unprofitable (Lopez Pareja, 2016).

3.3.4. Solar potential

Lobaccaro (2014) studies the overshadowing effect on the façade of Sentralbygg 2 caused by the shadow produced by Sentralbygg 1. Sentralbygg 1 and Sentralbygg 2 are located in the middle of NTNU Gløshaugen and are the tallest buildings of the campus. They are separated by a lower building and face each other in north-west/south-east direction.

The study analyses several geometric configurations of Sentralbygg 2 in order to reach the maximal solar potential at the early design stage. The results show that the optimal solar design can improve the solar access of Sentralbygg 2 by 4% compared to the existing form and even by 16% while considering solely the most irradiated façade (south-east) of the building. In addition, Lobaccaro (2014) estimates the amount of energy that could be generated thanks to using solar active systems based on the results of solar radiation on the south-east façade. The exposed area of the south-east façade is 11 171 m^2 and the actual energy demand of Sentralbygg 2 is around 607 MWh/year. PV-monocrystalline cell panels could cover up to 12% of the building's electricity demand, whereas heat from solar thermal collectors could compensate for 49% of the building's heat demand.

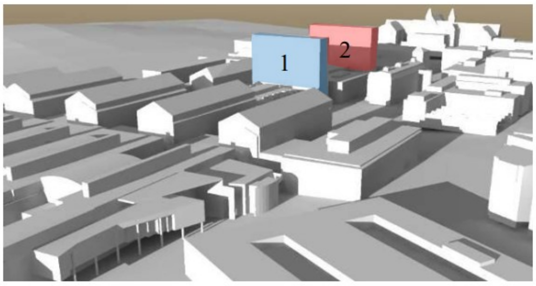


Figure 17. *North-west view of the NTNU Gløshaugen (left) and south-east view of the 3D model in February (right) (Lobaccaro, 2014)*

Furthermore, the study of Lobaccaro, Carlucci, Croce, Paparella & Finocchiaro (2017) propose several solar urban planning recommendations in order to maximize the solar potential and accessibility in the Nordic climate and boost energy generation from solar active systems integrated in urban environment. Lobaccaro et al. (2017) come to the conclusion that south, south-east and south-west façade is preferable for installation of solar active systems in the North. Moreover, Lobaccaro et al. (2017) emphasise that the aspect ratio between the average height of a building and the average width of a street between buildings significantly affects direct, diffuse and indirect solar radiation and therefore it results in the change of the total annual global solar radiation.

4. Methodology

4.1. PVsyst

A PVsyst software is a tool that accurately evaluates energy generation from photovoltaic systems. The software allows for detailed study, sizing and hourly simulation of solar energy production. The PVsyst (version 6) is used in this Master thesis in order to estimate solar energy potential of NTNU Gløshaugen. Meteorological data for Trondheim is applied in the simulation. The data comes from the Meteonorm 7.1 database and contains monthly temperature and irradiation data. From the monthly values, Meteonorm calculates hourly values using a stochastic model (Meteonorm).

4.2. Zero Emission Neighbourhood model

The Zero Emission Neighbourhood model is developed by Næss et al. (2018) within the ZEN Centre. The model investigates the development of a neighbourhood building stock over time in the context of its size, composition, energy use and greenhouse gas emissions associated with energy consumption at neighbourhood level. The model is generic and can be used for any type of neighbourhood (residential, service or mixed) (Næss et al., 2018).

In this Master thesis, the ZEN model is applied to NTNU Gløshaugen case in order to develop energy demand and greenhouse gas emissions scenario analysis. The following subsections describe in detail principles of the ZEN model based on Næss et al. (2018).

4.2.1. Zero Emission Neighbourhood building stock model

The Zero Emission Neighbourhood model is founded on dynamic material flow analysis principles and allows for analysing the long-term development of a neighbourhood building stock. The outline of the ZEN building stock model is illustrated in Figure 18.

At the start of a modelling period, the model uses a detailed description of the initial stock $B(t_0)$ as well as given or assumed plans for future construction $B_{new}(t)$. In addition, demolition B_{dem} and renovation B_{ren} can be foreseen or modelled by the use of probability distribution functions. The size of the building stock changes over time as a result of demolition and construction activities as described in Equation 8 and Equation 9. The ZEN model calculates the state of the neighbourhood building stock for each year in the modelling period.

$$B(t) = B(t-1) + \frac{d}{d(t)} B(t) \tag{8}$$

$$B(t) = B(t-1) - B_{dem}(t) + B_{new}(t) \tag{9}$$

$B(t)$ represents the building stock at the end of year t, whereas $B_{dem}(t)$ and $B_{new}(t)$ correspond to demolition and construction in year t, respectively. Furthermore, renovation activity B_{ren} affects the composition of the building stock.

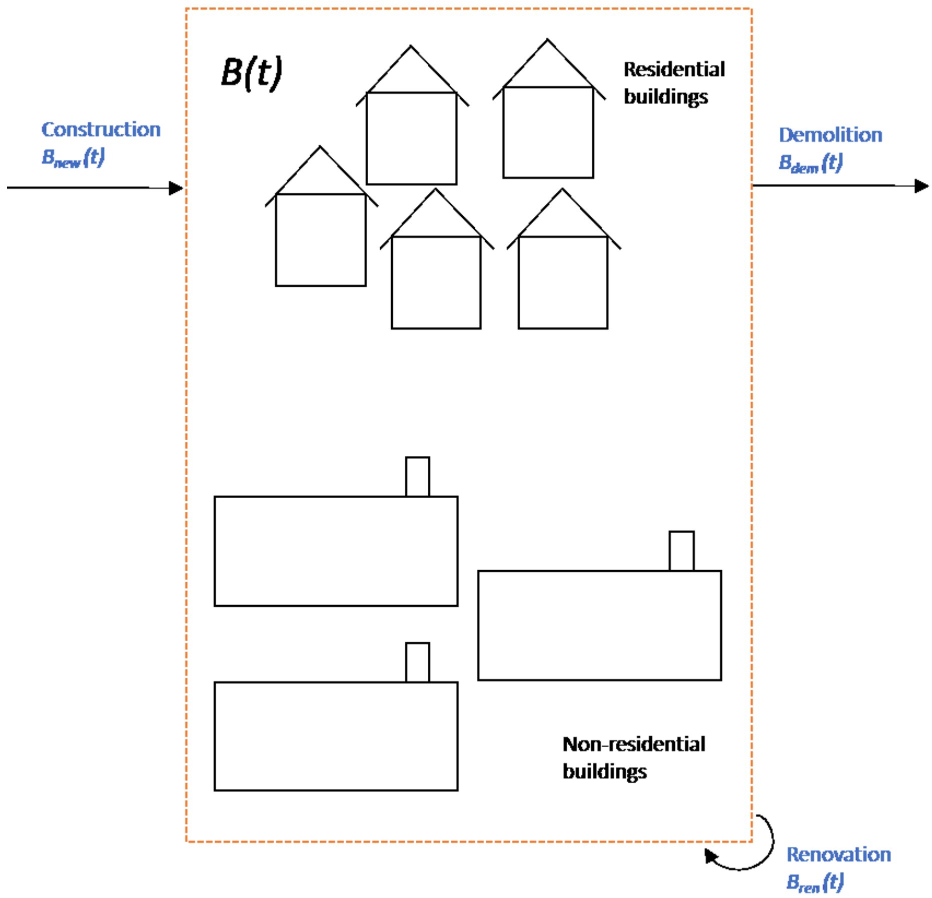


Figure 18. *Outline of the Zero Emission Neighbourhood building stock model (Næss et al., 2018)*

The building stock is divided into archetypes. The segmentation of the building stock into archetypes is made based on construction period determined by cohort c, floor area class z and renovation state r. The ZEN model calculates the heated floor area A for each archetype for every year of simulation. Buildings can shift from one archetype to another when they are renovated. Renovation of a building can occur several times during the building's lifetime and various types of renovation activities (e.g. the replacement of windows, heating systems, the renovation of façade) take place at different intervals. Renovation activity simulated in the model by probability distribution functions is characterised by the renovation cycle R_c which describes the average time between renovation of a given type. The model makes it possible to use up to 3 different renovation states for each building.

Units are fundamental components of the building stock. A building is composed of one or a few units. A unit can be, for instance, an office or a dwelling. Each unit is a part of the building b, cohort c, renovation state r and floor are type y. Cohort includes a group of buildings which were constructed in a specified period. In addition, each floor area type belongs to a floor area class z. As shown in Figure 19, floor area types are aggregated into a floor area class based on similarities between functions and energy use characteristics through the year. Building which have just one floor area type are described as simple buildings, whereas buildings which have several floor area types as complex.

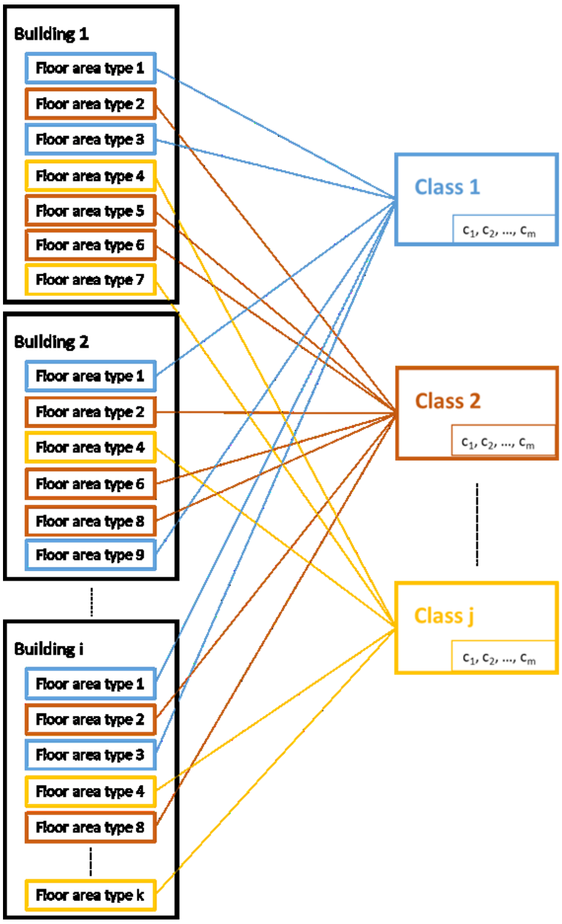


Figure 19. *Floor area class formation (Næss et al., 2018)*

As each building consists of at least one unit, the total heated floor area of a building A_b is equal to the sum of heated floor area of all units in the building A_u (Equation 10). Moreover, the total heated floor area of a floor area type in a building $A_{b,y}$ is equal to the sum of the floor area of all units which belong to that floor area type in the building, as described in Equation 11. Finally, the total heated floor area of a class in a building $A_{b,z}$ is equal to the sum of all floor area types which belong to that floor area class in the building (Equation 12).

$$A_b = \sum_{u \in b} A_u \tag{10}$$

$$A_{b,y} = \sum_{u \in y} A_{b,u} \tag{11}$$

$$A_{b,z} = \sum_{y \in z} A_{b,y} \tag{12}$$

Equation 13, 14 and 15 describe the heated floor area at the building stock level. The total heated floor area of a given floor area type A_y in the neighbourhood is equal to the sum of the given floor area type A_y in all buildings in the system. Additionally, the total heated floor area of a given floor area class A_z in the neighbourhood is equal to the sum of the heated floor area of the given floor area class A_z in all buildings in the system. This is equivalent to the sum of all floor area types A_y belonging to the given floor area class A_z. Lastly, the total heated floor area in the building stock A_B is equal to the sum of the heated floor area of all units A_u in the neighbourhood. This corresponds to the sum of the heated floor area in all buildings A_b in the system. Furthermore, the total heated floor area in the building stock A_B can also be expressed as the sum of the heated area of all floor area types A_y in the system or as the sum of the heated floor area of all floor area classes A_z in the system.

$$A_y(t) = \sum_b A_{b,y}(t) \tag{13}$$

$$A_z(t) = \sum_b A_{b,z}(t) = \sum_{y \in z} A_y(t) \tag{14}$$

$$A_B(t) = \sum_u A_u(t) = \sum_b A_b(t) = \sum_y A_y(t) = \sum_z A_z(t) \tag{15}$$

4.2.2. Zero Emission Neighbourhood energy model

The ZEN model allows to carry out a detailed long-term energy analysis of a neighbourhood building stock. Energy carriers in the system are defined as an input. Hourly load profiles can be implemented at the archetype level as energy intensity profiles or empirical energy profiles at the building level. In addition, building or neighbourhood specific hourly energy generation profiles and parameters of energy storage can be included in the analysis. The model aggregates energy delivered by different energy carriers for each year of the simulation based on the state of the system. The outline of the ZEN energy model is illustrated in Figure 20.

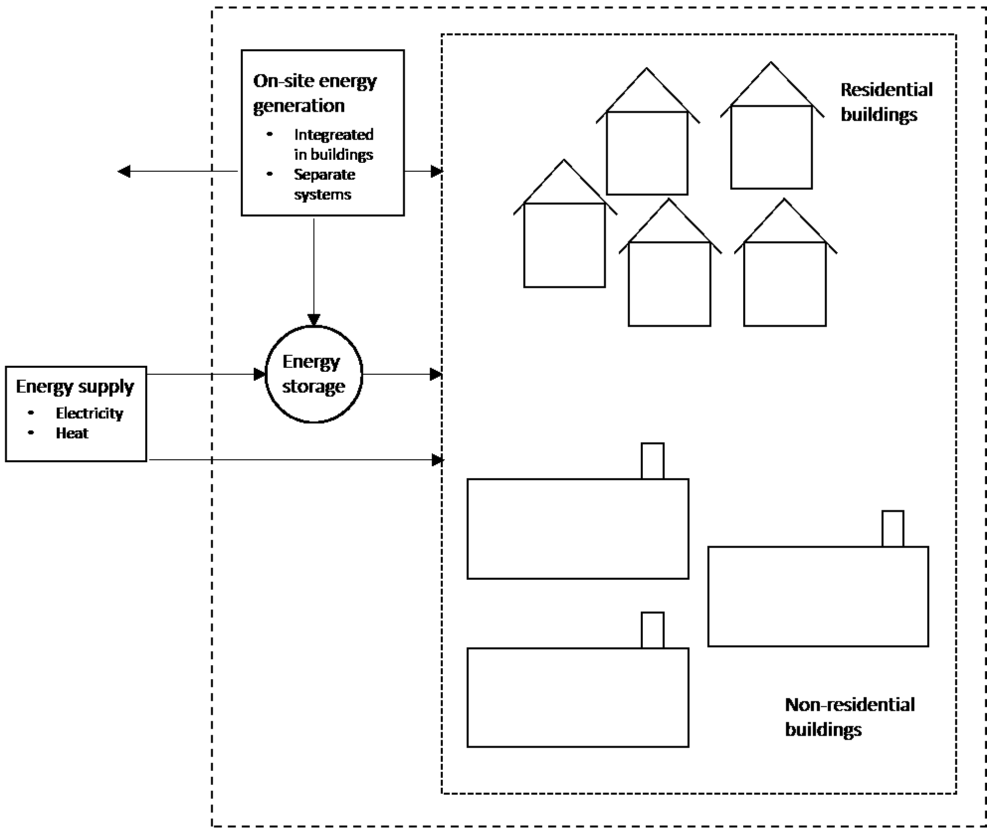


Figure 20. *Outline of the Zero Emission Neighbourhood energy model (Næss et al., 2018)*

The delivered energy to a building by each energy carrier $E_{b,e}$ is equal to the delivered energy by the given carrier to all units $E_{u,e}$ belonging to the building. This corresponds to the product of the floor area of a unit A_u and the energy intensity of the given floor area type and energy carrier $E_{i,e,y}$ to which the unit belongs (Equation 16). Furthermore, the delivered energy per floor are type to a given building $E_{b,y}$ is equal to the sum of the delivered energy to all units $E_{b,u}$ in the building belonging to the given floor area type (Equation 17), whereas the delivered energy per floor area class to a given building $E_{b,z}$ is equal to the sum of the delivered energy to all floor area types $E_{b,y}$in the building belonging to the given floor area class (Equation 18). Finally, the total delivered energy to the building E_b is equal to the sum of the delivered energy to all units E_u belonging to that building. This is equivalent to the sum of the delivered energy by all energy carriers to the building $E_{b,e}$ (Equation 19).

$$E_{b,e}(t) = \sum_{u \in b} E_{u,e}(t) = \sum_{u \in b} A_u E_{i,e,y}(t) \tag{16}$$

$$E_{b,y}(t) = \sum_{u \in y} E_{b,u}(t) \tag{17}$$

$$E_{b,z}(t) = \sum_{y \in z} E_{b,y}(t) \tag{18}$$

$$E_b(t) = \sum_{u \in b} E_u(t) = \sum_e E_{b,e}(t) \tag{19}$$

Equations 20, 21, 22 and 23 describe the delivered energy aggregated to the building stock level. The delivered energy to the building stock for each floor area type E_y is equal to the sum of the delivered energy to all buildings in the stock for the given floor area type $E_{b,y}$. In addition, the delivered energy to the buildings stock for each floor area class E_z is equal to the sum of the delivered energy to all buildings for the given floor area class $E_{b.z}$. This is equivalent to the sum of the delivered energy to the building stock for all floor area types E_y belonging to the given floor area class. The delivered energy by each energy carrier to the stock E_e is equal to the delivered energy to all units in the stock by the given energy carrier $E_{u,e}$. This corresponds to the delivered energy to all buildings in the stock by the given energy carrier $E_{b,e}$, the delivered energy to all floor area types in the stock by the given carrier $E_{y,e}$ and the delivered energy to all floor area classes in the stock by the given carrier $E_{z,e}$. Lastly, the total delivered energy to the building stock E_B is equal to the total delivered energy to all units in the stock E_u, the total delivered energy to all buildings in the stock E_b, the total delivered energy to all floor area types in the stock E_y, the total delivered energy to all floor area classes E_z and the total delivered energy by all carriers E_e.

$$E_y(t) = \sum_b E_{b,y}(t) \tag{20}$$

$$E_z(t) = \sum_b E_{b,z}(t) = \sum_{y \in z} E_y(t) \tag{21}$$

$$E_e(t) = \sum_u E_{u,e}(t) = \sum_b E_{b,e}(t) = \sum_y E_{y,e}(t) = \sum_z E_{z,e}(t) \tag{22}$$

$$E_B(t) = \sum_u E_u(t) = \sum_b E_b(t) = \sum_y E_y(t) = \sum_z E_z(t) = \sum_e E_e(t) \tag{23}$$

4.2.3. Zero Emission Neighbourhood GHG emissions model

The evaluation of greenhouse gas emissions G is done based on the output from the ZEN energy model as well as carbon intensities I. The model allows to use different carbon intensities over time (on monthly or annual basis).

The total GHG emissions per energy carrier G_e are the product of the delivered energy to the stock by the given energy carrier and carbon intensity of that carrier (Equation 24). Furthermore, the total GHG emissions associated with heat use $G_{B,heat}$ are the sum of GHG emissions related to heat use in the system for all energy carriers (α_e stands for the share of delivered electricity used for purposes other than heating such as lighting, appliances, etc.) as presented in Equation 25, whereas the total GHG emissions associated with electricity use $G_{B,el}$ are the sum of GHG emissions related to electricity use in the system for all energy carriers (Equation 26). Lastly, the total GHG emissions in the building stock are the sum of the total GHG emissions related to electricity and heat use in the system (Equation 27).

$$G_e(t) = E_e(t) \times I_e(t) \tag{24}$$

$$G_{B,heat}(t) = \sum_e E_{B,e}(t) \times I_e(t) \times (1 - \alpha_e) \tag{25}$$

$$G_{B,el}(t) = \sum_e E_{B,e}(t) \times I_e(t) \times \alpha_e \tag{26}$$

$$G_B(t) = \sum_e G_{B,e}(t) = G_{el}(t) + G_{heat}(t) \tag{27}$$

4.3. Case study of NTNU Gløshaugen

NTNU Gløshaugen is the main campus of the Norwegian University of Science and Technology and is located around 2 km southeast from the city centre of Trondheim. In a period 2016-2025 NTNU's Campus Development Project aims to cluster the university in a united campus around the Gløshaugen area (Figure 21), which involves a substantial expansion of the current Gløshaugen building stock in the next few years *(NTNU's campus development).*

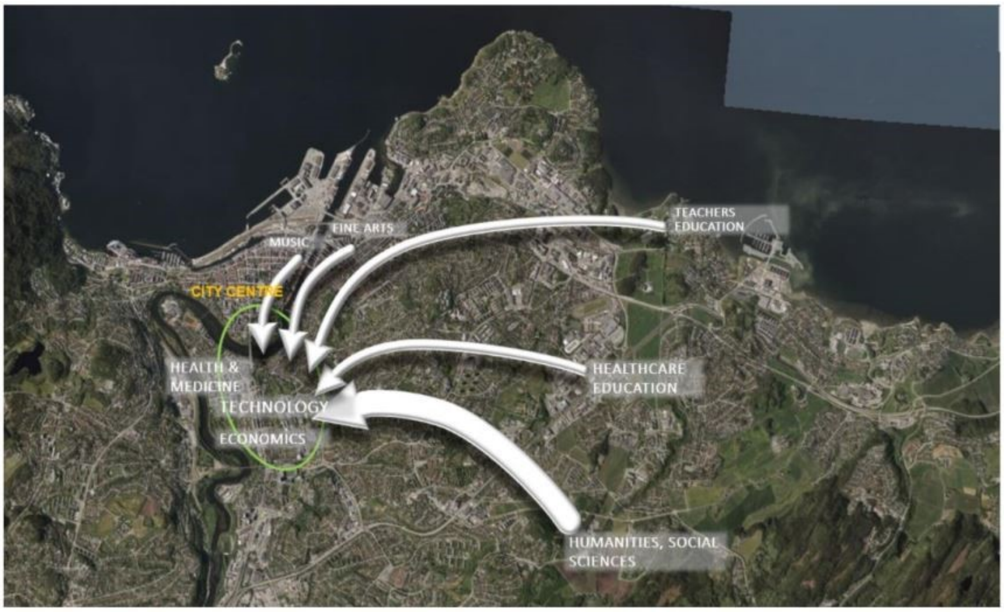


Figure 21. *Future development plan of NTNU Gløshaugen (NTNU's campus development)*

NTNU's ambition is to create a campus which is unifying, a network of hubs, urban, sustainable and a living laboratory at the same time. Unifying means a more concentrated campus. A network of hubs stands for a good connection between the buildings on the campus as well as between the campus and the city. An urban campus is open, represents urban features and shares facilities with the city. A sustainable campus is durable, energy efficient and has a minimal impact on environment during its entire lifecycle. A living laboratory campus is innovative and has an easily accessible experimental infrastructure (*Kvalitetsprogram: NTNUs campusutvikling 2016 - 2030*).

In this Master thesis the energy consumption by the Gløshaugen building stock in the year 2016 is analysed as it represents the latest available data. The amount of consumed energy depends largely on atmospheric conditions including temperature. Figure 22 shows the average annual temperature in the period 1988-2017 measured on the Værnes observation site in the Stjørdal municipality. The Værnes observation site is located about 30 km to the east of NTNU

Gløshaugen and is the nearest weather station to Trondheim which provides climate statistics. In 2016 the average temperature in Stjørdal was 6,3°C, slightly above the average in a period of 30 years (the average was 6,2°C, marked the red dotted line in Figure 22) *(Yr)*. Therefore, the year 2016 is considered as representative for the study case.

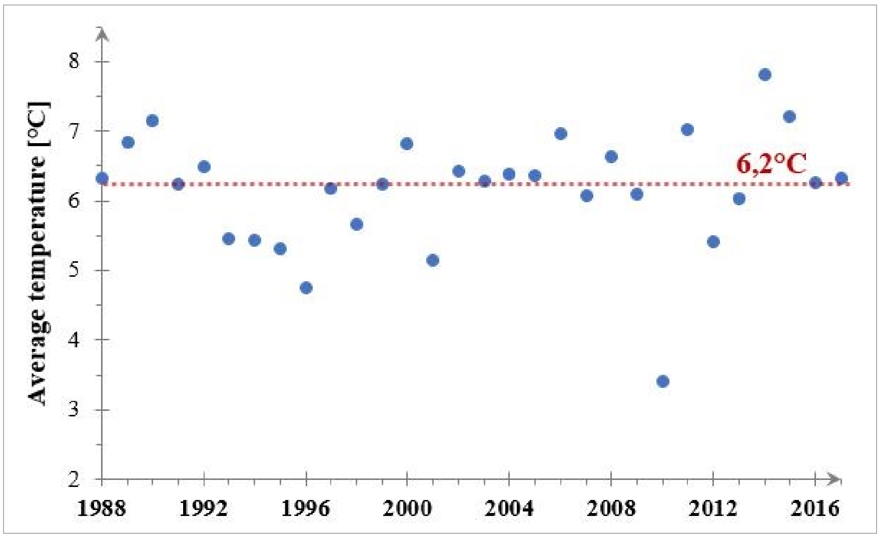


Figure 22. *Average annual temperature on the Værnes observation site (Stjørdal) in the period 1988-2017 (Yr)*

The information about the current building stock at NTNU Gløshaugen including the building size, floor area type, construction year as well as the list of protected buildings was provided by NTNU Drift *(Rønning, personal communication, September 2017; Tanche-Nilssen, personal communication, December 2017).* The information about the future constructions was found in Fysisk Plan of NTNU's Campus Development 2016-2030 (KOHT Arkitekter, 2017). The empirical data on electricity and district heating consumption (hourly resolution profiles of the buildings) was collected from the web-based Schneider Electric Energy Operation platform for the year 2016 (Schneider Electric Energy Operation, 2017).

4.3.1. NTNU Gløshaugen today

NTNU Gløshaugen consists of 46 buildings each of them is defined by a number in the 301-365 range as shown in Figure 23. The buildings were constructed between the year 1850 and 2013. They are classified into four cohort groups as presented in Figure 24. Over a half of the current building stock (26 buildings) was built between 1951 and 1970 which corresponds to

46% of the total heated floor area. During the period 2000-2016 just three buildings were erected. However, they account for a quarter of the total heated floor area.

A detailed description of the current building stock at NTNU Gløshaugen (construction year, gross floor area, net floor area and net floor area of floor area types) as well as the distribution of classes in each cohort group and the share of each cohort group in different classes are presented in Appendix A.

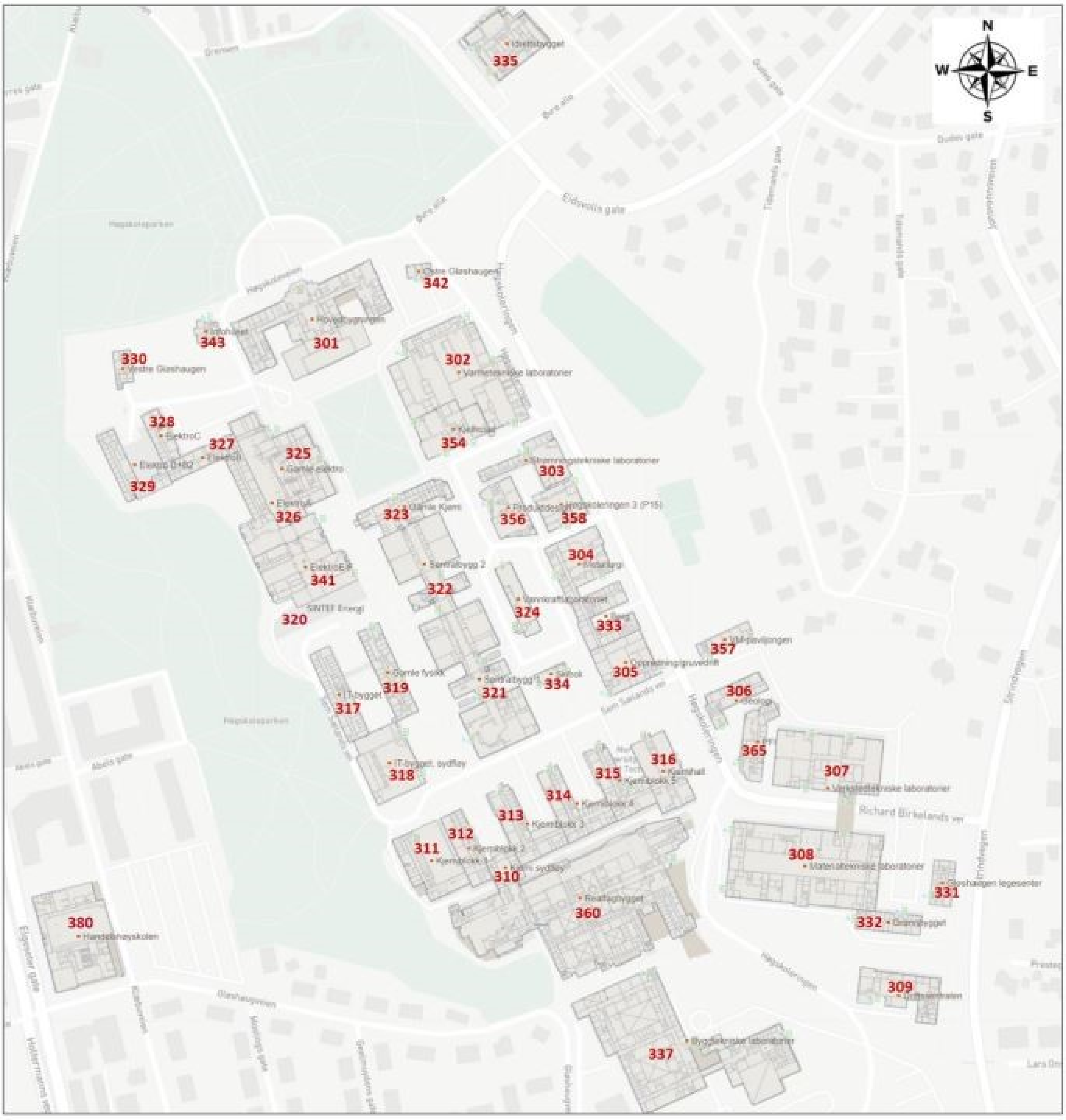


Figure 23. *Current building stock of NTNU Gløshaugen*

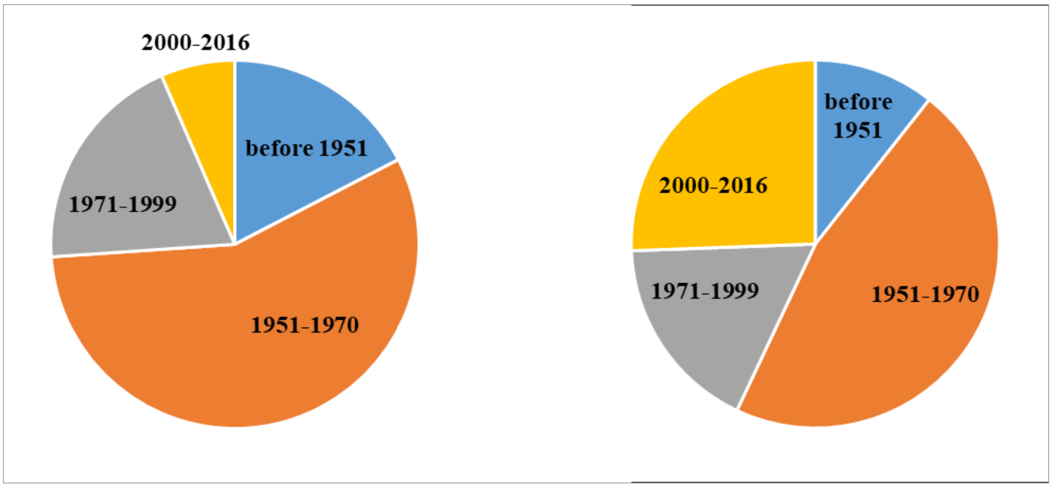


Figure 24. *Share of the buildings in four cohort groups (left) and share of the total heated floor area in four cohort groups (right)*

NTNU Gløshaugen is home of the departments of engineering, natural sciences, mathematics, informatics and architecture. The buildings are not homogeneous and they perform several functions. NTNU Drift differentiates between 17 floor area types *(Rønning, personal communication, September 2017).* The floor area types and the corresponding gross and net floor area are presented in Table 1.

Table 1. *Floor area types in the current Gløshaugen building stock*

Floor area type	Gross floor area [m^2]	Net floor area [m^2]	Share in gross floor area
1. Kontorarealer **(Office area)**	77 111	67 094	22,7 %
2. Undervisningsrom **(Lecture rooms)**	20 173	17 966	6,0 %
3. Laboratoriearealer **(Laboratory)**	44 835	39 794	13,2 %
4. Studentarbeidsplasser **(Student work area)**	28 491	25 404	8,4 %
5. Bibliotek **(Library)**	6 035	5 273	1,8 %
6. Forretningsarealer **(Business area)**	1 524	1 389	0,4 %
7. Kantinearealer **(Canteen area)**	4 200	3 846	1,2 %
8. Utstillingsarealer **(Exhibition areas)**	847	759	0,2 %
9. Verksted **(Workshop)**	7 776	6 966	2,3 %
10. Idrettsrom **(Sports rooms)**	3 032	2 702	0,9 %
11. Sykehusrom **(Hospital rooms)**	468	424	0,1 %
12. Tekniske rom **(Technical rooms)**	25 137	21 778	7,4 %
13. Vask- og sanitærrom **(Sanitary facilities)**	7 379	6 371	2,2 %
14. Trafikkareal **(Traffic area)**	84 397	73 982	24,9 %
15. Lager **(Storage)**	21 786	18 833	6,4 %
16. Tilfluktsrom **(Shelters)**	4 065	3 466	1,2 %
17. Diverse, annet **(Other)**	1 774	1 498	0,5 %
Total	**339 031**	**297 546**	**100 %**

The floor area types are incorporated into 7 classes. The procedure for aggregating the floor area types into classes is described in section 4.5.1. Figure 25 illustrates the class distribution in the current building stock. Traffic area is the largest part and accounts for a quarter of the total heated floor area. The second largest is office area which constitutes almost a quarter of the total heated floor area. Laboratory composes 13% of the current building stock, whereas technical rooms accounts for 17% of the total heated floor area.

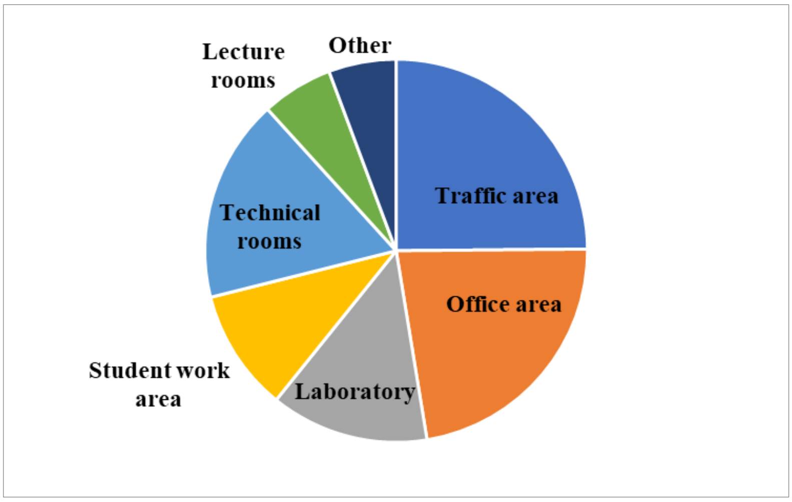


Figure 25. *Class distribution in the current building stock*

Some of the buildings at NTNU Gløshaugen are a vital part of national heritage and cannot be demolished. The protected buildings are Hovedbygning (301), Varmeteknisk (302), Gamle Fysikk (319), Gamle Kjemi (323), Vannkraftlaboratoriet (324), Gamle Elektro (325), Vestre Gløshaugen (330), Østre Gløshaugen (342) and Infohuset (343) *(Tanche-Nilssen, personal communication, December 2017).*

A large majority of the buildings are owned by NTNU but there are few which belong to other institutions. SINTEF Energi (320) is owned by SINTEF, Idrettsbygget (335) and Høgskoleringen 3 (358) are a part of Studentsamskipnaden, while Handelshøyskolen (380) belongs to KLP Eiendom Trondheim AS *(Rønning, personal communication, September 2017).*

The gross floor area of the buildings at NTNU Gløshaugen is approximately 340 000 m^2. The heated floor area is equal to the net floor area and amounts to nearly 300 000 m^2.

District heating and heat pumps on NTNU Gløshaugen

A large majority of the buildings on NTNU Gløshaugen use district heating for space heating and hot water. NTNU Gløshaugen has its own district heating grid in the form of the ring which is directly connected with the Trondheim district heating grid. The main heat exchanger is located in Gamle Elektro (325), marked with the red dot in Figure 26. Since 2010 NTNU has been implementing heat pumps in the buildings. The location of heat pumps is illustrated in Figure 26. The amount of heat generated by each heat pump is included in Appendix B. In addition, in 2014 a combined system of ammonia chiller and heat pump (NH3) for cooling the super computers in Byggteknisk (337) was installed. The system is integrated into the Gløshaugen district heating grid *(Engan, personal communication, April 2018).*

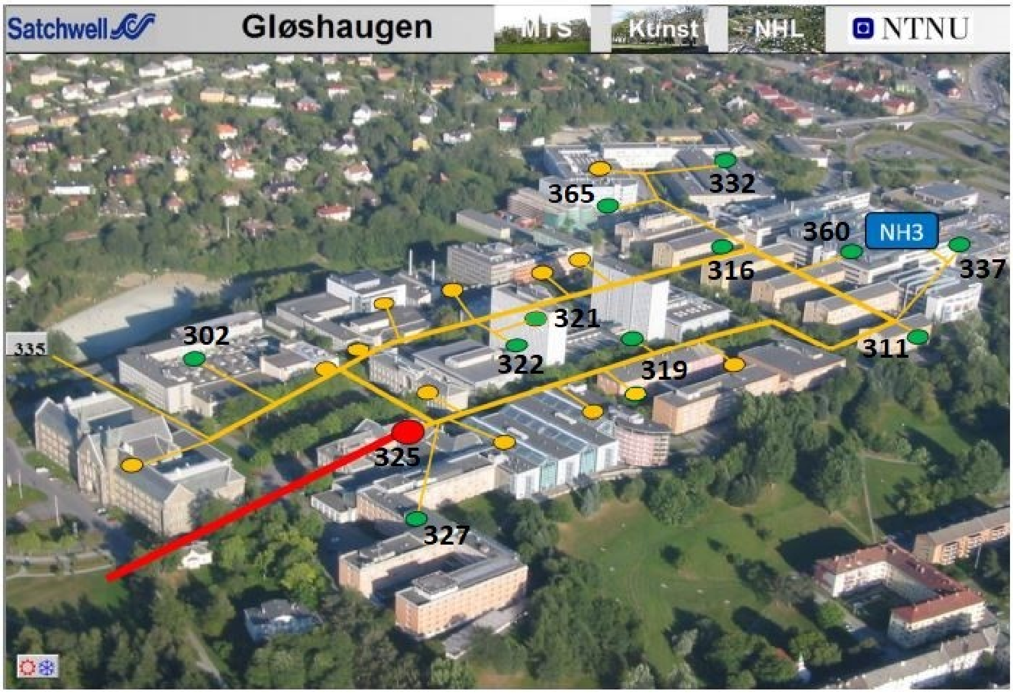


Figure 26. *District heating ring on NTNU Gløshaugen (the yellow line) and the location of heat pumps (the green dots) (Engan, Stene, & Høyem)*

Energy consumption of the building stock at NTNU Gløshaugen in 2016

In the year 2016 the buildings at NTNU Gløshaugen consumed 47,1 GWh of electricity. Figure 27 illustrates hourly electricity consumption in 2016. The fluctuations in electricity consumption were rather regular through the year. The highest electricity consumption was measured between 10 and 16 on weekdays, reaching approximately 8 000 kWh.

A significant decrease in electricity consumption was observed in the end of March (due to the Easter break), during summer months (due to summer holidays) and between the end of December and the beginning of January (due to the Christmas break) as shown in Figure 27. Hourly electricity consumption over the usual week in 2016 is presented in Appendix B.

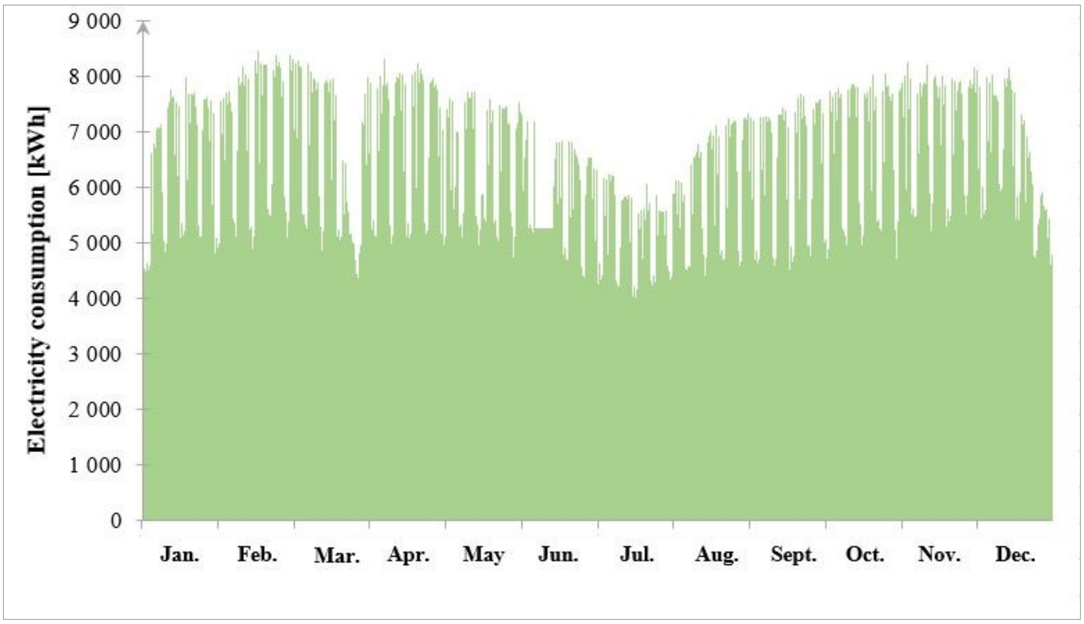
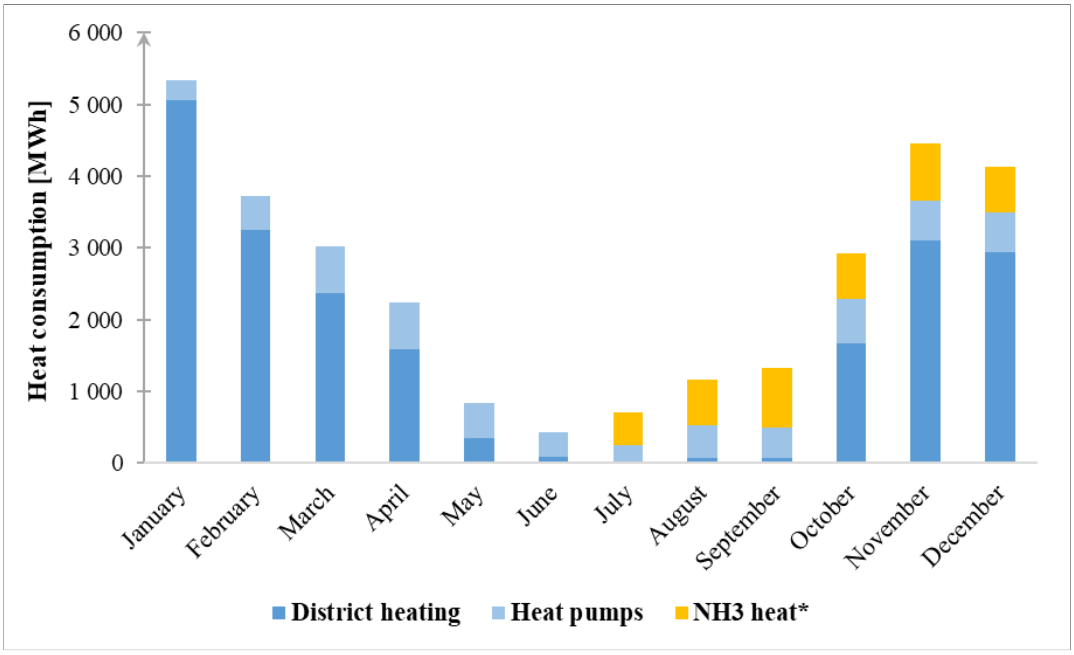


Figure 27. *Hourly electricity consumption in 2016*

Moreover, there are three energy technologies which supply heat to NTNU Gløshaugen: district heating, heat pumps and a combined system of ammonia chiller and heat pump (NH3). Figure 28 presents monthly consumption of heat produced by three different energy technologies.

In 2016 district heating constituted 68% of the total supplied heat. Additionally, heat generated from heat pumps accounted for 19% and from NH3 for 13% of the total supplied heat. However, a share of heat generated by NH3 was in fact higher since the data on heat production by NH3 in 2016 is incomplete. The amount of heat generated by NH3 is fairly constant through the year, on average, 720 MWh per month *(Engan, personal communication, April 2018).* Heat production from heat pumps varied with each month (the lowest generation occurred in January, the highest in April).

Hourly district heat consumption over two weeks in March in 2016 is presented in Appendix B.



*lack of data on heat production by NH3 from January to June 2016

Figure 28. *Monthly heat consumption with respect to energy technology in 2016*

The building stock at NTNU Gløshaugen consumed 20,5 GWh of district heat in 2016. Figure 29 shows hourly district heat consumption in 2016. District heat consumption varied greatly during the year as it is directly affected by weather conditions. The highest consumption occurred in the winter, the lowest in the summer. The peak took place on the 8th of January 2016, amounting to 14 000 kWh.

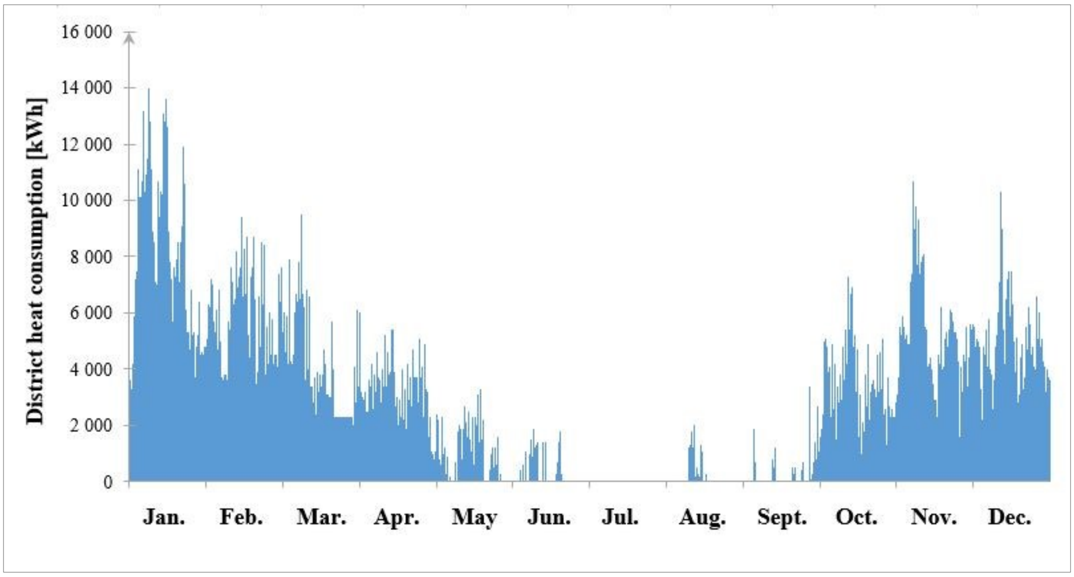


Figure 29. *Hourly district heat consumption in 2016*

Figure 30 represents the weighted average electricity and district heat intensities in the Gløshaugen building stock in the year 2016 with respect to cohort group. The electricity intensity varied greatly between the cohort groups and within each cohort. The highest average electricity intensity occurred in the cohort group 1971-1999 (310 kWh/m^2), whereas the lowest appeared in the oldest buildings (112,7 kWh/m^2).

In contrast to the electricity intensity, the average district heat intensity did not differ significantly between the cohort groups. However, it varied within each cohort. The cohort group 1951-1970 was characterized by the highest district heat intensity (119,8 kWh/m^2). The lowest district heat intensity occurred in the buildings built between 1971 and 1999 (102,9 kWh/m^2).

The minimum, maximum and the weighted average electricity and district heat intensities are listed in Appendix B.

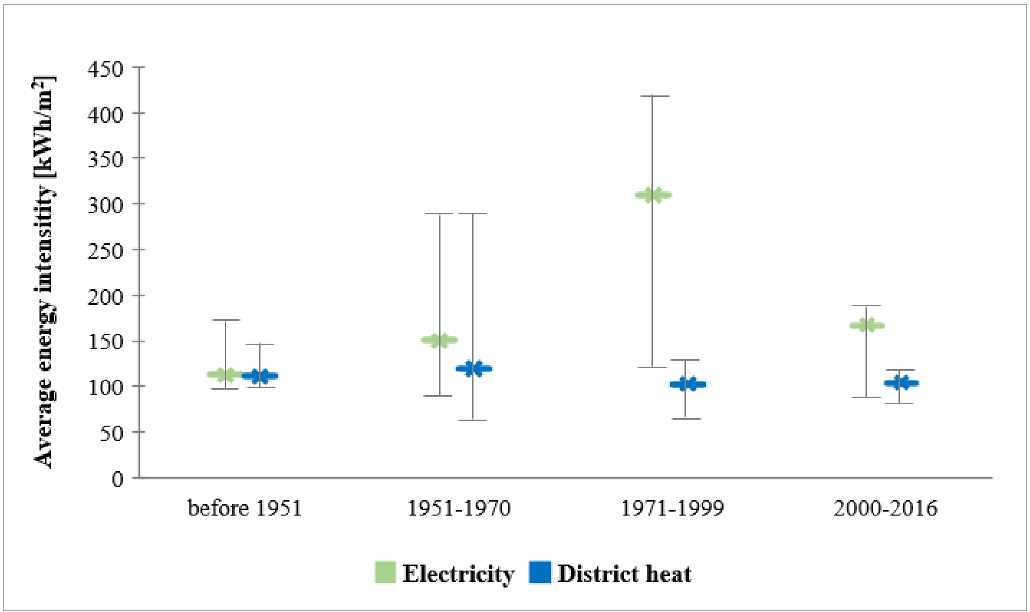


Figure 30. *Average electricity and district heat intensities in four cohort groups in 2016*

4.3.2. NTNU Gløshaugen in the future

Due to the relocation of human and social sciences campuses (Dragvoll, Tunga, Rotvoll, Moholt and Olavskvartalet), the Campus Development Project requires substantial construction activities in the area around NTNU Gløshaugen. The Campus Development Project is currently in the stage in which needs of users and opportunities of developing NTNU Gløshaugen are being determined. In the summer 2018 the design phase is about to start, whereas construction is planned in a period of 2020-2025 (Campus of the Future).

Three projects on the possible placement and size of the future buildings are examined. Two of the strategies (Alternative 1 and 2) are based on the winning proposal in a competition for the concept of the future NTNU Gløshaugen and include construction in the Høgskoleparken and Elgeseter park. Alternative 0 involves the area development without intervention in the park area, on sites whose status is regulated in compliance with the municipal local area plans of Trondheim (KOHT Arkitekter, 2017). The planned size of the new construction is presented in Table 2.

Table 2. *Planned size of the new buildings (KOHT Arkitekter, 2017)*

	Planned size of the new buildings [m^2]
Alternative 1	119 500
Aternative 2	118 500
Alternativ 0	153 500

Beside three above-mentioned alternatives, KOHT Arkitekter (2017) recommend several possible locations of the new buildings which will make NTNU fulfil its ambitions. The suggested placement and size of the new buildings is shown in Figure 31. The proposed project assumes a development in north-west direction from NTNU Gløshaugen and is divided into two priority categories. The first priority category buildings (marked in red in Figure 31) are considered to be key components in pursuit of achieving the goals. The northern, central and southern parts of the development project create a hub which ensures good connection between Gløshaugen, St. Olavs, Kalvskinnet campuses and the city centre. The second priority buildings (marked in blue in Figure 31) are expected to provide the highest possible density of the development and limit the distance between St. Olav's and NTNU Gløshaugen. However, the second category includes construction activity in the Høgskoleparken and Elgeseter park (2 blue buildings: 9 500 m^2 and 11 500 m^2, respectively in Figure 31). The parks belong to conservation area and therefore the future construction within the parks is associated with some uncertainty concerning a building permit from Trondheim municipality. The projected size of the first priority area is equal to 118 500 m^2 while the second priority area is 43 000 m^2. The reserve area (marked in green in Figure 31), south from the existing NTNU Gløshaugen, represents a development opportunity in case of the further future expansion of NTNU Gløshaugen. The estimated size of the reserve area is in the 40 000 - 50 000 m^2 range. KOHT Arkitekter (2017) emphasise that the proposal is flexible and there is a possibility of taking out areas which will turn out to be too problematic or challenging.

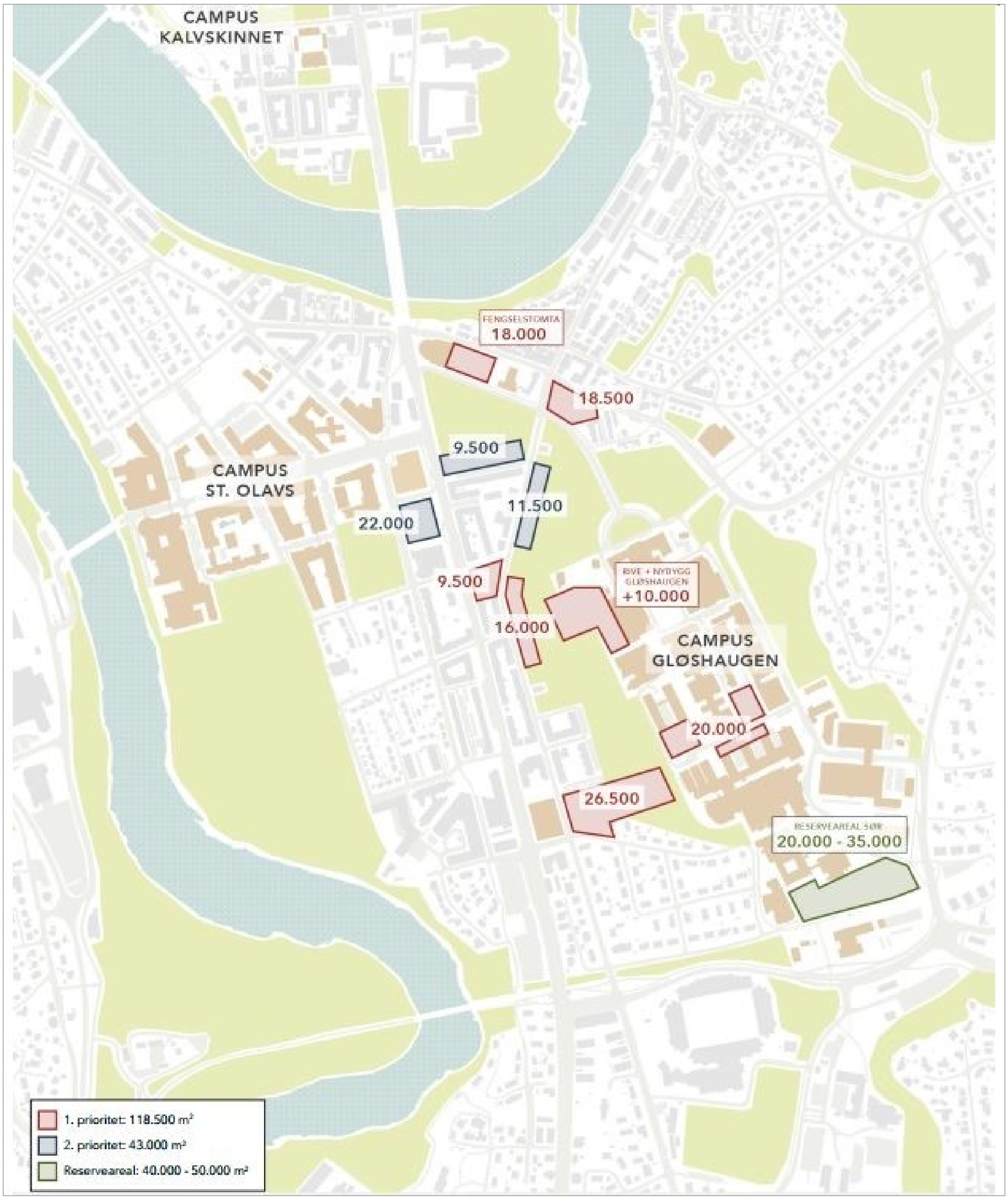


Figure 31. *Recommended location of the future development (KOHT Arkitekter, 2017)*

So far, neither greenhouse gas emissions target nor energy requirements for existing building stock and new constructions have been explicitly defined in the Campus Development Project. However, there are few documents which concern energy and emissions issues. As stated in (*Kvalitetsprogram: NTNUs campusutvikling 2016 - 2030*), NTNU Gløshaugen should be energy efficient and have low greenhouse gas emissions. (*NTNU 2016 Visjoner for Campusutvikling*, 2014) underlines that energy efficiency in already existing buildings has to be improved and new buildings have to be nearly zero emission buildings. Furthermore, NTNU aims to reduce its energy consumption by 20% compared with 2010 level by the year 2020. Regarding a long-term perspective, NTNU has a vision of the zero energy building stock in 2060. The concept predicts that the new buildings are plus energy buildings and they supply energy to buildings which are not self-sufficient (*NTNU 2016 Visjoner for Campusutvikling*, 2014).

In January 2018 the Norwegian government decided to finance 92 000 m^2 of gross floor area of the new buildings and 45 000 m^2 gross floor area of refurbishment of the existing buildings (Regjeringen, 2018).

4.4. Scenario analysis

Four scenarios were developed in order to analyse possible future energy demand and related GHG emissions of NTNU Gløshaugen in a period of 2017-2050. The scenarios include two different aspects: renovation of the existing building stock and energy supply systems at NTNU Gløshaugen.

1. Baseline scenario

Baseline scenario consists of assumptions about future development of the existing and new buildings that are regarded as most probable. The assumptions follow current trends and are in compliance with present policy and regulations. The existing building stock is assumed to undergo standard renovation in a 40-year renovation cycle. The new buildings are expected to be built according to passive house requirements. Regarding energy supply systems, PV modules installed on the south façades of the new buildings are presumed to be a source of electricity besides the electrical grid. Heat pumps and NH3 are expected to be a source of low carbon heat and district heating will remain a primary source of heat.

2. Extensive local energy production scenario

Extensive local energy production scenario concentrates on generating energy from renewable sources within NTNU Gløshaugen. The use of heat pumps, photovoltaics and a biogas-based CHP is expected to decrease the amount of imported energy and make NTNU Gløshaugen less dependent on the energy grid. The assumptions about renovation of the existing building stock and energy efficiency of the new buildings are considered to be identical to Baseline scenario.

3. Advanced renovation scenario

Advanced renovation prioritizes increased energy efficiency of the Gløshaugen building stock above local energy generation. The existing buildings are expected to undergo advanced renovation (a 40-year cycle), whereas the new buildings are presumed to be built according to passive house requirements. Energy supply systems are assumed to be the same as in Baseline scenario. Energy export to the grid in case energy generation exceeds energy consumption is assumed to be feasible.

4. Hybrid scenario

The hybrid scenario is a combination of Extensive local energy production and Advanced renovation scenarios. The hybrid scenario is the most ambitious from all the presented development paths and is characterized by the highest chance to meet a Zero Energy/Emission balance at neighbourhood level. Energy export to the grid in case energy generation exceeds energy consumption is assumed to be feasible.

4.5. Model input

4.5.1. Zero Emission Neighbourhood building stock model input

The study case takes into account all the buildings located at NTNU Gløshaugen, both owned by NTNU and other institutions. There are 46 existing buildings. Although many of them are not physically separate buildings, they compose a part of a larger building. Regarding the future development of NTNU Gløshaugen, all the three alternatives presented in Table 2 exceed considerably the size of the future construction financed by the Norwegian government (92 000 m^2). As mentioned in section 4.3.2 the recommendation plan developed by KOHT Arkitekter (2017) is flexible and allows for variations.

Figure 32 illustrates the selected sites for the new buildings. The choice of the buildings is made in compliance with the limitation placed on the size of the new buildings by the Norwegian government. Nearly all the first priority buildings (apart from two exceptions) are selected as an input into the ZEN building stock model, accounting for 92 000 m^2. The two buildings are not included due to the fact that they are situated in Høgskoleparken and their construction is related to a degree of uncertainty over building permits. The building with the floor area of 16 000 m^2 is excluded from the plan and the large building located partially within the park area is divided into two sections: one within the park and the other outside the park. The part outside the park area like in Alternative 0 is taken into account.

The detailed data on the new buildings (construction year, gross floor area, net floor area and net floor area of floor area types) are presented in Appendix C.

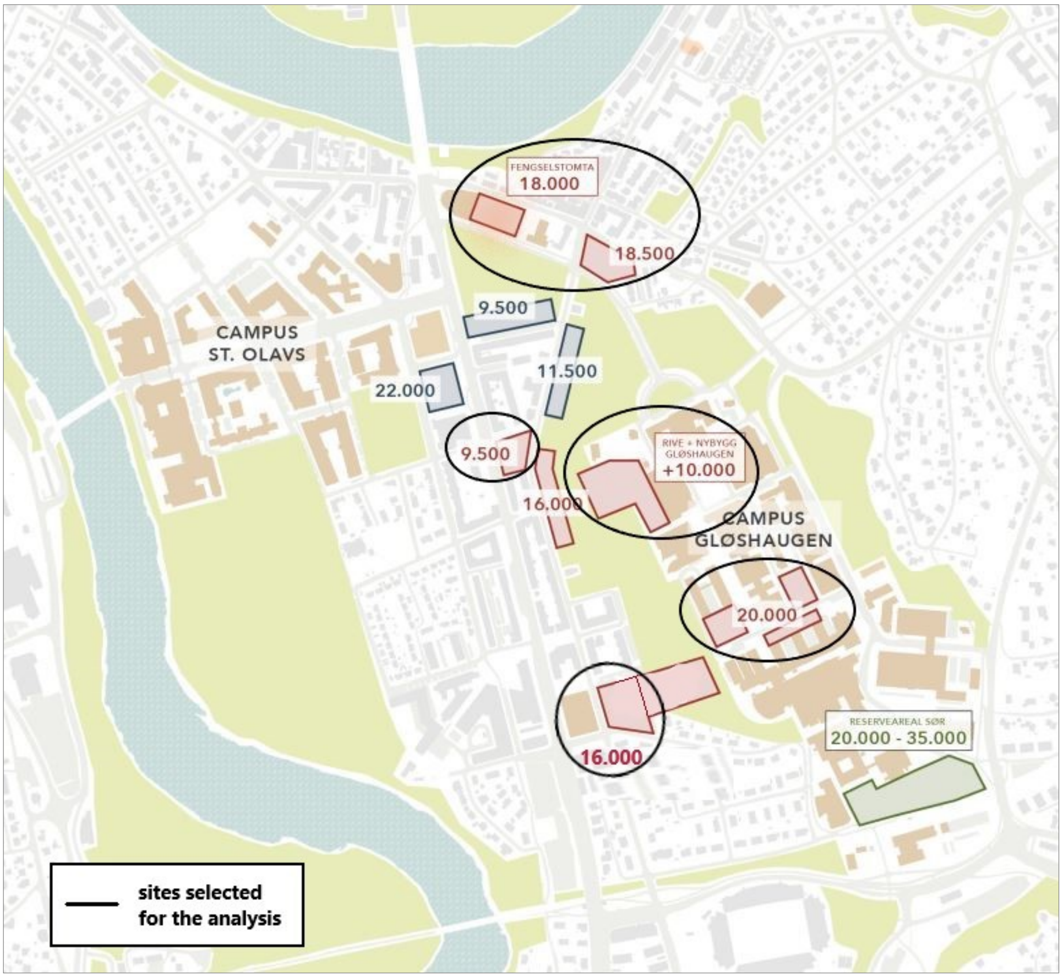


Figure 32. *Selection of the sites for the new buildings based on (KOHT Arkitekter, 2017)*

The building stock is divided into 5 cohort groups, 4 of them involve the current building stock and 1 refers to the future development, as shown in Table 3. The ratio of net floor area to gross floor area of the existing buildings (0,877) is applied while calculating the net floor area of the new buildings. The lifetime of each building is estimated to be 125 years. 9 out of 46 buildings are protected and the rest undergo demolition activity modelled by using Weibull distribution.

Table 3. *Cohort groups*

Cohort group	Number of buildings	Number of protected buildings	Gross floor area [m^2]	Net floor area [m^2]
before 1951	8	8	38 692	31 630
1951-1970	26	1	156 452	138 036
1971-1999	9	-	58 915	51 763
2000-2016	3	-	85 046	76 117
2020-2025	8	-	92 000	80 684
	54	**9**	**431 105**	**378 230**

17 different floor area types presented in Table 1 are incorporated into 7 classes. The aggregation is made based on similarities between floor area types or as in the case of 'Other' class in order to integrate secondary floor area types into one class. The distribution of floor area types between classes is shown in Table 4.

Table 4. *Class formation*

Floor area type	Class
Office area	**Office area**
Lecture rooms	**Lecture rooms**
Laboratory	**Laboratory**
Student work area Library	**Student work area**
Traffic area	**Traffic area**
Business area Canteen area Exhibition areas Sports rooms Hospital rooms Sanitary facilities Other	**Other**
Technical rooms Storage Shelters Workshop	**Technical rooms**

The share of office area, lecture rooms, laboratory, etc. in the new buildings has not been specified yet. Therefore, in this Master thesis it is assumed that the distribution of floor area types in the new buildings will correspond to the distribution of floor area types in the relocated campuses (Dragvoll, Tunga, Rotvoll, Moholt and Olavskvartalet) which is presented in Table 5. The floor area types are aggregated into 7 classes on the basis of the class formation given in Table 4.

Table 5. *Distribution of floor area types in the new buildings*

Floor area type	Share in gross floor area
1. Kontorarealer **(Office area)**	23 %
2. Undervisningsrom **(Lecture rooms)**	13 %
3. Laboratoriearealer **(Laboratory)**	2 %
4. Studentarbeidsplasser **(Student work area)**	9 %
5. Bibliotek **(Library)**	3 %
6. Forretningsarealer **(Business area)**	1 %
7. Kantinearealer **(Canteen area)**	3 %
8. Utstillingsarealer **(Exhibition areas)**	0 %
9. Verksted **(Workshop)**	0 %
10. Idrettsrom **(Sports rooms)**	3 %
11. Sykehusrom **(Hospital rooms)**	0 %
12. Tekniske rom **(Technical rooms)**	6 %
13. Vask- og sanitærrom **(Sanitary facilities)**	2 %
14. Trafikkareal **(Traffic area)**	28 %
15. Lager **(Storage)**	4 %
16. Tilfluktsrom **(Shelters)**	2 %
17. Diverse, annet **(Other)**	1 %

4.5.2. Zero Emission Neighbourhood energy model input

All input into the Zero Emission Neighbourhood model are set at hourly resolution.

Scenario specification

The detailed specifications of four scenarios are listed in Table 6. The assumptions made about renovation activity and energy supply systems are presented in the sections below.

Table 6. *Scenario specification*

		Baseline	**Extensive local energy production**	**Advanced renovation**	**Hybrid scenario**
Existing buildings	**Renovation (a 40-year cycle)**	Standard	Standard	Advanced	Advanced
New buildings	**Construction**	Passive house standard	Passive house standard	Passive house standard	Passive house standard
Energy supply systems	**Electricity supply**	Electrical grid PV on the new construction *(60% of full potential)*	Electrical grid PV on the new construction *(full potential)* PV on the exisiting buildings *(full potential)* CHP based on biogas	Electrical grid PV on the new construction *(60% of full potential)*	Electrical grid PV on the new construction *(full potential)* PV on the exisiting buildings *(full potential)* CHP based on biogas
	Heat supply	District heating Heat pumps NH3	District heating Heat pumps NH3 CHP based on biogas	District heating Heat pumps NH3	District heating Heat pumps NH3 CHP based on biogas

IDA ICE energy use profiles

Hourly energy use profiles of the buildings at NTNU Gløshaugen are developed by Nesgård & Ngo (2018) in IDA Indoor Climate and Energy (IDA ICE) software. Five reference building models are established; one for each cohort group (the cohort distribution is the same as presented in Table 3). For the existing building stock, the reference models are derived from the buildings of the corresponding cohort group and their energy use in the year 2016. Energy use profile for the new buildings is modelled according to passive house standards. In addition, it is assumed that all of the reference models have identical geometry, operation and use, whereas building structures and technical systems are different for each reference model. The reference model is expected to consist of five zones, known as classes in this Master thesis (office area, study work area, lecture rooms, special rooms (known as laboratories), and traffic area) (Nesgård & Ngo, 2018).

Beside the current energy use profiles, Nesgård & Ngo (2018) introduce several energy efficiency measures into energy use profiles. The energy efficiency measures are adopted in two packages: Standard Package (P1) and Ambitious + Technical Package (P4). P1 includes improving energy efficiency of building envelope through outer wall and roof insulation, the replacement of windows and sealing of building structures. P1 meets minimum requirements of TEK17 (Norwegian building regulations). P4 focuses both on increasing energy efficiency of a building envelope and implementing technical solutions in a building such as the replacement of a heat recovery unit and the deployment of low temperature heating system. A detailed description of the energy efficiency measures in both packages is provided in Appendix C. P1 corresponds to a standard renovation state, whereas P4 relates to an advanced renovation state in the Zero Emission Neighbourhood model.

Furthermore, Nesgård & Ngo (2018) develop a detailed energy use profile which includes hourly energy use by each zone. The energy use profile relates solely to the reference model of the cohort group 1951-1970. The energy use distribution between zones from the cohort group 1951-1970 is applied to the remaining reference models in order to feed the Zero Emission Neighbourhood model with energy use profiles at archetype level.

PV generation – existing building stock

The solar energy potential of the existing building stock at NTNU Gløshaugen is estimated by (Johansen, Rennan, & Søraas, 2018) in the PVsyst software and is used as input to the Zero Emission Neighbourhood model. Johansen et al. (2018) take into account all areas of roofs which are neither fully nor partially shaded and without any obstacles (windows, vents, pipes, etc.), in total 15 760 m^2. East-west mounting systems of PV modules are considered for flat roofs (with a slope of less than 10°), whereas tilted roofs determined tilt angles and orientation of PV installation. Polycrystalline solar modules IBC PolySol 275 GX5 with a nominal power of 275 Wp and efficiency of 16,8% are chosen for the simulation. The nominal power of 2,3 MWp is installed. The total annual energy output is estimated to be 1,7 MWh. For hourly values of the total PV power, see Appendix C.

PV generation – new buildings

Since the designs for the new buildings have not been declared yet, there is great flexibility in an estimation of the area suitable for PV. Therefore, a reference building is sketched out in order to assess PV generation in the best possible way. The building is assumed to have 6 floors and the gross floor area of 11 450 m^2. The south façade is considered to be covered with PV modules, thereby replacing a traditional roof cover with Building Integrated PhotoVoltaics (BIPV). The tilt angle of the south façade is expected to be 45° to maximize energy output from PV. The surface of the south façade is 3 786,5 m^2. The cover ratio, a proportion of the PV surface to the south façade area is assumed to be 95%. Azimuth (the angular direction which the panels are facing) is considered to be 0°, indicating due south for the northern hemisphere. The exact dimensions and elevations of the reference building are presented in Appendix C.

Monocrystalline silicon modules from LG Solar with a nominal power of 300 Wp at STC (Standard Test Conditions) and efficiency of 18,3% are chosen for the simulation. 2185 such modules are expected to be installed on the tilted south façade covering 3 597 m^2. The modules are connected in 115 strings; each string contains 19 modules. In addition, a central inverter from Ingeteam with a maximum power point tracking system (MPPT) and maximum efficiency of 98,5% is selected. The nominal power of the system at STC is equal to 656 kWp and the nominal AC power of the inverter is 526 kW.

In order to simplify the calculations, in this Master thesis it is assumed that 8 identical buildings are expected to be erected accounting for nearly 92 000 m^2 of the gross floor area according to the decision of the Norwegian government. Moreover, the azimuth, tilt angle and system components are expected to be the same in all the new buildings and thus energy production from PV will take place at the same time. Simulated in PVsyst energy generation from one building is multiplied by the number of new buildings. To sum up, the total area of PV installed on the new buildings is assumed to be 30 292 m^2 with a nominal power of 5,2 MWp. Shading from nearby buildings and vegetation are not included in the simulation.

Biogas-based combined heat and power plant (CHP)

A biogas-based CHP is presumed to be one of sources of heat and electricity for the building stock at NTNU Gløshaugen. The CHP plant is assumed to be located within NTNU Gløshaugen area. The CHP plant in the Heimdal high school project described in section 3.2.2 is used as the template for the Gløshaugen case. The biogas-based cogeneration is expected to produce approximately 339 MWh of heat and 162 MWh of electricity annually. Energy generation is assumed to be constant through the year *(Wigenstad, personal communication, May 2018).*

Heat pumps

It is considered that NTNU will continue installing heat pumps in the buildings. Therefore, heat pumps are integrated into energy use profiles. The share of heat demand met by heat pumps and the coefficient of performance (COP) of heat pumps in each cohort group and in each state are presented in Table 7. The current state represents the share of heat demand satisfied by heat pumps in 2016 and the average COP of the heat pumps at NTNU Gløshaugen. The COP of new heat pumps is assumed to be 4. Additionally, the energy use profile of Building 5A is used in Baseline and Extensive local energy production scenarios, whereas the energy use profile of Building 5B is applied in Advanced renovation and Hybrid scenarios.

Table 7. *Share of heat demand met by heat pumps in each cohort group and COP of heat pumps in parentheses*

Reference model	Cohort group	Current state	Standard Package (P1)	Ambitious + Technical Package (P4)
Building 1	before 1950	-	40% (4)	60% (4)
Building 2	1951-1970	14% (3,4)	40% (4)	60% (4)
Building 3	1971-1999	27% (3,4)	40% (4)	60% (4)
Building 4	2000-2016	16,5% (3,4)	40% (4)	60% (4)
Building 5A	2017-2025	60% (4)	-	-
Building 5B	2017-2025	80% (4)	-	-

Combined system of ammonia chiller and heat pump (NH3)

Data on heat production by NH3 in 2016 is incomplete and thus the data from August 2016 to July 2017 (the data for the second of 2017 was not available) is taken into account. Based on the received monthly values an hourly profile is created assuming constant heat generation across the year (8,7 GWh annually).

4.5.3. Zero Emission Neighbourhood GHG emissions model input

Monthly carbon intensities of electricity from the grid and district heating in 2016 are listed in Table 8. The values of the carbon intensity of electricity form the grid comes from the European Network of Transmission System Operators (ENTSO-E) and refer to the Norwegian bidding zone NO3 (within which Trondheim is located). The carbon intensity of electricity from the grid is assumed to be constant during the modelling period 2017-2050. The projected annual carbon intensity is the average of monthly values from a period 2015-2017 and totals 28,9 g of CO_2-eq/kWh (Dæhlin, 2018).

Furthermore, data on the carbon intensity of district heating is provided by Statkraft Varme, a local district heating company. According to Dæhlin (2018), the emission intensity of district heating varies widely depending on assumptions about the allocation of emissions.

The allocation by economic value (62,5% of emissions allocated to waste management and 37,5% to district heating) is considered while calculating the GHG emission of NTNU Gløshaugen. The annual carbon intensity of district heating is assumed to be constant after 2020 and is equal to 64,1 g of CO_2-eq/kWh. The carbon intensity of district heating in 2017, 2018 and 2019 totals 81,4, 75,6 and 69,7 g of CO_2-eq/kWh, respectively (Dæhlin, 2018).

The carbon intensity of biogas is assumed to be constant over the modelling period and totals 27 g of CO_2-eq/kWh (Lien, 2013).

Table 8. *Carbon intensities of electricity form the grid and district heating in 2016*

Month	Carbon intensity of electricity from the grid [g CO_2-eq/kWh]	Carbon intensity of district heating [g CO_2-eq/kWh]
January	28,8	125,2
February	30,0	97,4
March	33,9	83,6
April	30,4	83,8
May	26,2	65,4
June	28,7	64,5
July	36,3	64,0
August	39,4	65,4
September	26,9	64,9
October	27,5	83,4
November	27,1	128,2
December	26,1	107,4

5. Results

5.1. Building stock characteristics of future NTNU Gløshaugen

5.1.1. Model results

Figure 33 presents the future development of the Gløshaugen building stock in a period 2017-2050. The size of the building stock grows until the year 2025 and in the same year the stock reaches its maximum (361 336 m^2) as a consequence of a completion of the construction. After 2025 the stock gradually decreases due to the fact that no subsequent construction is planned and because of the building ageing process. At the end of the modelling, in 2050, the total heated floor area of the stock is expected to be equal to 310 714 m^2. The only buildings which undergo demolition are the ones from the cohort group 1951-1970. The floor area of the oldest buildings (built before the year 1951) remain unchanged as these buildings are a part of a national heritage and cannot be demolished.

A slight decline in the heated floor area occurring at the beginning of the simulation period is the effect of the stochastic method of predicting demolition activity used in the Zero Emission Neighbourhood model.

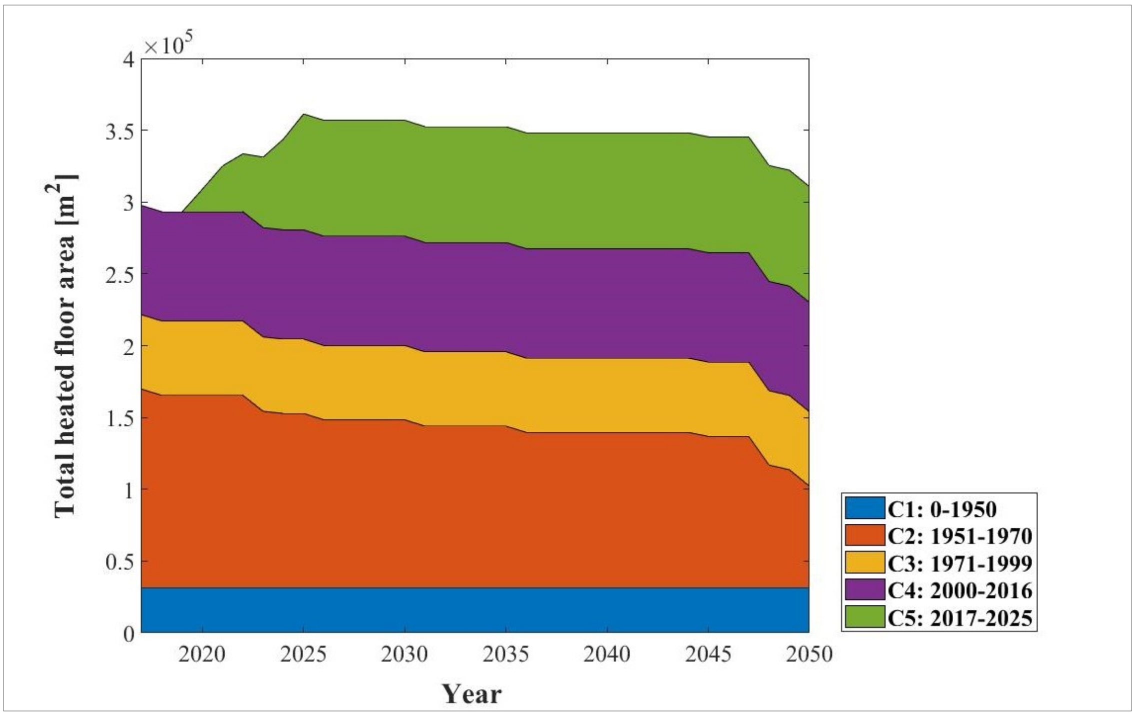


Figure 33. *Total heated floor area per cohort*

During the modelling period (2017-2050) the class distribution within the Gløshaugen building stock changes continually as shown in Figure 34. Total heated floor area per floor area class. The floor area type distribution over a period of 2017-2050 is included in Appendix D. The development of each floor area class does not alter analogously to a change in size of the Gløshaugen building stock by reason of different class distribution in the existing building stock and the new buildings.

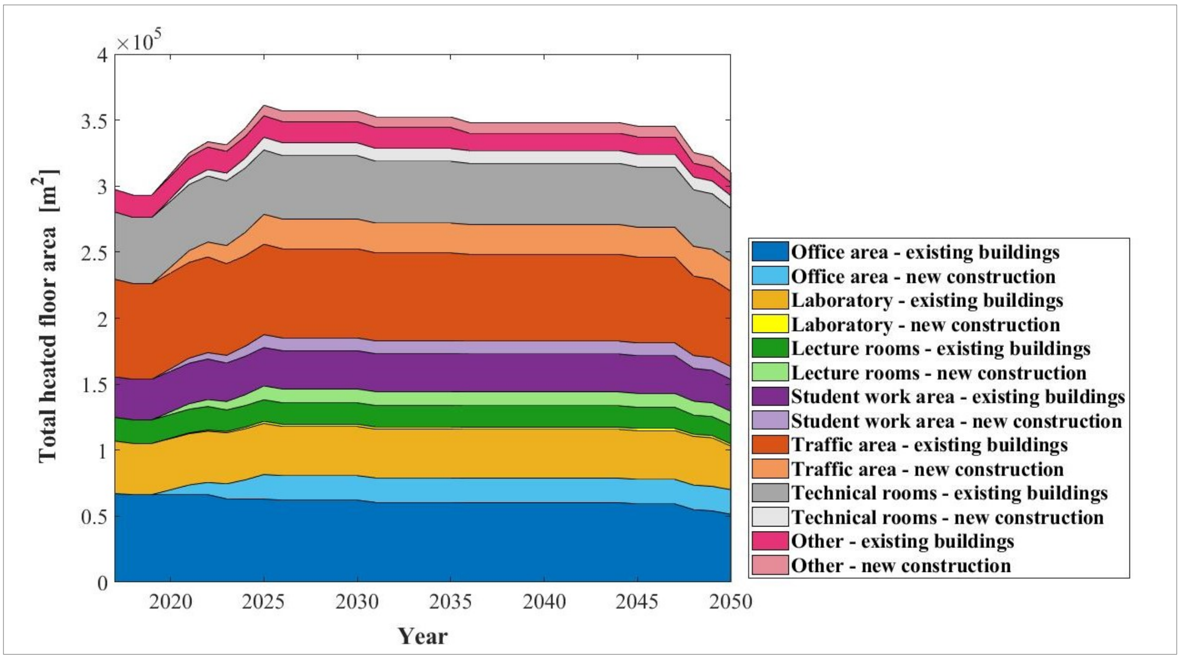


Figure 34. *Total heated floor area per floor area class*

Table 9 represents the class distribution at the beginning of the modelling period, in the year 2025 (when the building stock reaches a maximum size) and at the end of the simulation. The greatest difference can be observed in a share of laboratories which is expected to decrease by 2,3% at the end of the modelling period compared to the year 2017. In addition, a share of technical rooms is estimated to decline by 1,1% during the simulation period. Moreover, a share of lecture rooms is forecast to rise by 2% from 2017 to 2050. Besides the lecture rooms, shares of three other classes (traffic area, student work area and other) are expected to increase. The percentage of office area in the class distribution is estimated to remain constant.

Table 9. *Class distribution through the modelling period*

Class	2017	2025	2050
Office area	22,6 %	22,6 %	22,6 %
Laboratories	13,4 %	11,2 %	11,1 %
Lecture rooms	6,0 %	7,4 %	8,0 %
Student work area	10,3 %	10,7 %	10,9 %
Traffic area	24,9 %	25,2 %	25,7 %
Technical rooms	17,1 %	16,2 %	16,0 %
Other	5,7 %	6,7 %	5,8 %

5.2. Energy use characteristics of future NTNU Gløshaugen

5.2.1. Preliminary energy results – PV generation

The estimated annual energy output from PV installed on the south façades of the new buildings is 5,1 GWh. Figure 35 shows hourly energy production through the year, whereas Figure 36 presents monthly energy output from PV. As seen in Figure 35, PV generation is significantly lower during the winter due to short days, little solar irradiation and higher shading losses because of snow cover. The month with the highest energy output is May (756 MWh) and the lowest energy production occurs in December (44 MWh). Although the amount of irradiation in May, June and July is very similar (Figure 36), the energy output in May is higher compared to the other 2 months by reason of lower temperatures as high temperatures impact negatively the efficiency of PV modules.

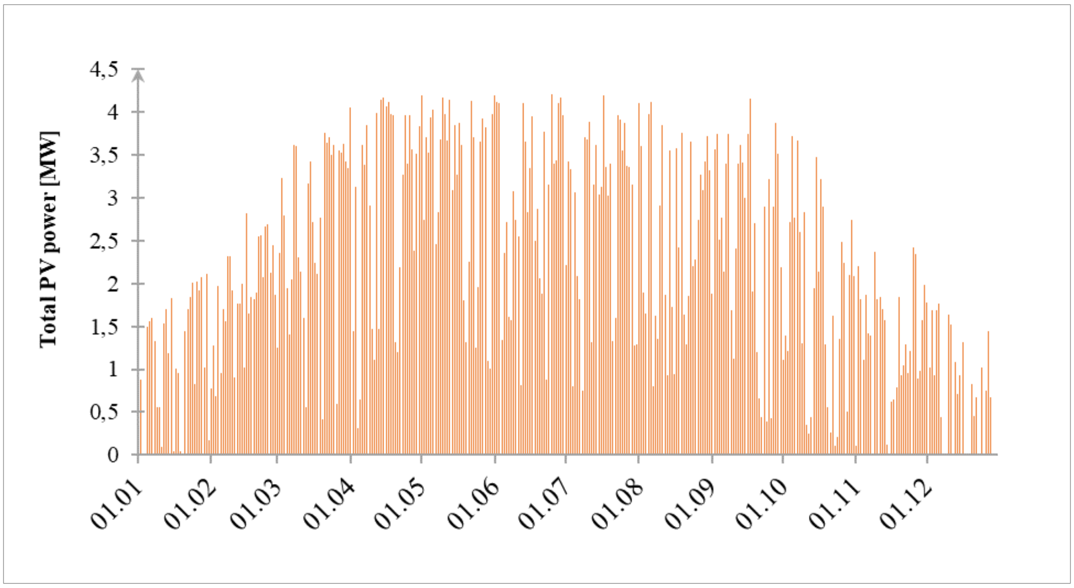


Figure 35. *Total PV power, hourly values*

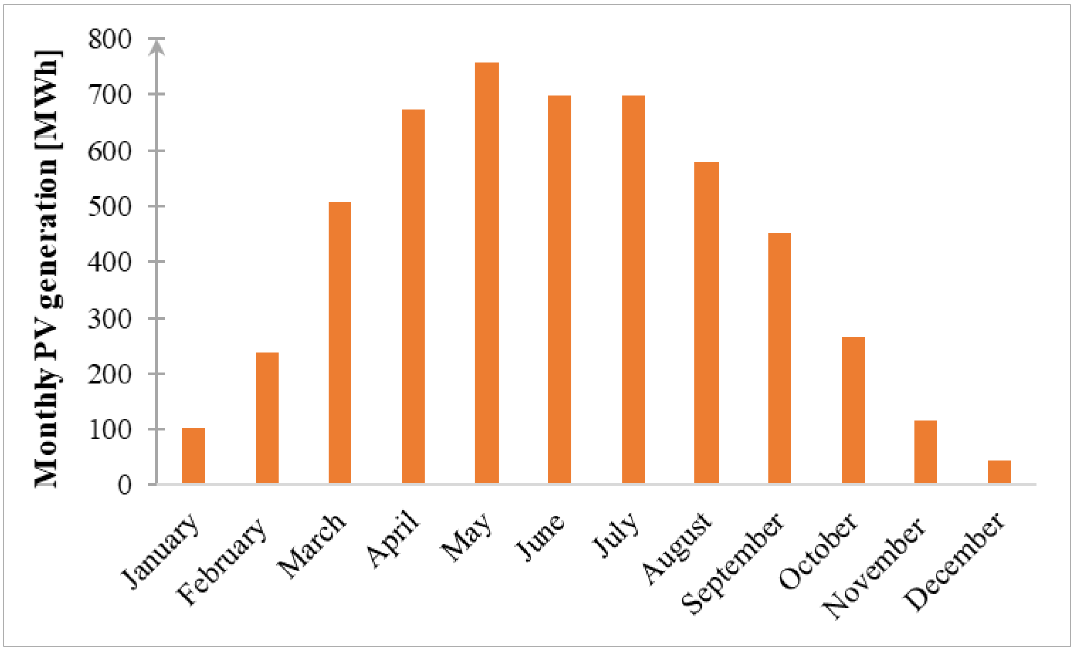


Figure 36. *Total PV production, monthly values*

5.2.2. Scenario analysis

The results obtained from the modelling of possible future development of energy demand and GHG emissions of NTNU Gløshaugen in a period 2017-2050 are presented in this section.

1. Baseline scenario

Energy intensity results

Figure 37 illustrates the energy intensity of each cohort group during the modelling period 2017-2050. The changes in the value of energy intensities are the result of the projected standard renovation activity. As shown in Figure 37, only the energy intensity of the newest cohort group remains unchanged as the buildings have been recently built and they are not in need of renovation during the modelling period. The energy intensities of the cohort group 1, 3 and 4 decrease slightly, whereas the energy intensity of the cohort group 2 fluctuates during the simulation. It is difficult to explain this variation, but it might be related to the demolition of already renovated buildings or the demolition of buildings with a lower share of highly energy-intensive floor area classes like laboratory.

The energy intensities constitute input into the aggregated results of energy demand for both Baseline and Extensive local energy production scenarios.

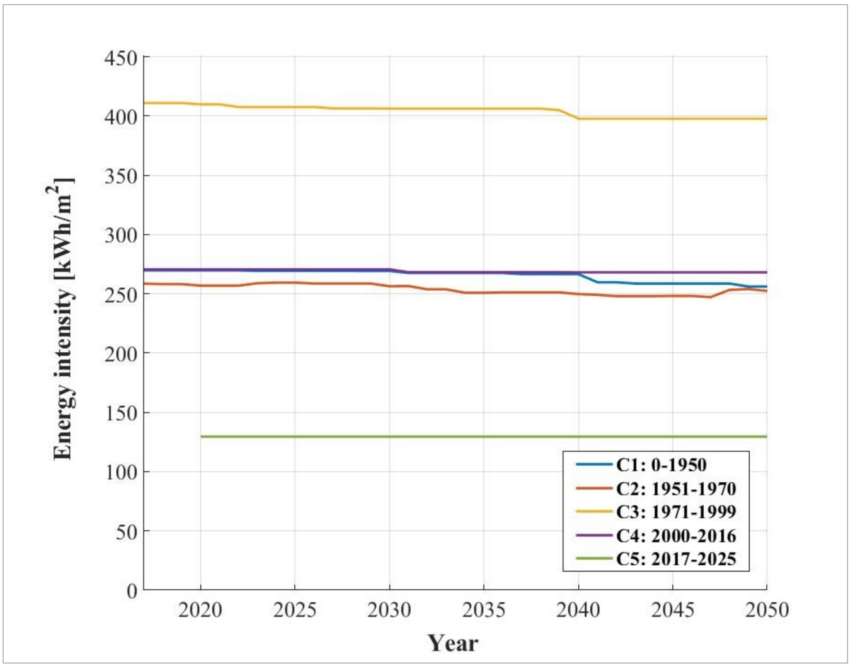


Figure 37. *Energy intensity per cohort group during the modelling period*

Aggregated results for floor area and energy demand

Figure 38 shows the total heated area of the building stock in terms of renovation state. It can be seen that at the end of the modelling period nearly two-thirds of the building stock will have undergone standard renovation. None of the buildings will have reached advanced renovation due to the fact that a standard renovation cycle lasts 40 years.

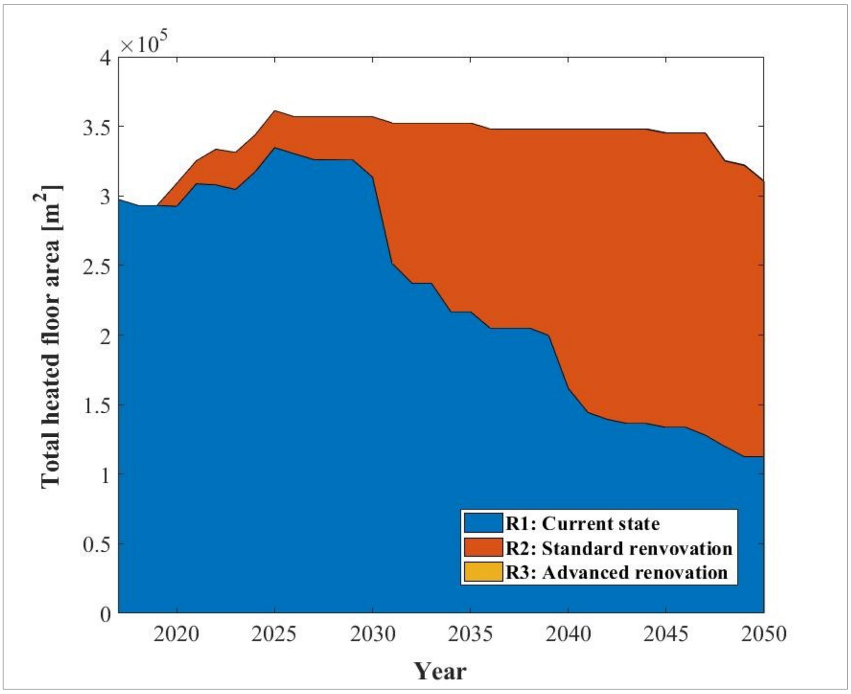


Figure 38. *Total heated floor area with respect to renovation state*

The total energy demand of the Gløshaugen building stock regarding cohort groups is illustrated in Figure 39. At the beginning of the simulation, the energy demand increases due to the planned expansion of NTNU Gløshaugen reaching a maximum of 92 GWh in the year 2025 (in the same year when the building stock reaches maximum size). With time the total energy demand decreases due to renovation and demolition. Compared to the 2017 level, the energy demand of the Gløshaugen building stock in 2050 is estimated to be 10% lower.

The energy demand of the cohort group 1, 3 and 4 drops slightly as a result of renovation activity while the energy demand in buildings from the newest cohort, after the completion of the construction, remains at the same level. Interestingly, the energy demand of the cohort group 2 (marked red in Figure 39) diminishes substantially over the modelling period. The reason for this is demolition and renovation activities which occur in this cohort group.

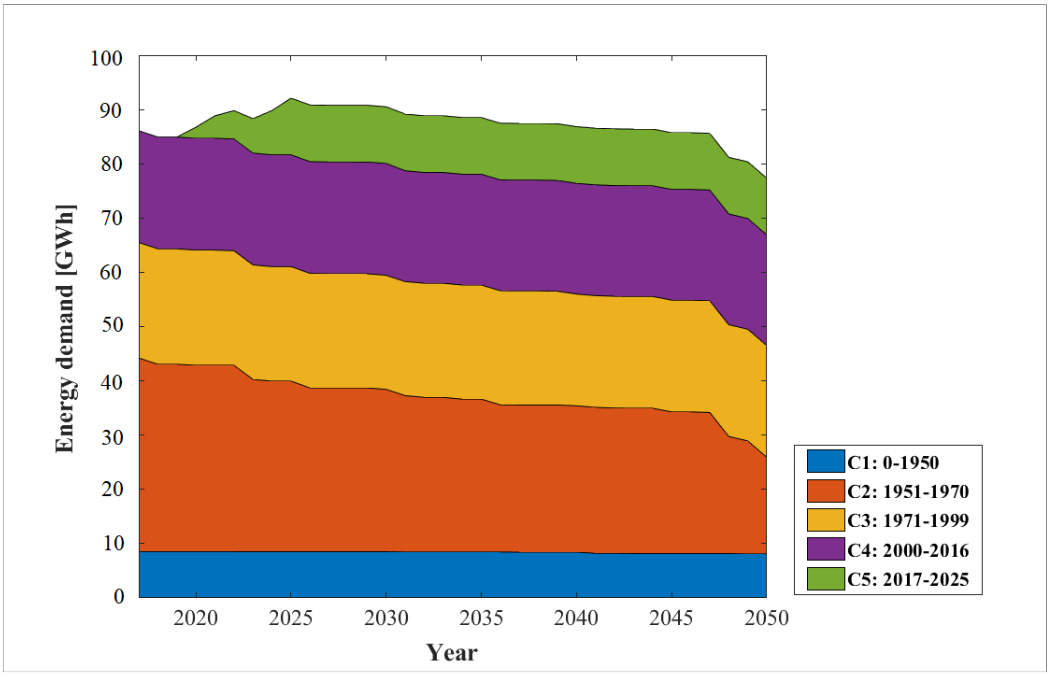


Figure 39. *Energy demand with respect to cohort group*

Figure 40 represents the total energy demand with respect to floor area class and Table 10 shows the exact share of each class in the total energy demand at the beginning of the simulation, in 2025 and at the end of the modelling period. Technical rooms consume the most energy during the whole modelling period, accounting for nearly a quarter of the total energy demand. Traffic area, which represents a quarter of the heated floor area of NTNU Gløshaugen, constitutes for almost 20% of the total energy demand. A decrease in energy use in laboratories (1,6%) and an increase in energy consumption in lecture rooms (1,4%) from 2017 to 2050 are caused by the demolition of buildings with a high share of laboratories and the new constructions with a higher share of lecture rooms compared to the current building stock at NTNU Gløshaugen.

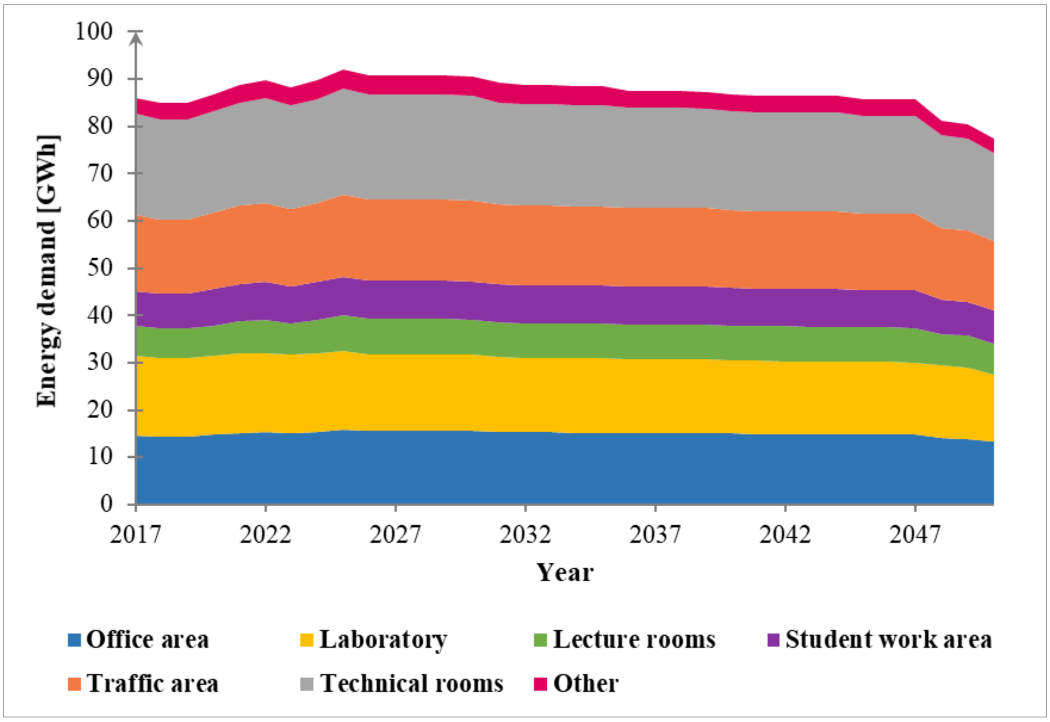


Figure 40. *Energy demand with respect to class*

Table 10. *Share of each class in the total energy demand through the modelling period*

Class	2017	2025	2050
Office area	16,9 %	17,1 %	17,3 %
Laboratories	19,7 %	18,2 %	18,1 %
Lecture rooms	7,2 %	8,1 %	8,6 %
Student work area	8,7 %	8,9 %	9,1 %
Traffic area	18,5 %	18,7 %	19,1 %
Technical rooms	24,9 %	24,4 %	24,1 %
Other	4,0 %	4,5 %	3,8 %

Figure 41 shows energy demand in terms of energy use purpose. Electricity accounts for a large majority of the total energy consumed by the buildings at NTNU Gløshaugen. In 2017 electricity represents 62% and in 2050 nearly 70% of the total energy demand. Electricity used for equipment constitutes 42% of the total energy demand at the beginning of the simulation and up to 47% at the end of the modelling. Additionally, electricity for heat pumps grows gradually as a result of the installation of heat pumps. A share of HVAC and lighting in the total energy demand is fairly constant over the modelling period and accounts for 15% and 4%, respectively. A share of cooling in the total energy demand is negligible. Space heating and hot water represent 38% of the total energy demand in 2017 and 30% in 2050. A decline in heat demand is caused by an improvement of energy efficiency in the buildings through standard renovation activity.

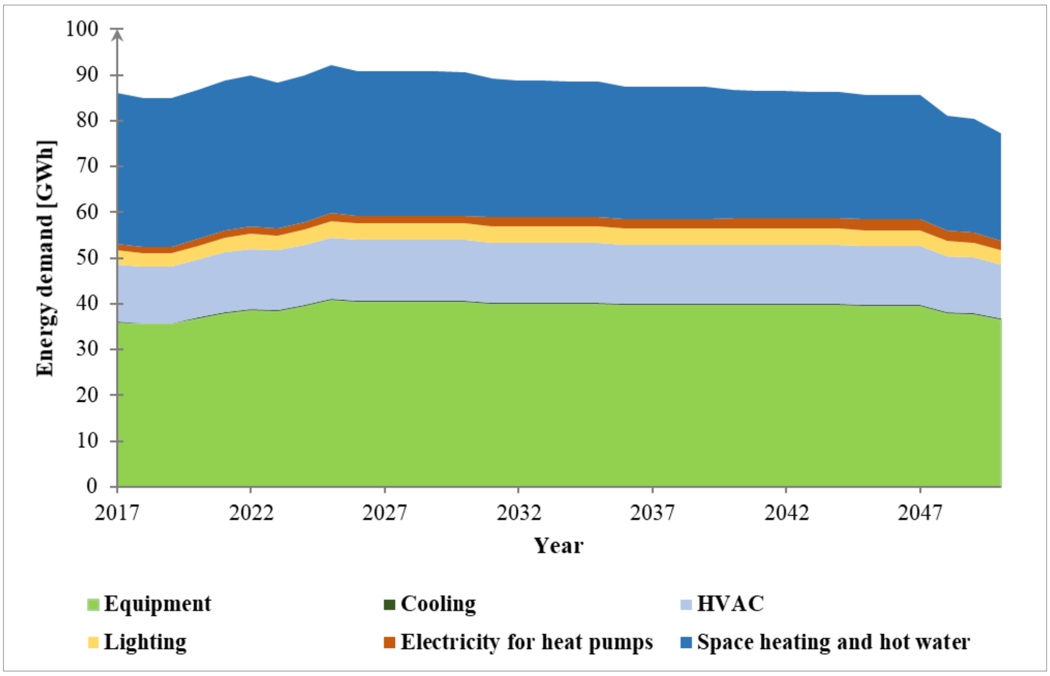


Figure 41. *Energy demand with respect to energy use purpose in Baseline scenario*

Figure 42 presents the total energy demand with respect to energy carriers. As it can be seen from Figure 42 the electrical grid remains a primary carrier of electricity over the entire modelling period. The PV modules installed on the new buildings cover barely 5,7% of the total electricity demand in 2050. Furthermore, heat is supplied by three different energy systems: district heating, NH3 and heat pumps. A share of each technology in the heat supply varies widely during a period 2017-2050. At the start of the simulation, in the year 2017 district heating accounts for nearly 60%, whereas NH3 and heat pumps constitute 26% and 15% of the supplied heat, respectively. However, at the end of the modelling the locally produced heat (from NH3 and heat pumps) represents over 70% of the total supplied heat.

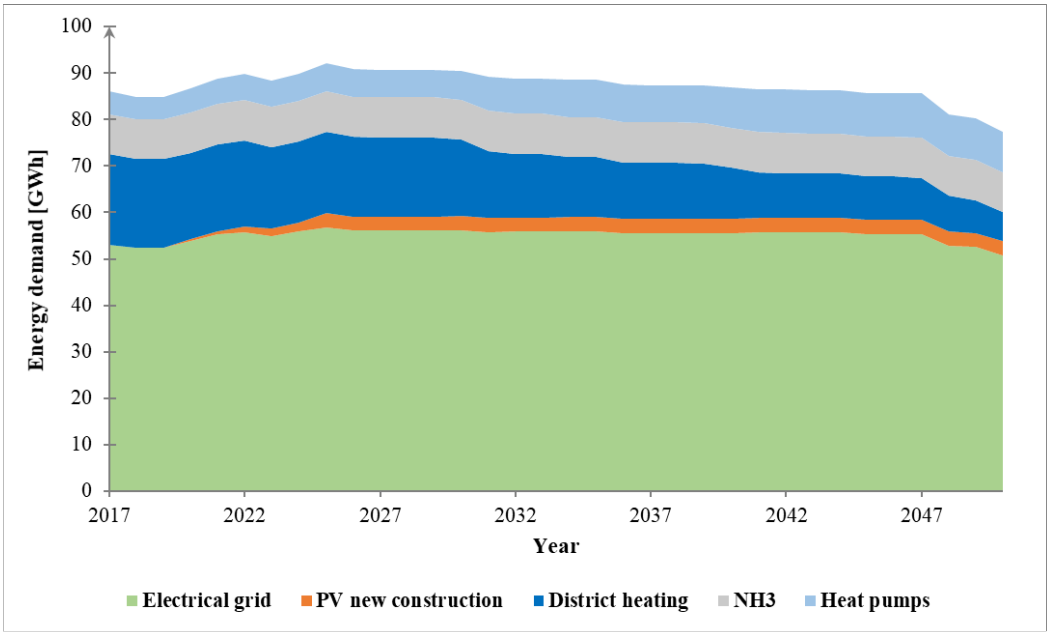


Figure 42. *Energy demand with respect to energy carrier in Baseline scenario*

2. *Extensive local energy production scenario*

Since the building stock in Extensive local energy production scenario undergoes standard renovation, the energy intensity of each cohort group during the modelling period, total heated floor area in terms of renovation state as well as energy demand with respect to cohort group, class and energy use purpose are identical to Baseline scenario (see Figure 37, 38, 39, 49 and 41).

Figure 43 shows the total energy demand of the Gløshaugen building stock in relation to energy carrier. The electrical grid is a dominant carrier of electricity during the whole modelling period. The PV modules installed on the new buildings cover 9,5% of the total electricity demand in 2050 while the photovoltaic systems on the existing buildings barely 3%. The contribution of CHP to the electricity supply is negligible. Regarding the heat supply, at the beginning of simulation district heating is a primary energy technology constituting 60% of the supplied heat. However, with time the importance of district heating diminishes as a share of heat produced by heat pumps increases. In addition, the amount of heat generated by NH3 is constant over the simulation period. Heat from CHP accounts for only 1,4% of the supplied heat.

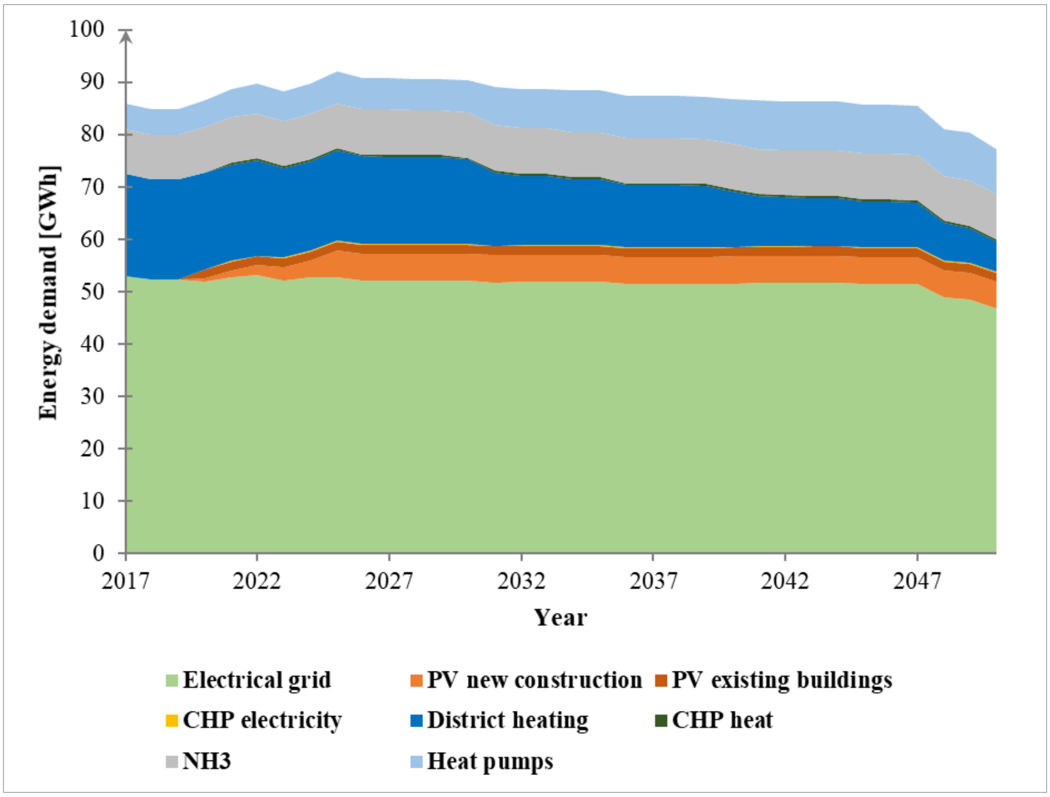


Figure 43. *Energy demand with respect to energy carrier in Extensive local energy production scenario*

3. Advanced renovation scenario

Energy intensity results

Figure 44 represents the energy intensity of each cohort group during the modelling period 2017-2050. The changes in the value of energy intensities are the result of the projected advanced renovation activity. As can be seen in Figure 44, only the energy intensity of the newest cohort group remains unchanged as the buildings have been recently built and they are not in need of renovation during the modelling period. The energy intensities of all the remaining cohort groups decrease significantly.

The energy intensities constitute input into the aggregated results of energy demand for both Advanced renovation and Hybrid scenarios.

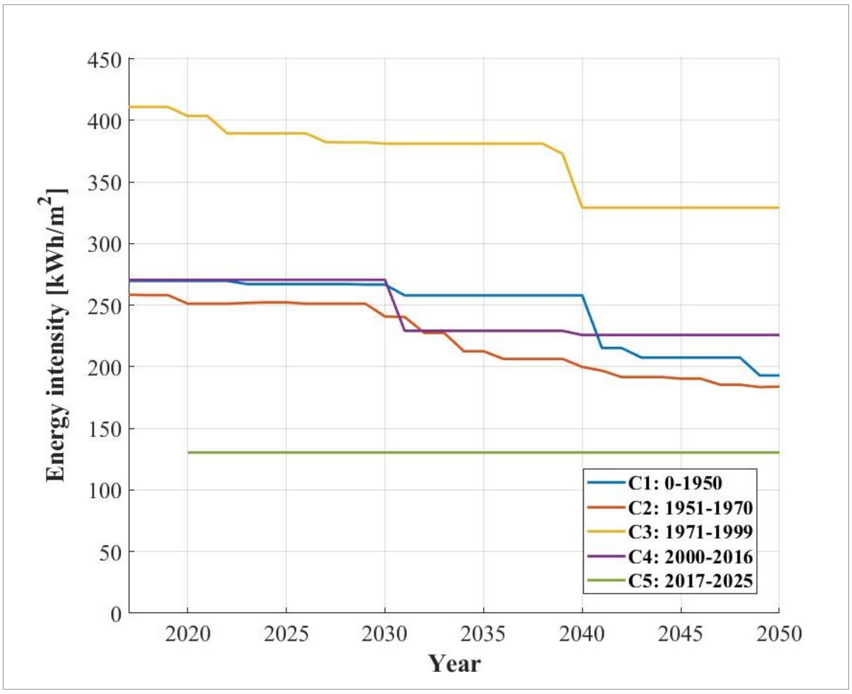


Figure 44. *Energy intensity per cohort group in the modelling period*

Aggregated results for floor area and energy demand

Figure 45 shows the total heated area of the building stock in terms of renovation state. It can be seen that at the end of the modelling period nearly two-thirds of the building stock will have undergone advanced renovation.

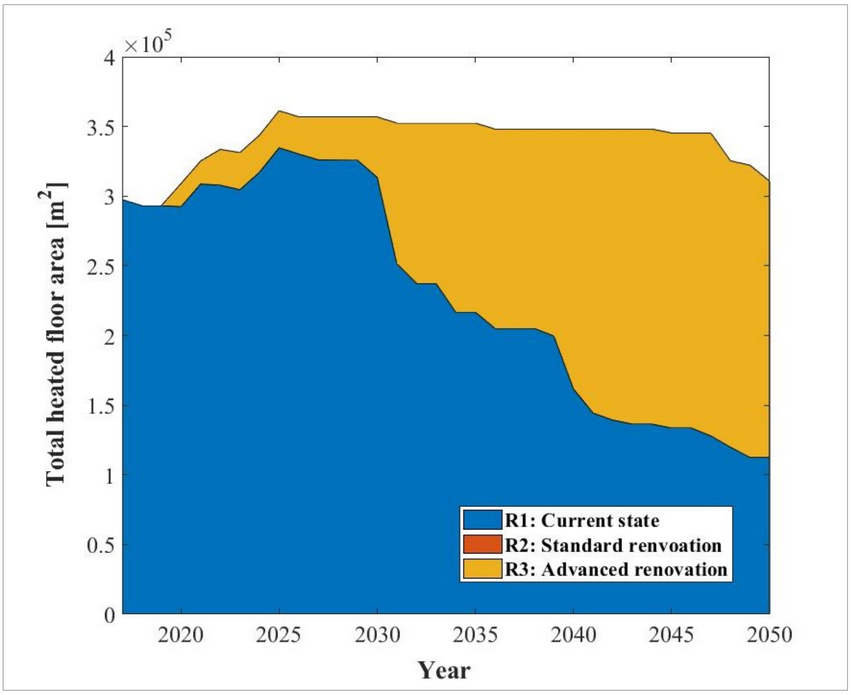


Figure 45. *Total heated floor area with respect to renovation state*

The total energy demand of the Gløshaugen building stock in terms of cohort groups is illustrated in Figure 46. At the beginning of the simulation, the energy demand increases due to the emergence of new construction reaching a maximum of 90 GWh in the year 2025. The total energy demand decreases constantly due to renovation and demolition. Compared to the 2017 level, the energy demand of the Gløshaugen building stock in 2050 is expected to be 26% lower.

The drastic decline in energy demand (by almost 60% compared to the 2017 level) occurs in the cohort group 2 as a result of demolition and renovation activities. The energy demand of the cohort groups 1,3 and 4 diminishes over the simulation period and the energy demand of the newest cohort group remains unchanged after 2025 until the end of the modelling.

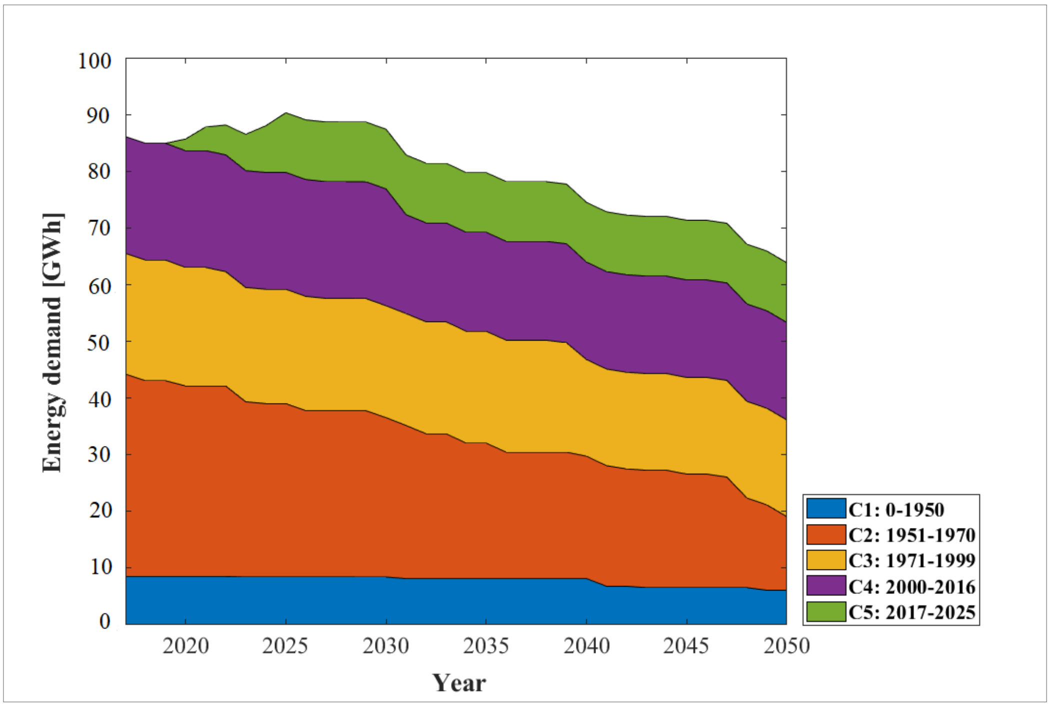


Figure 46. *Energy demand with respect to cohort group in Advanced renovation scenario*

Figure 47 represents the total energy demand with respect to floor area class and Table 11 shows the exact share of each class in the total energy demand at the beginning of the simulation, in 2025 and at the end of the modelling period. Technical rooms use the most energy from all the classes during the whole modelling period, accounting for nearly a quarter of the total energy demand. Traffic area, which represents a quarter of the heated floor area of NTNU Gløshaugen, constitutes for almost 20% of the total energy demand. A decrease in energy use in laboratories (2,5%) and an increase in energy consumption in lecture rooms (1,8%) from 2017 to 2050 are caused by the demolition of buildings with a high share of laboratories and the new constructions with a higher share of lecture rooms compared to the current building stock at NTNU Gløshaugen.

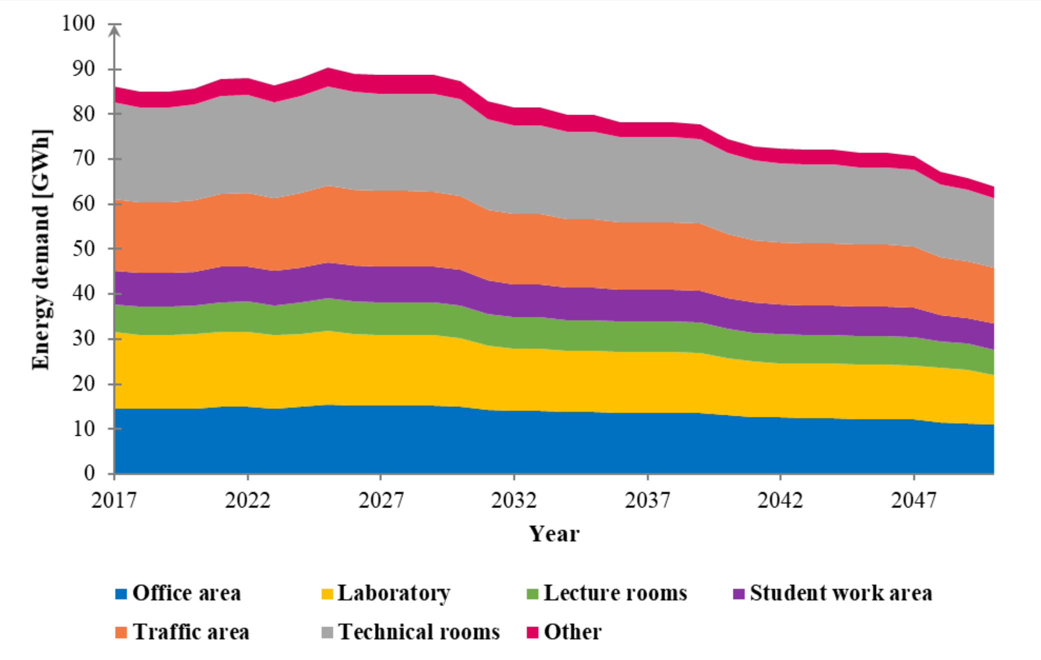


Figure 47. *Energy demand with respect to class*

Table 11. *Share of each class in the total energy demand through the modelling period*

Class	2017	2025	2050
Office area	16,9 %	17,0 %	17,2 %
Laboratories	19,7 %	18,1 %	17,2 %
Lecture rooms	7,2 %	8,1 %	9,0 %
Student work area	8,7 %	8,9 %	9,0 %
Traffic area	18,5 %	18,8 %	19,3 %
Technical rooms	24,9 %	24,4 %	24,2 %
Other	4,0 %	4,6 %	4,0 %

Figure 48 shows energy demand regarding energy use purpose. Electricity accounts for a vast majority of the total energy consumed by the Gløshaugen building stock. In 2017 electricity represents 62% and in 2050 almost 83% of the total energy demand. Electricity used for equipment constitutes 42% of the total energy demand at the beginning of the simulation and over half (57%) at the end of the modelling. Energy demand for HVAC and lighting increases slightly over the modelling period due to construction activity. A share of cooling in the total energy demand is negligible. Furthermore, energy demand for space heating and hot water declines significantly. Compared to the 2017-level, heat demand is reduced by two-thirds at the end of the modelling. A decline in heat demand is caused by a substantial improvement of energy efficiency in the buildings through advanced renovation activity.

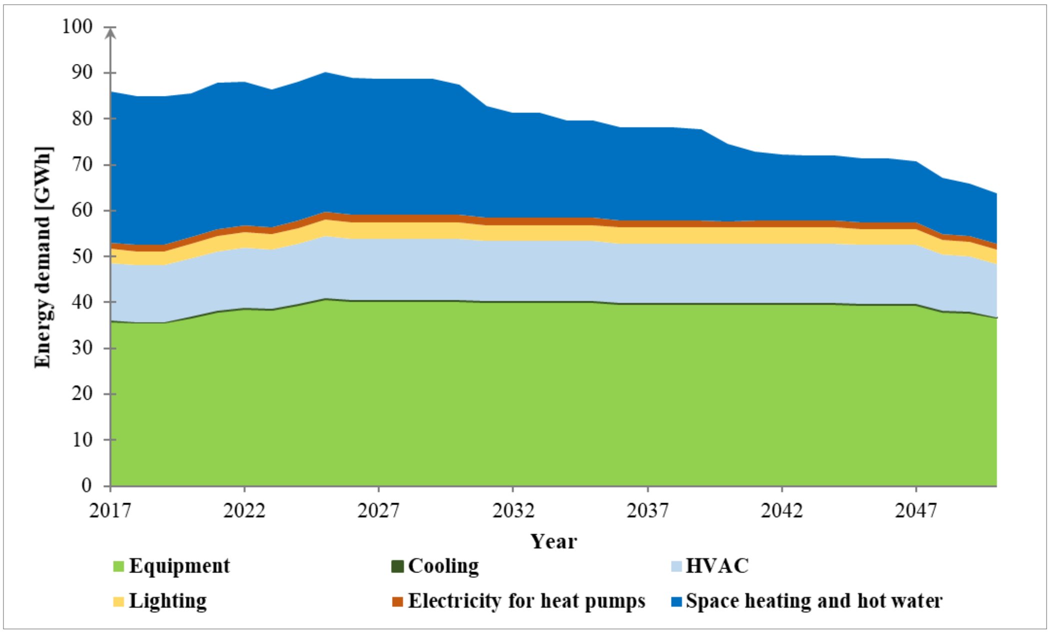


Figure 48. *Energy demand with respect to energy use purpose in Advanced renovation scenario*

Figure 49 illustrates the energy demand in terms of energy carrier. The electrical grid is a main carrier of electricity during the whole modelling period. The PV modules installed on the new buildings cover 5,8% of the total electricity demand in 2050. Regarding the heat supply, at the beginning of simulation district heating is a primary energy technology constituting 60% of the supplied heat. However, with time the importance of district heating diminishes and in the year 2043 the Gløshaugen becomes a self-sufficient neighbourhood regarding heat supply. The heat generated by NH3 and heat pumps exceeds a demand for heat of NTNU Gløshaugen. The surplus heat is exported to the district heating grid.

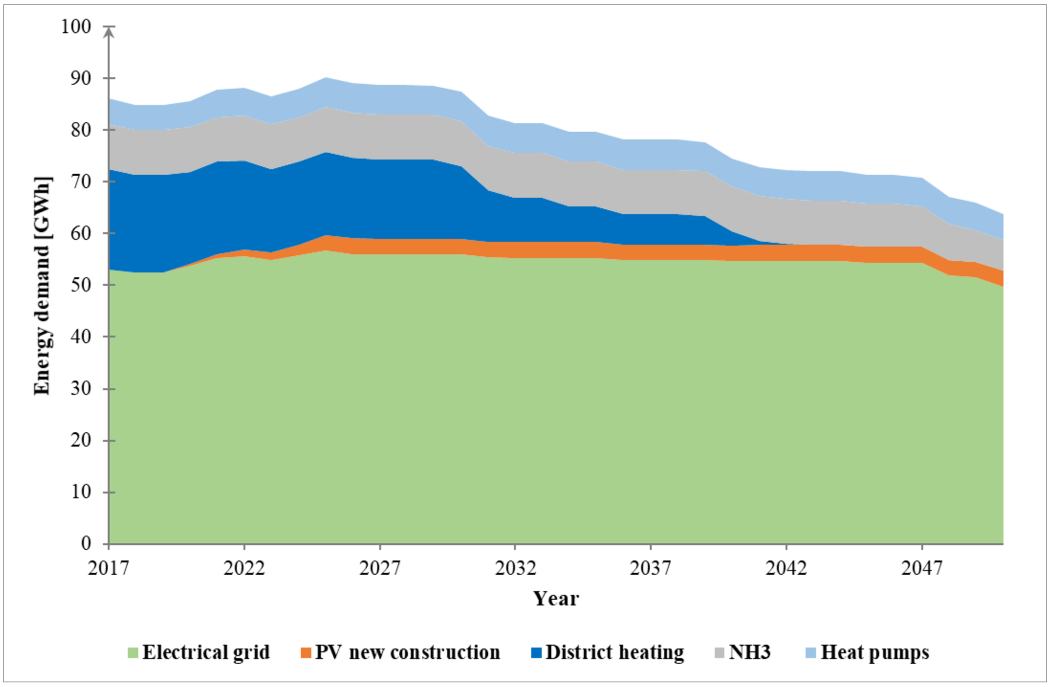


Figure 49. *Energy demand with respect to energy carrier in Advanced renovation scenario*

4. Hybrid scenario

Since the building stock in Hybrid scenario undergoes advanced renovation, the energy intensity of each cohort group during the modelling period, total heated floor area in terms of renovation state as well as energy demand with respect to cohort group, class and energy use purpose are identical to Advanced renovation scenario (see Figure 44, 45, 46, 47 and 48).

Figure 50 shows the total energy demand of the Gløshaugen building stock in terms of energy carrier. The electrical grid is a basic carrier of electricity during the whole modelling period. The PV modules installed on the new buildings cover 9,7% of the total electricity demand in 2050 while the photovoltaic systems on the existing buildings barely 3%. The contribution of CHP to the electricity supply is negligible. In 2017 district heating delivers 60% of the total heat demand. Until 2041 a share of district heating in the heat supply decreases considerably and in 2042 heat is supplied entirely by NH3, heat pumps and CHP. Starting from the year 2042 the local heat production exceeds the heat demand of the Gløshaugen building stock. The surplus heat is exported to the district heating grid.

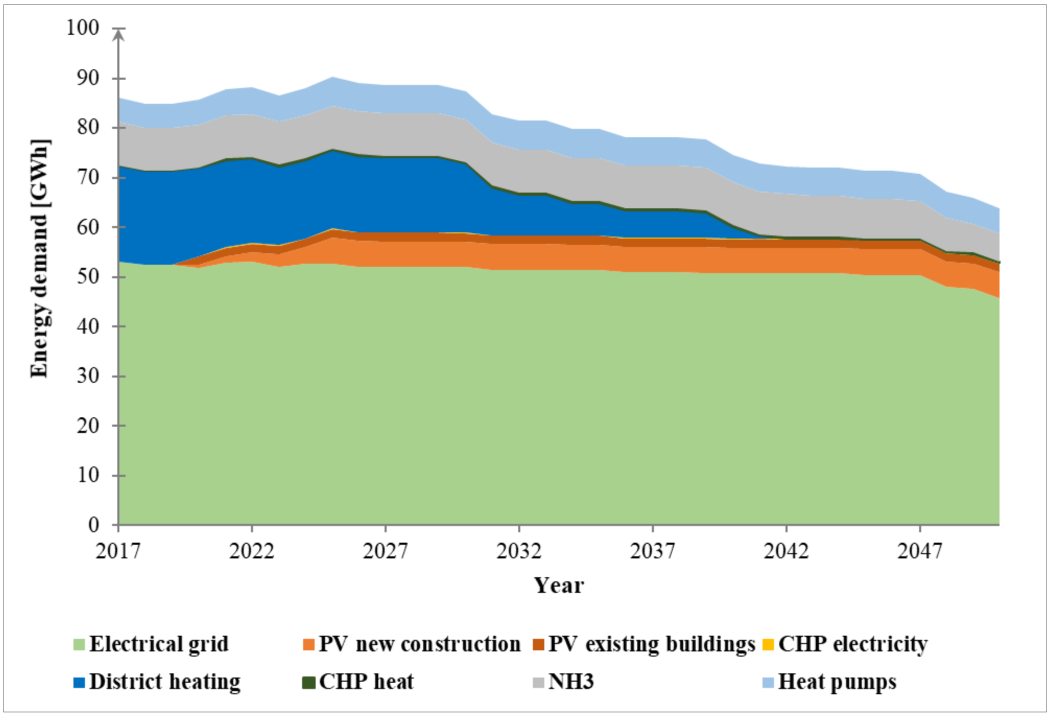


Figure 50. *Energy demand with respect to energy carrier in Hybrid scenario*

5.3. GHG emissions characteristics of current and future NTNU Gløshaugen

5.3.1. Current monthly GHG emissions from energy carriers

Figure 51 shows the estimated current monthly GHG emissions from energy carriers used at NTNU Gløshaugen in the year 2016 based on the emission intensities of district heating and electrical grid given in Table 8. GHG emissions in 2016 totaled approximately 3,6 kt of CO_2-eq. The majority of the GHG emissions (around 60%) were associated with district heating due to its high emission intensity (on average nearly three times higher than the emission intensity of the electrical grid). Heat pumps accounted for nearly 3% of the total GHG emissions assuming that an average COP for heating for heat pumps located on NTNU Gløshaugen was 3,4 and 2,7 for NH3. It has to be noticed that the data on heat production in 2016 by NH3 is incomplete and the share of heat pumps in the total GHG emissions would increase up to 2,5%. Nevertheless, it does not affect significantly the final result, leaving district heating the major contributor to GHG emissions. Electricity from the grid, excluding electricity used for the operation of heat pumps, constituted 37% of the total GHG emissions. As shown in Figure 51, the GHG emissions were the largest in winter months due to high demand for heat and the lowest in summer months. GHG emissions from electricity were rather constant through the year, as a result of even demand for electricity.

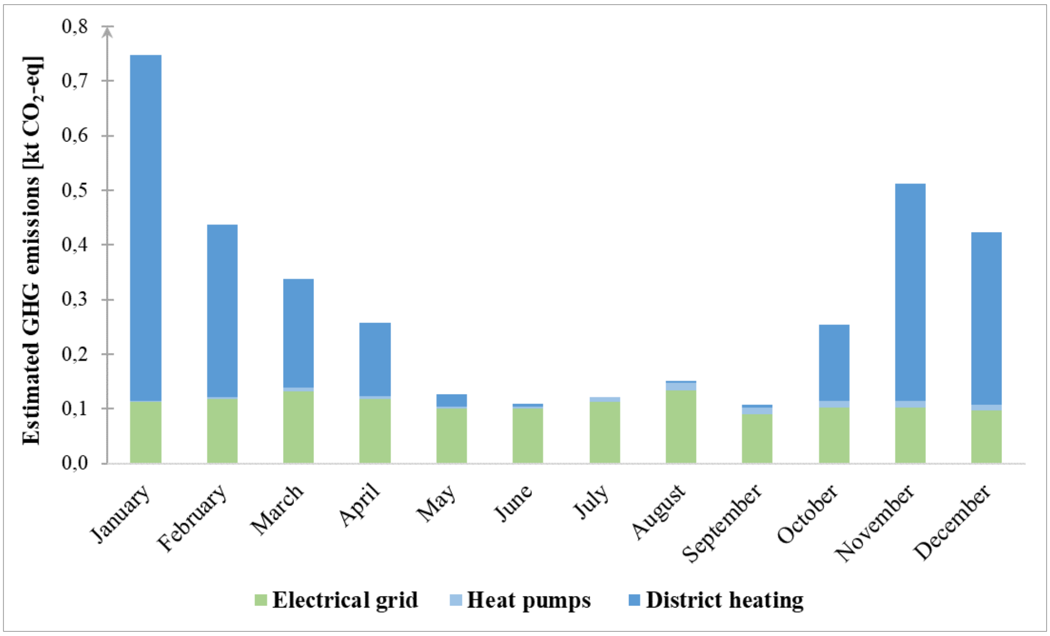


Figure 51. *Estimated monthly GHG emissions from energy carriers used at NTNU Gløshaugen in 2016*

5.3.2. Future GHG emissions from energy carriers

1. Baseline scenario

Figure 52 represents the estimated GHG emissions over the modelling period in the Baseline scenario. The GHG emissions are expected to decrease by 40% compared to the 2017 level, mainly due to a reduction in demand for district heating. At the start of the simulation the GHG emissions are fairly evenly distributed among the electrical grid and district heating (49% and 51%, respectively). It is worth noticing that in 2017 the district heating delivers nearly three times less energy than the electrical grid. The reason for a substantial share of the district heating in the total GHG emissions is nearly three times higher value of the emission intensity of district heating. This phenomenon occurs in all the scenarios.

At the end of the modelling the total GHG emissions account for 1,9 kt of CO_2-eq. The electrical grid constitutes almost 80% of the total GHG emissions and the district heating represents slightly above 20%.

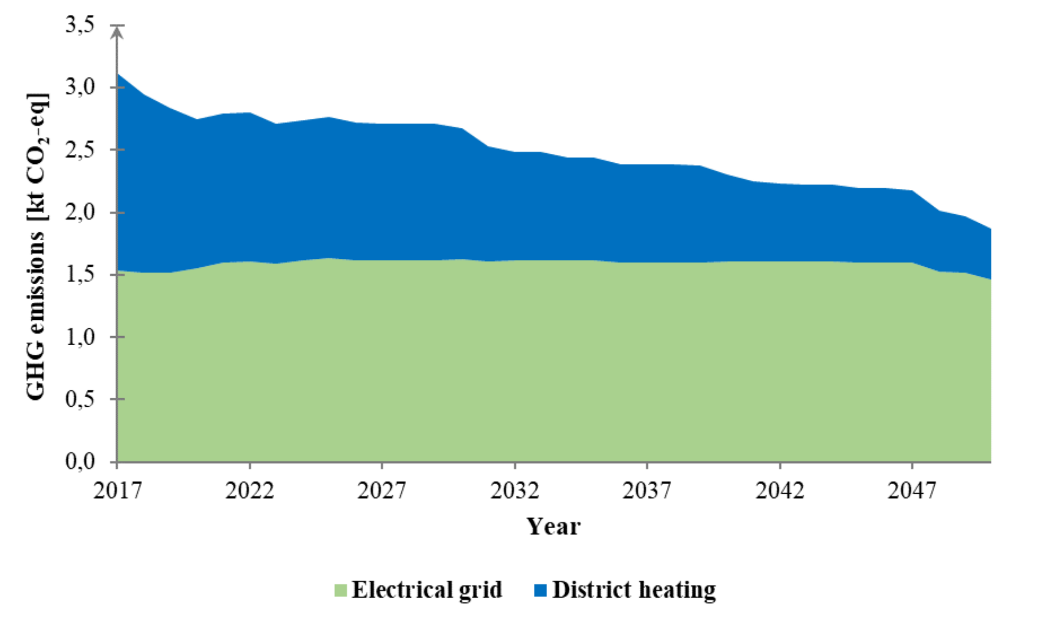


Figure 52. *Estimated yearly GHG emissions in Baseline scenario*

2. Extensive local energy production scenario

Figure 53 illustrates the total GHG emissions from energy carriers during a period 2017-2050 in the Extensive local energy production scenario. In 2050 the total GHG emissions accounts for 1,7 kt of CO_2-eq. The electrical grid constitutes nearly 80% of the total GHG emissions and the district heating represents slightly above 20%. The results are very similar to the Baseline scenario. The contribution of CHP to the total GHG emissions is insignificant (less than 1%).

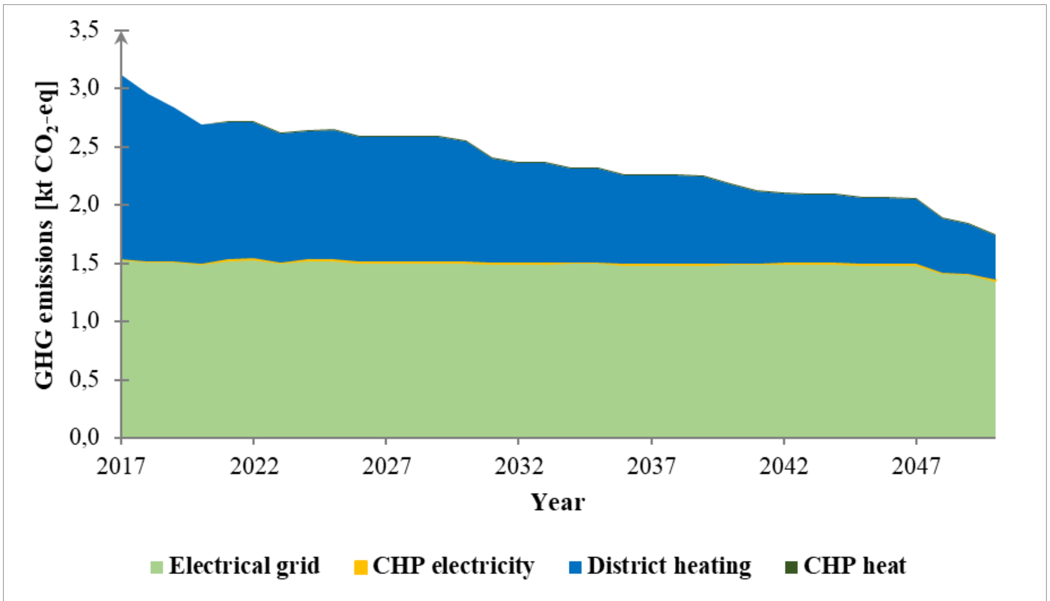


Figure 53. *Estimated yearly GHG emissions in Extensive local energy production scenario*

3. *Advanced renovation scenario*

Figure 54 shows the GHG emissions through the modelling period in the Advanced renovation scenario. The GHG emissions decline by 54% compared to the 2017 level, accounting for 1,4 kt of CO_2-eq in 2050. The substantial decrease is primarily caused by the fact that the district heating is replaced by low carbon heat technologies (electricity for the operation of heat pumps is included in electric grid emissions). In the last years of the simulation the only source of the GHG emissions is electricity from the electrical grid.

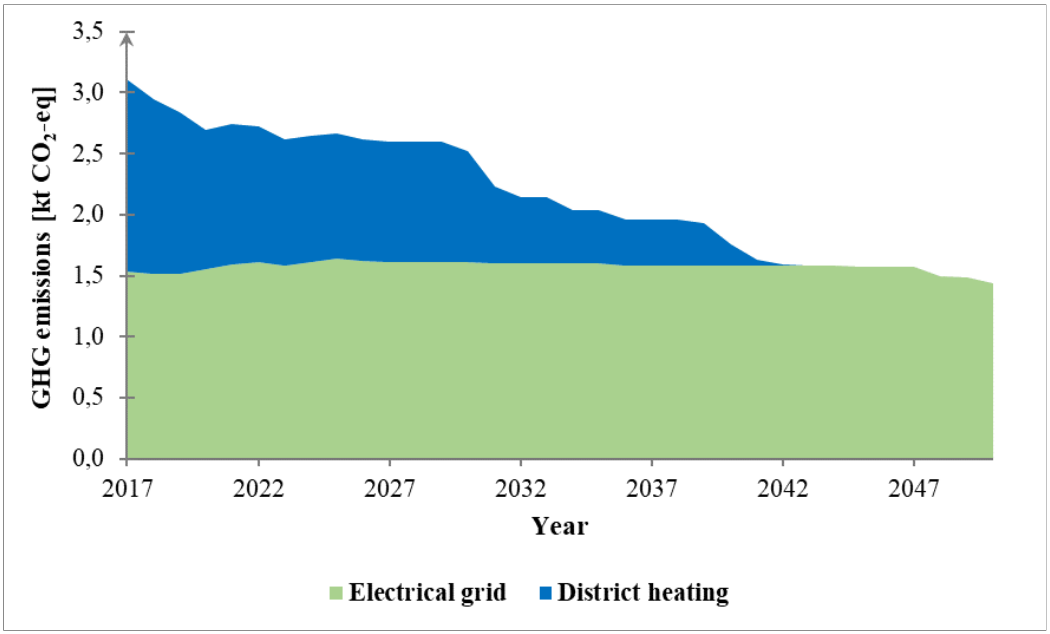


Figure 54. *Estimated yearly GHG emissions in Advanced renovation scenario*

4. *Hybrid scenario*

Figure 55 presents the GHG emissions in a period 2017-2050 in the Hybrid scenario. The total GHG emissions decrease by 57% compared to the 2017 level, accounting for 1,3 kt of CO_2-eq in 2050. The major source of the GHG emissions is electricity from the electrical grid. In comparison with the Advanced renovation scenario, the total GHG emissions in the Hybrid scenario is slightly lower due to the contribution of PV which is characterised by zero emission in the operation phase.

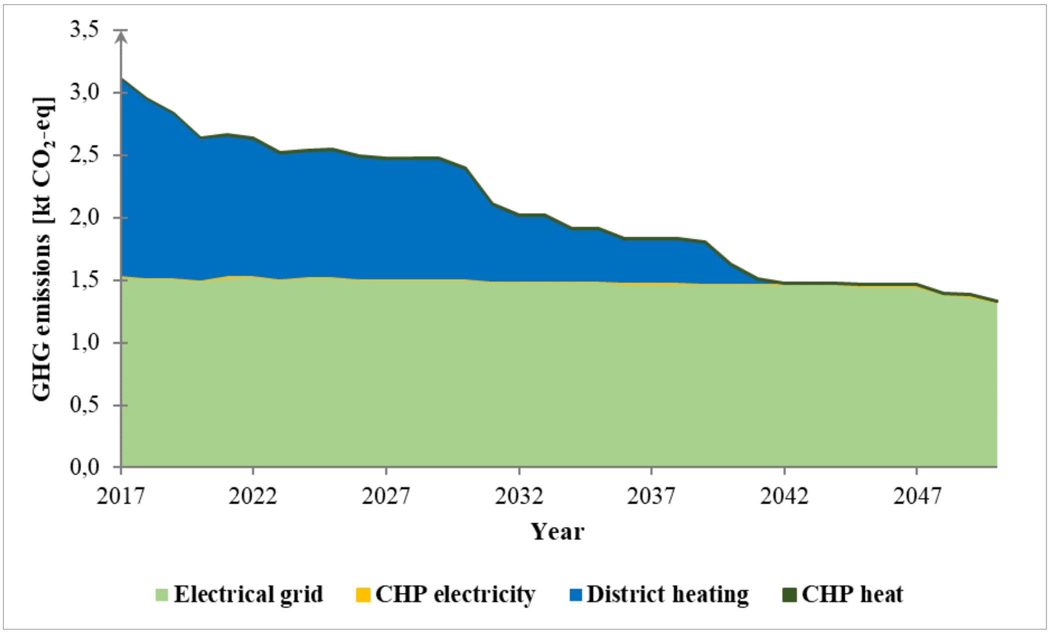


Figure 55. *Estimated yearly GHG emissions in Hybrid scenario*

5.4. Summary of the scenario results

The results obtained from the scenario analysis are summarised in Table 12. The results show a percentage decrease/increase in the value of energy demand and GHG emissions at the end of the modelling in regard to the 2017 level. The analysis reveals that despite stock growth, the total energy demand declines by 10,2% in Baseline and Extensive local energy production scenarios and by 25,9% in Advanced renovation and Hybrid scenarios from 2017 to 2050. The reduction in energy demand is mainly caused by a substantial decrease in heat demand. The GHG emissions diminish in all of the scenarios by 40, 1% up to 57,1% in the most optimistic scenario.

Table 12. *Energy demand and GHG emissions in all the scenarios in 2050 compared to the 2017 level*

	Baseline	**Extensive local energy production**	**Advanced renovation**	**Hybrid**
Energy demand	**- 10,2%**	**- 10,2%**	**- 25,9%**	**- 25,9%**
Electricity demand	+1,4%	+1,4%	- 0,5%	- 0,5%
Heat demand	- 28,7%	- 28,7%	- 66,7%	- 66,7%
GHG emissions	**-40,1 %**	**-44,0 %**	**-53,9 %**	**-57,1 %**
GHG emissions associated with electricity supply	-4,4 %	-11,5 %	-6,3 %	-13,4 %
GHG emissions associated with heat supply	-74,7 %	-75,5 %	-100,0 %	-99,4 %

Table 13 shows the share of each energy carrier in satisfying energy demand in the year 2050. The analysis presents that the Gløshaugen building stock depends greatly on the electrical grid while meeting electricity demand. PV can cover 5,7% (in Baseline scenario) up to 12,9% (in the most optimistic scenario) of the electricity demand and the contribution of CHP is negligible. Furthermore, the results demonstrate that in 2050 NTNU Gløshaugen is self-sufficient (in the case of Advanced renovation and Hybrid scenarios) or only partially dependent on district heating (in the case of Baseline and Extensive local energy production scenarios) regarding heat supply. Interestingly, Extensive local energy production scenario does not considerably decrease reliance on energy delivered from the grid (compared to Baseline scenario by barely 1,4% in the case of heat supply and 7,3% in the case of electricity supply)s.

Table 13. *Share of each energy carrier in meeting energy demand in 2050*

	Baseline	**Extensive local energy production**	**Advanced renovation**	**Hybrid**
Share of electricity demand met by:				
electrical grid	94,3 %	87,0 %	94,2 %	86,7 %
PV new construction	5,7 %	9,5 %	5,8 %	9,7 %
PV existing building stock	0,0 %	3,2 %	0,0 %	3,2 %
CHP	0,0 %	0,3 %	0,0 %	0,3 %
Share of heat demand met by:				
district heating	26,5 %	25,1 %	0,0 %	0,0 %
heat pumps	36,7 %	36,7 %	45,9 %	45,9 %
NH3	36,8 %	36,8 %	54,1 %	51,0 %
CHP	0,0 %	1,4 %	0,0 %	3,1 %

Table 14 illustrate the calculated Zero Energy/Emission balance in terms of delivered and exported energy during operation phase in 2050. It can be seen that none of the scenarios achieve the Zero Energy or Emission balance. The amount of the surplus heat generated in Advanced renovation and Hybrid scenarios is not enough to offset either delivered energy or the GHG emissions.

Table 14. *Zero Energy/Emission balance during operation phase in 2050*

	Baseline	**Extensive local energy production**	**Advanced renovation**	**Hybrid**
Delivered energy [GWh]	57,0	52,7	49,8	45,8
Exported energy [GWh]	0	0	2,7	3,1
ZEB-O [GWh]	**57,0**	**52,7**	**47,1**	**42,7**
GHG emissions [kt CO_2-eq]	1,87	1,74	1,44	1,34
Saved GHG emissions [kt CO_2-eq]	0	0	0,17	0,20
ZEB-O [kt CO2-eq]	**1,87**	**1,74**	**1,27**	**1,14**

6. Discussion

6.1. Main findings

The case study of NTNU Gløshaugen indicates that nearly a half of the area of the current building stock, including 60% of the total laboratory area, almost 50% of the office area and approximately one third of the lecture rooms and student work area was built between 1951 and 1970. Furthermore, the results show that during the modelling period (2017-2050) solely the buildings from the cohort group 1951-1970 are expected to undergo demolition as they are one of the oldest buildings on NTNU Gløshaugen (apart from the buildings constructed before the year 1950 which are protected and therefore cannot be demolished).

The buildings on NTNU Gløshaugen are not homogenous regarding floor area type. The class distribution is closely dependent on activities which take place in a building and thus the class distribution varies greatly between the cohort groups. What is surprising is that the share of traffic area within all the cohort groups is fairly constant and accounts for approximately a quarter of the total floor area. The relocation of human and social sciences campuses to the Gløshaugen area, which is presently home of engineering disciplines and natural sciences, will affect the current class distribution. The results present that a significant decrease in laboratory area will occur and at the same time the share of lecture rooms will rise as a result of the construction of the new buildings.

The results of scenario analysis show that the Gløshaugen building stock is far from reaching a Zero Energy balance in 2050. High demand for electricity and limited local electricity generation result in a heavy dependence on imported electricity. Moreover, renovation activity demonstrates great potential for a reduction in heat demand, particularly advanced renovation (nearly 67% decrease in 2050 compared to the 2017 level). Thanks to advanced renovation and extensive use of heat pumps, NTNU Gløshaugen is expected to be self-sufficient regrading heat supply in Advanced renovation and Hybrid scenarios. Extensive local energy production scenario reveals limited potential of NTNU Gløshaugen to reduce reliance on the electrical grid. The PV modules installed on the new construction can cover 9,5% of the total electricity demand and the PV system on the existing buildings barely 3,2%. In addition, the contribution of CHP to the electricity and heat supply is insignificant. The CHP suited for the Heimdal high school, which has substantially lower energy demand, constitutes merely a fraction of the total electricity demand of the Gløshaugen building stock. Therefore, further study on scaling up a capacity of the Heimdal's CHP could assess the cost-effectiveness of this installation on NTNU Gløshaugen.

Finally, the GHG emissions are expected to decrease gradually over a period 2017-2050. However, NTNU Gløshaugen will not become a Zero Emission Neighbourhood in 2050. In the most optimistic scenario the GHG emissions are reduced by 57% compared to the 2017 level as shown in Table 12. The substantial decline in the GHG emissions is caused by the replacement of district heating with low carbon heat technologies such as heat pumps and NH3. Furthermore, the emission reduction potential from photovoltaics and biogas-based CHP is rather finite. Considering relatively low carbon intensity of electricity from the grid in Norway, the savings from decreasing imports of electricity will be relatively modest. Additionally, the potential emissions savings from heat generated by CHP are quite limited when assuming a capacity of CHP identical to the one in Heimdal high school. As stated before, further research is needed to determine if CHP is a cost-effective solution in the case of NTNU Gløshaugen.

These results suggest that advanced renovation activity including extensive use of heat pumps is the most promising strategy for reduction in energy demand and GHG emissions. It will decrease not only energy demand and make NTNU Gløshaugen self-sufficient in heat supply but also it will considerably reduce the GHG emissions. Local energy production such as photovoltaics and CHP is proven to be insufficient to cover a significant share of the total energy demand, particularly electricity demand, and due to low carbon intensity of electricity from the grid, this development path has limited potential to decrease energy imports and GHG emissions.

6.2. Consistency with literature

Although these results differ from the study of Næss et al. (2018) on NTNU Gløshaugen, they confirm the importance of assumptions about future construction and energy use profiles in the final results. In both studies the development of the building stock follows the same trend towards 2050 and the size of the stock is expected to have the same order of magnitude. The differences can be explained by quite distinct assumptions about future construction. Næss et al. (2018) assume that NTNU Gløshaugen will expand according to one of the alternatives proposed by KOHT Arkitekter (2017), whereas this study adopts a resolution financing 92 000 m^2 of gross floor area of the new buildings by the Norwegian government. Furthermore, Næss et al. (2018) apply an identical IDA ICE energy use profile, representing an average building at NTNU Gløshaugen, to each cohort and renovation state which results in the development of energy demand corresponding to the development of heated floor area of the building stock. However, in spite of using individual energy profiles for each cohort group and renovation state, it can also be seen in two scenarios presented in this thesis (Baseline and Extensive local energy production) that the development of the total energy demand follows the trend for the stock heated floor area. The reason for this is standard renovation activity which in comparison to advanced renovation does not significantly decrease energy demand.

Moreover, the findings of this study are in agreement with Elliott and Brown's (2010) findings which showed that deep energy efficiency measures are the key to reducing energy demand, and consequently together with renewable energy generation achieving zero net energy. Although this study demonstrates that it is not feasible for NTNU Gløshaugen to become zero net energy campus towards 2050, advanced renovation is proven to decrease significantly energy demand (by nearly 26% compared to the 2017 level).

6.3. Strengths and weaknesses

The Zero Emission Neighbourhood model is generic and can be applied to any neighbourhood and to any period of time. In addition, the model is flexible in terms of the number of energy sources as it does not place limitations on how many energy sources can coexist in the system. Furthermore, it allows simplifications of complex floor areas of buildings using floor area types and classes, which is a key strength of this model.

The model can produce results with great precision with respect to time (hourly resolution). The user of the model chooses time resolution while providing inputs into the model. If less detailed data is accessible, the model can run simulations on monthly or even yearly basis. Overall, the model gives valuable insights into the development of a neighbourhood building stock, its energy demand and local energy production. The segmentation of the building stock into archetypes deepens an understanding of the significance of different classes and cohort groups in the building stock and its demand for energy. The results from scenario analysis contain detailed information and proves that the model is a powerful tool in projecting a long-term stock and energy demand development.

However, the model has a number of limitations. On the one hand, a requirement for detailed energy load profiles (class-specific in the Gløshaugen case) gives a profound insight into energy demand at both stock and class level but on the other hand, it is one of the main weaknesses of the model. The energy profiles for each building, class and renovation state were not available and therefore reference building models for each cohort group, class and renovation state were used in the model. Nevertheless, the data analysis of the energy consumption in 2016 has shown that the energy intensities within cohort group varies greatly (Figure 30). It is important to bear in mind that the integration of the buildings based on age is not entirely appropriate while simulating energy demand but it was the only accessible source of information at the time of writing this thesis. The university building stock is very complex and the best results can be obtained with individual energy profiles for each building.

6.4. Uncertainties

There is a degree of uncertainty over many of the input parameters of the model (Table 15). Three levels of uncertainties are determined (low, medium and high).

As shown in Table 15, there is low uncertainty over the total heated floor area results. The lifetime of the buildings is considered as fairly certain. In addition, a construction period of the new buildings is estimated according to the Campus Development Project assumptions and therefore the uncertainty is likely to be low (all the new buildings are supposed to be erected between 2020 and 2025 and in 2025 the building stock is expected to reach a maximum size). The distribution of floor area types in the new buildings and the ratio of net floor area to gross floor area are characterised by low uncertainty.

Although the IDA ICE energy use profiles describe building's energy demand in a fairly accurate way (modelled based on empirical data), as can be seen from Figure 30, electricity and district heat intensities vary greatly not only between cohort groups but also within each cohort. Furthermore, Nesgård & Ngo (2018) simplify the models by assuming identical geometry, operation and use in each of the reference building models. Even though the reference building models represent the average buildings from each cohort, the IDA ICE energy use profiles are associated with a medium degree of uncertainty.

Regarding the installation of PV, the size of area suitable for PV is characterised by medium uncertainty. The study is limited by the lack of information on the designs for the new buildings and a sketch of the reference building is questionable. The potential for PV installation on the current building stock is rather accurate. PV is an intermittent source of electricity and therefore energy output from PV is related to high uncertainty. Moreover, this study does not examine shadings from nearby buildings and vegetation and thus the real energy generation from PV is expected to be lower by a few percent (shading losses can be partially eliminated by using micro-inverters).

The installation of a biogas-based CHP is defined by medium uncertainty since NTNU prioritises implementing heat pumps. Electricity and heat production from CHP is constant and does not depend on atmospheric conditions and therefore is characterised by low uncertainty.

The uncertainty surrounding the installation of heat pumps is low as NTNU has been introducing heat pumps in the buildings since 2010.

Additionally, there is high uncertainty concerning emission intensities as the values of emission intensities are greatly influenced not only by the future development of energy systems at local, national and international level but also by politics.

Finally, there is high uncertainty related to the results of scenario analysis. The further into the future the simulation goes, the more uncertain it becomes.

Table 15. *Uncertainties in input parameters*

Results	Parameter	Uncertainty
Total heated floor area	Lifetime of the buildings	Low
	Construction year of the new buildings	Low
	Floor are type distribution in the new buildings	Low
	Ratio of net floor area to gross floor area	Low
Energy demand	Energy use profile	Medium
Energy supply	PV installation (size)	Medium
	PV production	High
	CHP installation	Medium
	CHP production	Low
	Heat pumps	Low
GHG emissions	Emission intensities	High

6.5. Future research

Further research needs to be done to investigate the impact of on-site energy production on energy demand of NTNU Gløshaugen at high time resolution, preferably on an hourly basis. It is suggested that load matching and grid interaction calculations are done in order to assess the building stock's dependence on the grid and the degree of the utilization of local energy generation with the building stock load.

Moreover, it would be interesting to explore possibilities and cost-effectiveness of energy storage at NTNU Gløshaugen. Another possible area of future research would be to investigate whether even more challenging renovation (aiming to reduce electricity demand) is feasible at NTNU Gløshaugen. Finally, it is recommended that life-cycle GHG emissions from renewable energy technologies and time-varying emission intensities of energy carriers are determined.

7. Conclusions

The purpose of this study was to determine whether the building stock at NTNU Gløshaugen is able to become a Zero Energy/Emission Neighborhood towards 2050. In addition, the most promising strategies for reduction in energy demand and GHG emissions at NTNU Gløshaugen were investigated. The Zero Emission Neighbourhood model was used for studying a long-term development of the building stock, energy demand and GHG emissions of NTNU Gløshaugen.

This study has shown that due to the planned relocation of campuses to NTNU Gløshaugen, the Gløshaugen building stock is expected to grow substantially until the year 2025 as a consequence of the construction activity. After 2025 the stock is estimated to gradually decrease as a result of the demolition of buildings from the cohort group 1951-1970 and in 2050 the heated floor area of the stock is expected to total 310 714 m^2.

Furthermore, the results of the scenario analysis demonstrate that NTNU Gløshaugen is far from becoming a Zero Energy/Emission Neighbourhood in 2050. Despite a considerable decrease in heat demand and a substitution of district heating with low carbon heat technologies (heat pumps and NH3), NTNU Gløshaugen remains heavily dependent on imports of electricity from the grid. The findings indicate that advanced renovation including extensive use of heat pumps is the most promising strategy for reduction in energy demand (by 26%) and GHG emissions (by 54%) of NTNU Gløshaugen. Local energy generation from photovoltaics and a biogas-based CHP is proven to be limited and insufficient to cover a significant share of the total energy demand, particularly electricity demand. Having taken into account relatively low carbon intensity of electricity from the grid in Norway, the savings from decreasing imports of electricity are expected to be relatively modest.

Finally, the study demonstrated that the Zero Emission Neighbourhood model is suitable for analyzing future building stock, energy demand and GHG emissions of a neighbourhood like NTNU Gløshaugen.

This research has thrown up many questions in need of further investigation. Further work needs to be done to assess the impact of local energy production on energy demand of NTNU Gløshaugen at high time resolution, preferably on an hourly basis. Another possible area of future research would be to investigate life-cycle GHG emissions from renewable energy technologies and estimate how emission intensities of energy carriers will vary over time.

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Appendix A

Table A1. *Data on the existing building stock (Rønning, personal communication, September 2017)*

	Building code	Building name	Year of construction	Gross floor area [m^2]	Net floor area [m^2]	Net floor area per floor area type [m^2]																
						1. Office area	2. Lecture rooms	3. Laboratory	4. Student work area	5. Library	6. Business area	7. Canteen area	8. Exhibition area	9. Workshop	10. Sports rooms	11. Hospital rooms	12. Technical rooms	13. Sanitary facilities	14. Traffic area	15. Storage	16. Shelters	17. Other
1.	301	Hovedbygningen	1910	17 215	13 930	5 570	587	0	129	2 146	0	0	0	0	0	0	600	297	3 854	699	0	47
2.	302	Varmeteknisk	1962	15 717	14 066	2 961	96	3 823	923	0	0	127	0	837	38	0	1 213	215	2 897	742	196	0
3.	303	Strømningsteknisk	1965	3 035	2 609	582	0	764	277	0	0	0	0	262	0	0	138	51	474	62	0	0
4.	304	Metallurgi	1951	2 309	2 142	191	44	698	220	0	0	0	0	0	132	0	160	35	333	329	0	0
5.	305	Oppredning/gruvedrift	1953	3 955	3 450	946	57	812	146	0	0	0	88	230	0	0	98	64	868	136	7	0
6.	306	Geologi	1960	3 168	2 797	960	186	9	144	0	0	0	6	0	0	0	127	64	791	450	60	0
7.	307	Verkstedteknisk	1966	12 336	11 130	2 912	829	1 926	1 056	0	0	114	0	545	0	0	630	136	2 097	536	347	3
8.	308	Materialteknisk	1958	12 616	11 473	2 475	110	3 826	450	0	0	0	0	839	59	0	270	219	2 170	1 042	0	14
9.	309	Driftssentralen	1960	2 109	1 886	907	0	0	0	0	0	0	0	278	0	0	78	40	334	239	11	0
10.	310	Kjemi sydfløy	1967	1 184	1 055	167	0	0	0	0	0	0	0	0	0	0	3	21	665	17	182	0
11.	311	Kjemi 1	1954	4 969	4 313	795	83	981	0	0	0	0	0	0	0	0	705	106	1 487	157	0	0
12.	312	Kjemi 2	1955	5 236	4 451	860	19	1 437	118	0	0	0	0	14	0	0	725	72	1 075	19	0	111
13.	313	Kjemi 3	1967	6 635	5 604	859	0	2 053	80	0	0	0	0	28	0	0	783	269	1 065	467	0	0
14.	314	Kjemi 4	1965	5 569	4 827	1 210	99	1 247	355	0	0	0	0	22	0	0	565	82	1 152	97	0	0
15.	315	Kjemi 5	1957	5 628	4 869	1 131	243	912	244	0	0	0	0	0	0	0	525	74	1 065	528	0	146
16.	316	Kjemihallen	1959	5 728	4 971	856	0	2 150	137	0	0	0	0	257	0	0	576	66	849	74	0	6
17.	317	IT-bygget	1973	6 185	5 467	2 369	55	181	449	0	0	0	0	35	0	0	336	227	1 405	314	97	0
18.	318	IT-bygget, sydfløy	1965	4 313	3 827	537	607	0	606	0	0	0	139	16	0	0	396	130	933	179	285	0
19.	319	Gamle fysikk	1924	4 968	4 147	1 463	226	492	246	0	0	0	0	0	0	0	424	90	881	46	0	279
20.	320	SINTEF Energi	1960	5 028	4 448	2 066	0	837	0	0	0	191	0	0	0	0	129	80	1 045	94	0	5
21.	321	Sentralbygg 1	1961	18 120	16 151	3 749	1 017	0	2 599	491	434	1 163	293	45	0	0	1 049	490	3 889	434	466	34
22.	322	Sentralbygg 2	1968	12 861	11 093	3 119	1 578	117	1 571	0	140	0	0	22	0	0	597	350	3 131	125	343	0
23.	323	Gamle kjemi	1910	3 703	2 912	1 759	52	0	66	0	0	0	0	0	0	0	61	71	854	14	0	36
24.	324	Vannkraftlaboratoriet	1916	2 525	2 050	379	0	602	125	0	0	0	0	108	0	0	104	34	404	260	0	35
25.	325	Gamle elektro	1910	9 061	7 571	320	1 700	210	734	0	0	0	0	52	0	0	587	129	2 318	681	178	661

26.	326	Elektro A	1961	6 265	5 653	1 032	115	1 098	517	0	0	284	0	0	0	0	361	112	1 755	357	22	0
27.	327	Elektro B	1959	3 599	3 203	999	99	94	326	0	0	0	0	0	0	0	548	168	905	65	0	0
28.	328	Elektro C	1960	2 900	2 521	803	0	317	264	0	0	0	0	358	0	0	37	74	483	135	47	4
29.	329	Elektro D+B2	1971	6 284	5 443	1 967	51	833	439	0	0	0	0	310	0	0	83	94	1 267	280	119	0
30.	330	Vestre Gløshaugen	1850	596	516	372	0	0	0	0	0	0	0	0	0	0	0	12	95	36	0	0
31.	331	Gløshaugen legesenter	1970	465	433	42	0	0	0	0	0	0	0	0	0	237	9	15	130	0	0	0
32.	332	Grønnbygget	1958	2 747	2 455	1 231	124	89	69	0	0	0	0	0	0	0	258	53	589	42	0	0
33.	333	Berg	1981	7 636	6 758	2 154	296	1 392	252	0	0	0	0	33	0	0	493	150	1 507	480	0	0
34.	334	Skiboli	1985	203	182	0	0	0	0	0	0	0	172	0	0	0	0	5	0	0	0	5
35.	335	Idrettsbygget	1966	4 906	4 312	165	0	0	0	0	0	0	0	0	2 605	0	234	143	858	190	116	1
36.	337	Byggteknisk	1975	19 882	17 016	3 966	880	2 276	1 794	0	0	0	0	749	0	0	1 252	270	4 293	1 376	161	0
37.	341	Elektro E/F	1986	10 460	9 523	1 606	169	2 074	881	0	0	0	0	394	0	0	642	93	2 998	663	0	4
38.	342	Østre Gløshaugen	1872	193	158	134	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0
39.	343	Infohuset	1898	430	346	184	0	0	0	0	0	0	0	0	0	0	3	4	68	87	0	0
40.	354	Kjelhuset	1951	5 053	4 295	42	1 098	0	504	0	0	550	0	0	0	0	652	149	1 062	183	0	54
41.	356	Produktdesign	1996	2 652	2 406	359	0	47	1 256	0	0	0	61	0	0	0	81	61	530	11	0	0
42.	357	VM-paviljongen	1996	829	760	0	0	0	485	0	0	0	0	0	0	0	34	23	206	12	0	0
43.	358	Høgskoleringen 3	2002	4 912	4 460	181	1 152	167	1 178	0	0	0	0	0	0	0	266	135	1 179	201	0	0
44.	360	Realfagbygget	2000	62 267	55 615	9 605	4 256	7 021	6 307	2 275	0	659	0	1 355	0	0	4 695	1 103	14 712	2 895	705	28
45.	365	PFI	1998	4 781	4 208	1 019	142	1 231	102	96	0	193	0	47	0	0	270	96	861	27	123	0
46.	380	Handelshøyskolen	2013	17 867	16 042	2 090	1 997	78	358	265	815	566	0	0	0	188	978	203	4 427	4 054	0	25

The distribution of classes varies considerably between the cohort groups as shown in Figure A1. The share of office area is distinctly different in each of the cohort groups accounting for 37,5% in the buildings built before 1951 and 16,3% in the cohort group 2000-2016. In addition, the share of laboratories differs between the cohort groups. Laboratories constitute merely 5,3% in the buildings constructed before 1951. The buildings erected between 1951 and 1970 have the largest share of laboratories (15,9%), followed by the cohort group 1971-1999 (14,3%). The share of traffic area is fairly constant within all of the cohort groups, accounting for approximately a quarter of the total floor area.

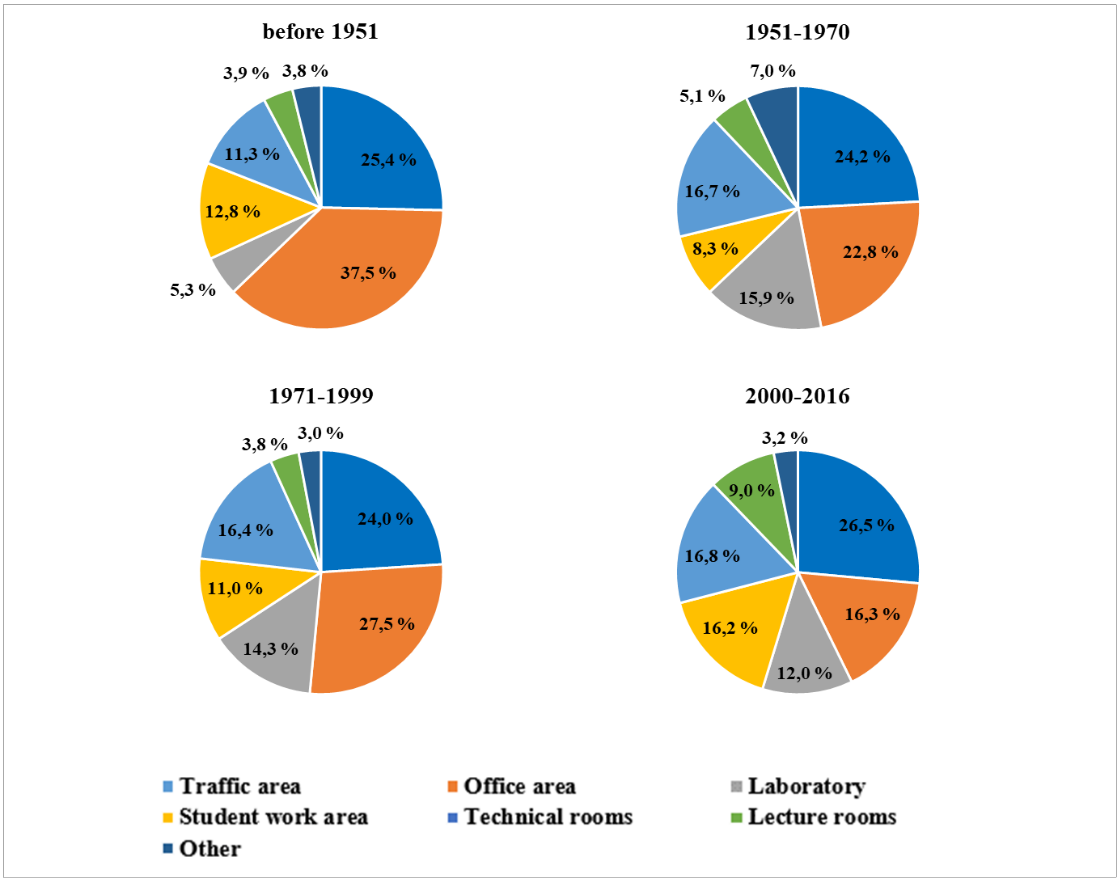

Figure A1. *Class distribution in four cohort groups of the existing buildings*

Figure A2 presents the share of each cohort group in different classes. Nearly a half of the total heated floor area of the building stock at NTNU Gløshaugen, including nearly 60% of the total laboratory area, almost 50% of the total office area and one third of the total student work area was built between 1951 and 1970. The buildings constructed between 1971 and 1999 contain one fifth of the total laboratory area and the same share of office area, whereas the buildings erected before the year 1950 include 15% of the total office area and just 3% of the total laboratory.

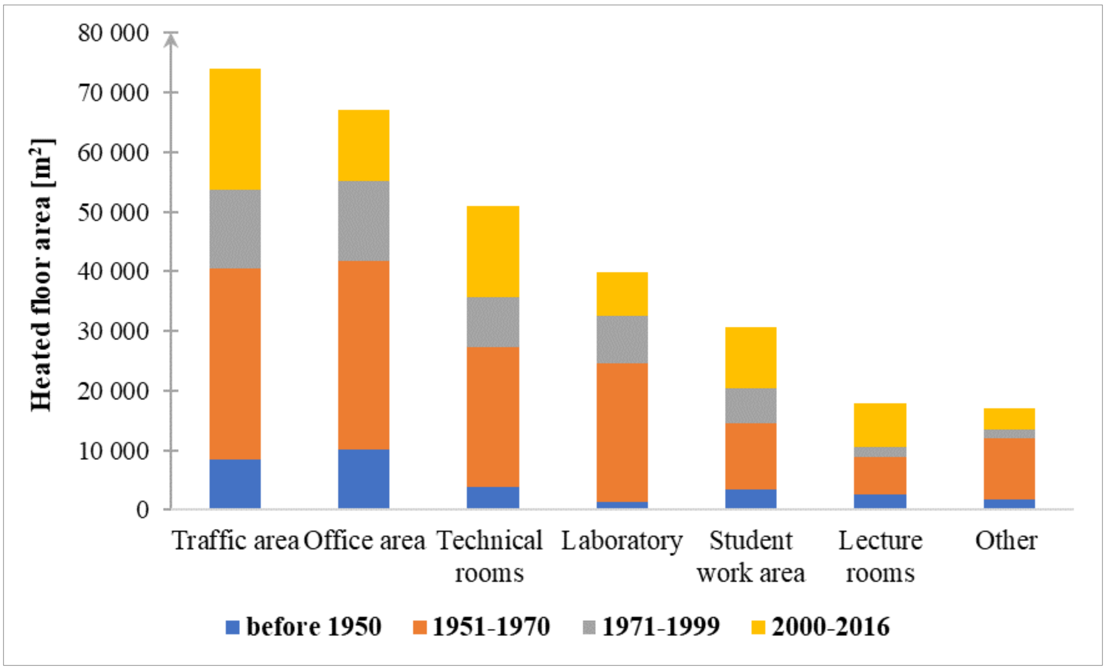

Figure A2. *Share of each cohort group in different classes*

Appendix B

Table B1. *Share of heat demand met by heat pump in each building (Engan, personal communication, April 2018).*

Building code	Building name	Cohort group	Heat supplied by heat pump [kWh/yr]	Heat supplied by district heating [kWh/yr]	Heat demand [kWh/yr]	Share of heat demand met by heat pump
302	Varmeteknisk	1951-1970	126 054	1 267 860	1 393 914	9,0 %
311	Kjemi	1951-1970	504 892	2 523 790	3 028 682	16,7 %
316	Kjemihallen	1951-1970	246 520	4 281 708	4 528 228	5,4 %
321	Sentralbygg 1	1951-1970	435 435	1 214 398	1 649 833	26,4 %
322	Sentralbygg 2	1951-1970	406 723	510 700	917 423	44,3 %
327	Elektro B	1951-1970	1 053 162	3 707 992	4 761 154	22,1 %
332	Grønnbygget	1951-1970	355 330	771 318	1 126 648	31,5 %
337	Byggteknisk	1971-1999	738 364	1 867 355	2 605 719	28,3 %
360	Realfagbygget	2000-2016	1 239 350	5 912 137	7 151 487	17,3 %
365	PFI	1971-1999	631 523	243 240	874 763	72,2 %

Table B2. *Share of heat demand met by heat pumps in each cohort group*

Cohort group	Heat supplied by heat pump [kWh/yr]	Heat supplied by district heating [kWh/yr]	Heat demand [kWh/yr]	Share of heat demand met by heat pumps
before 1950	*All of the heat produced by a heat pump located in Gamle fysikk (319) is transferred to IT-bygget, sydfløy (318; cohort group 1951-1970)*			
1951-1970	3 128 115	18 797 982	21 926 097	14,3 %
1971-1999	1 369 887	3 688 051	5 057 938	27,1 %
2000-2016	1 239 350	6 276 027	7 515 377	16,5 %

Figure B1 represents hourly electricity consumption over the usual week in 2016. Electricity consumption was considerably lower during weekends than on weekdays. Furthermore, electricity consumption at night differed significantly from consumption during day since electricity use is closely dependent on university activities.

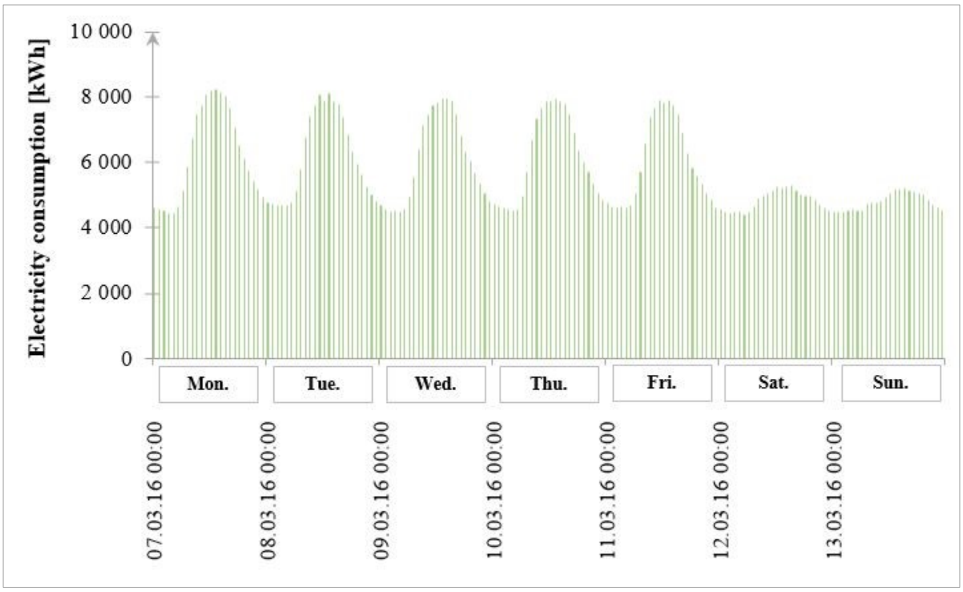

Figure B1. *Hourly electricity consumption in week 10, 2016*

Figure B2 shows hourly district heat consumption over two weeks in 2016. The highest district heat consumption happened in the mornings, between 6 and 10, and during weekends the peaks were significantly lower than on weekdays.

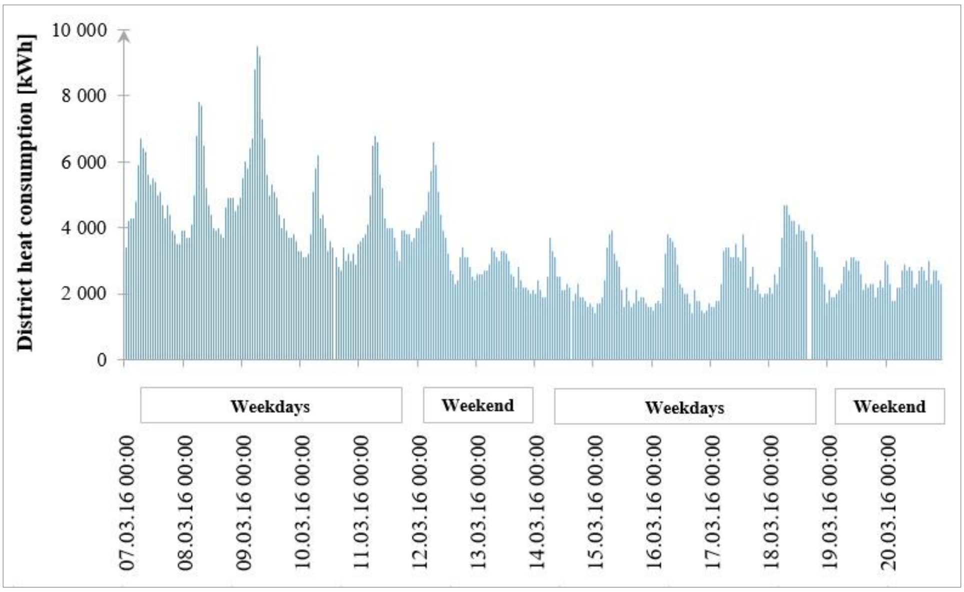

Figure B2. *Hourly district heat consumption in week 10 and 11, 2016*

Not every building at NTNU Gløshaugen has its own electricity and district heat meter. Some of the buildings share the meter and thus these buildings are combined based on the location of the meter. Table B3 represents the aggregated buildings and corresponding cohort group.

Table B3. *Aggregation of buildings with regard to energy meters*

Building	Year of construction	Cohort group
Hovedbygningen (301)	1910	**before 1950**
Østre Gløshaugen (342)	1872	
Infohuset (343)	1898	
Geologi (306)	1960	**1951-1970**
VM-paviljongen (357)	1996	
Materialteknisk (308)	1958	**1951-1970**
Gløshaugen legesenter (331)	1970	
Grønnbygget (332)	1958	
Sentralbygg 1 (321)	1961	**1951-1970**
Skiboli (334)	1985	
Sentralbygg 2 (322)	1968	**1951-1970**
Gamle kjemi (323)	1910	
Kjemi sydfløy (310)	1967	**1951-1970**
Kjemi 1 (311)	1954	
Kjemi 2 (312)	1955	
Kjemi 3 (313)	1967	
Kjemi 4(314)	1965	**1951-1970**
Kjemi 5 (315)	1957	
Kjemihallen (316)	1959	
Gamle elektro (325)	1910	**1951-1970**
Elektro A (326)	1961	
Elektro B (327)	1959	
Elektro C (328)	1960	
Elektro D+B2 (329)	1971	
Elektro E/F (341)	1986	
Vestre Gløshaugen (330)	1850	

Table B4. *Electricity intensity with respect to cohort group*

	Electricity intensity [kWh/m^2]		
Cohort group	**Minimum**	**Maximum**	**Weighted average**
before 1951	96,3	169,3	112,7
1951-1970	90,4	291,8	150,3
1971-1999	117,4	419,8	310,0
2000-2010	85,3	173,9	167,3

Table B5. *District heat intensity with respect to cohort group*

	District heat intensity [kWh/m^2]		
Cohort group	**Minimum**	**Maximum**	**Weighted average**
before 1951	100,6	149,7	111,1
1951-1970	53,7	291,9	119,8
1971-1999	57,8	118,0	102,9
2000-2010	81,6	106,3	104,5

Appendix C

Table C1. *Data on the new buildings*

	Year of construction	Gross floor area [m^2]	Net floor area [m^2]	Net floor area per floor area type [m^2]																
				1. Office area	2. Lecture rooms	3. Laboratory	4. Student work area	5. Library	6. Business area	7. Canteen area	8. Exhibition area	9. Workshop	10. Sports rooms	11. Hospital rooms	12. Technical rooms	13. Sanitary facilities	14. Traffic area	15. Storage	16. Shelters	17. Other
1.	2020	18 000	15 786	3 631	2 052	316	1 421	474	158	474	0	0	474	0	947	316	4 420	631	316	158
2.	2021	18 500	16 225	3 732	2 109	324	1 460	487	162	487	0	0	487	0	973	324	4 543	649	324	162
3.	2022	9 500	8 332	1 916	1 083	167	750	250	83	250	0	0	250	0	500	167	2 333	333	167	83
4.	2023	10 000	8 770	2 017	1 140	175	789	263	88	263	0	0	263	0	526	175	2 456	351	175	88
5.	2024	16 000	14 032	3 227	1 824	281	1 263	421	140	421	0	0	421	0	842	281	3 929	561	281	140
6.	2025	6 667	5 847	1 345	760	117	526	175	58	175	0	0	175	0	351	117	1 637	234	117	58
7.	2025	6 667	5 847	1 345	760	117	526	175	58	175	0	0	175	0	351	117	1 637	234	117	58
8.	2025	6 667	5 847	1 345	760	117	526	175	58	175	0	0	175	0	351	117	1 637	234	117	58

Table C2. *Energy efficiency measures in Standard Package and Ambitious + Technical Package (Nesgård & Ngo, 2018)*

		Energy efficiency measures
Standard Package (P1)	**Building envelope**	
	Outer walls	Insulation with 50 mm mineral wool
	Roof	Insulation with 50 mm mineral wool
	Windows	Replacement of window to TEK17 level (U-value 0,8 W/m^{2}K)
	Air tightness, leakage number N50	Improvement of leakage rate to 1,5 l/h
	Thermal bridges	Improvement of thermal bridges to 0,06 W/m^{2}K
Ambitious + Technical Package (P4)	**Building envelope**	
	Outer walls	Insulation with 100 mm mineral wool
	Roof	Insulation with 50 mm mineral wool
	Windows	Replacement of window to ambitious level (U-value 0,6 W/m^{2}K)
	Air tightness, leakage number N50	Improvement of leakage rate to 1,5 l/h
	Thermal bridges	Improvement of thermal bridges to 0,06 W/m^{2}K
	Technical solutions	
	Heat recovery ventilation	Replacement of heat recovery with 80%
	Low temperature heating system	Switch from 80/60°C to 60/40°C system

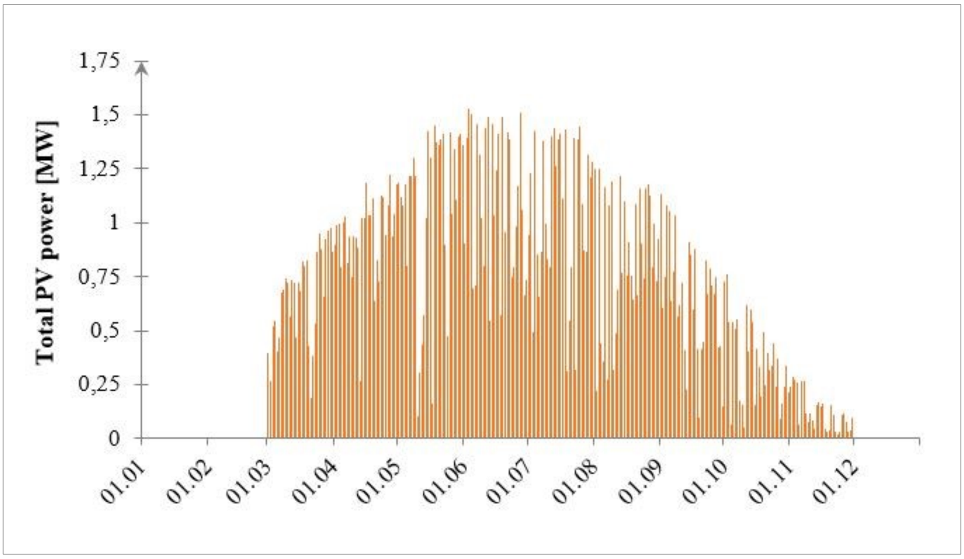

Figure C1. *Total PV power, hourly values (Johansen et al., 2018)*

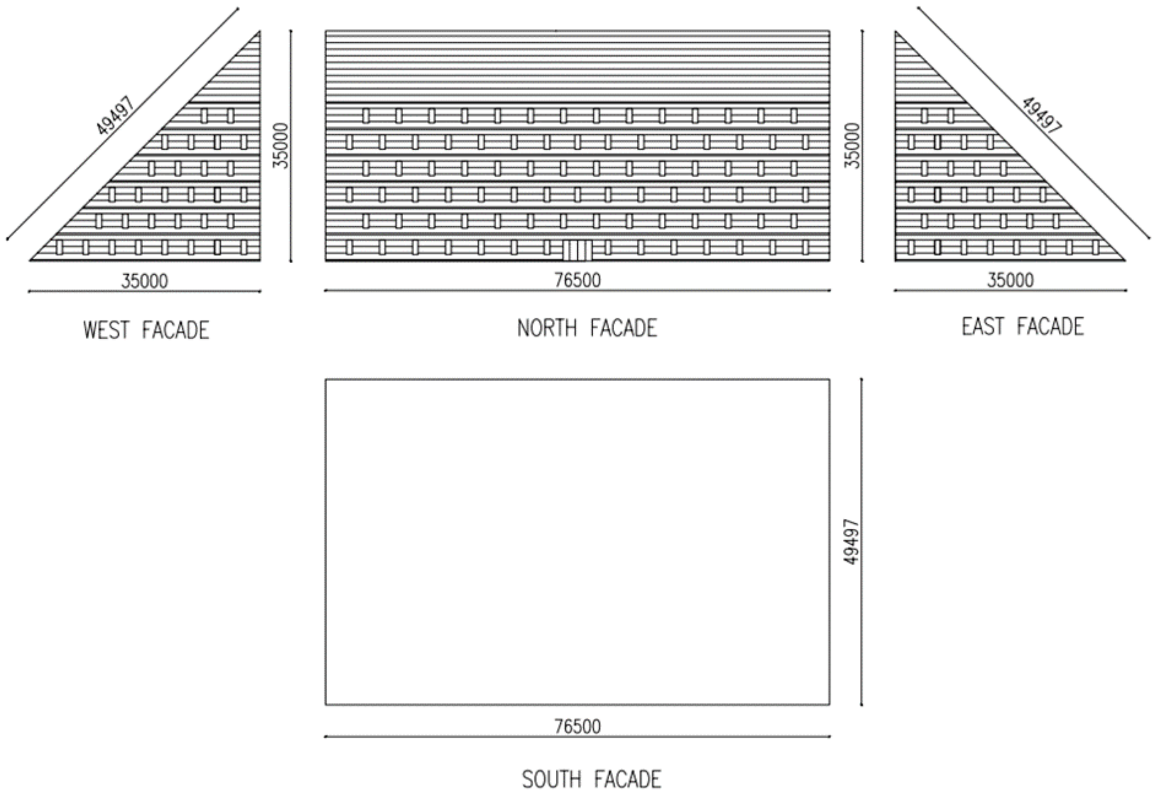

Figure C2. *Elevations of the reference buildings*

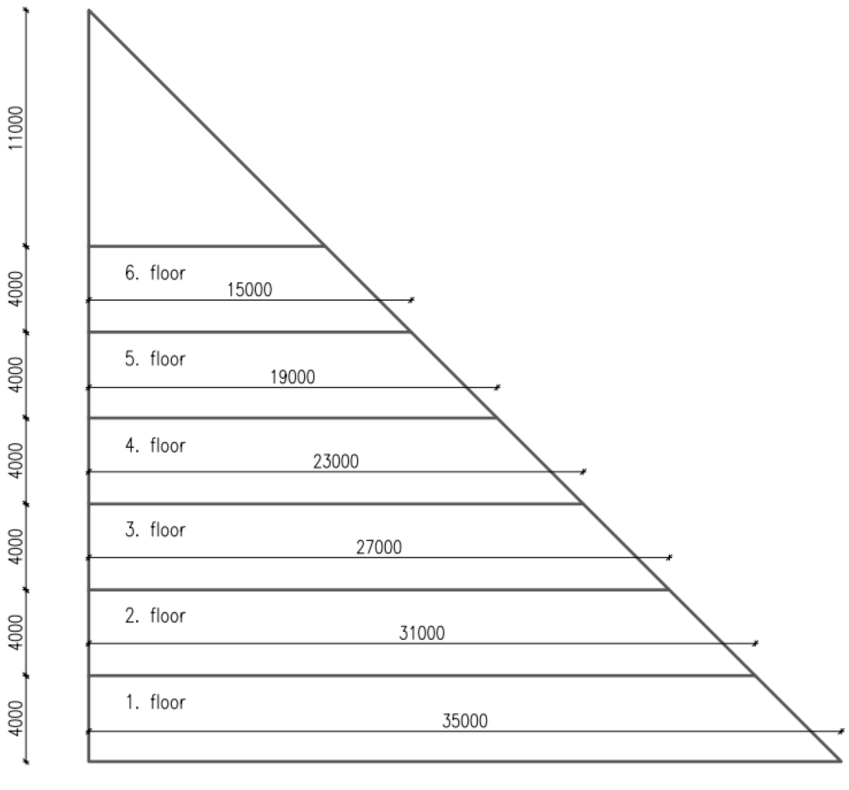

Figure C3. *Section of the reference building*

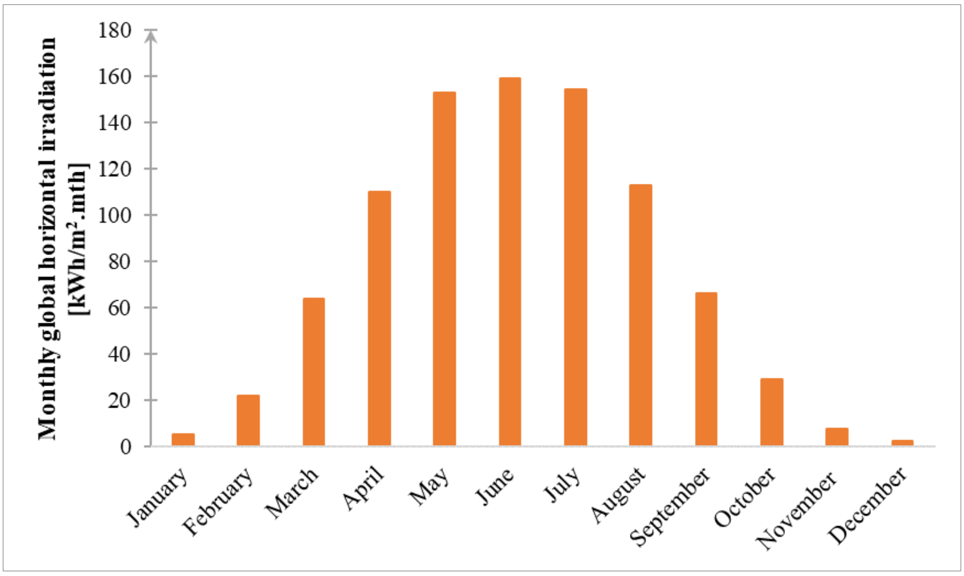

Figure C4. *Monthly global horizontal irradiation for Trondheim (Meteonorm)*

Appendix D

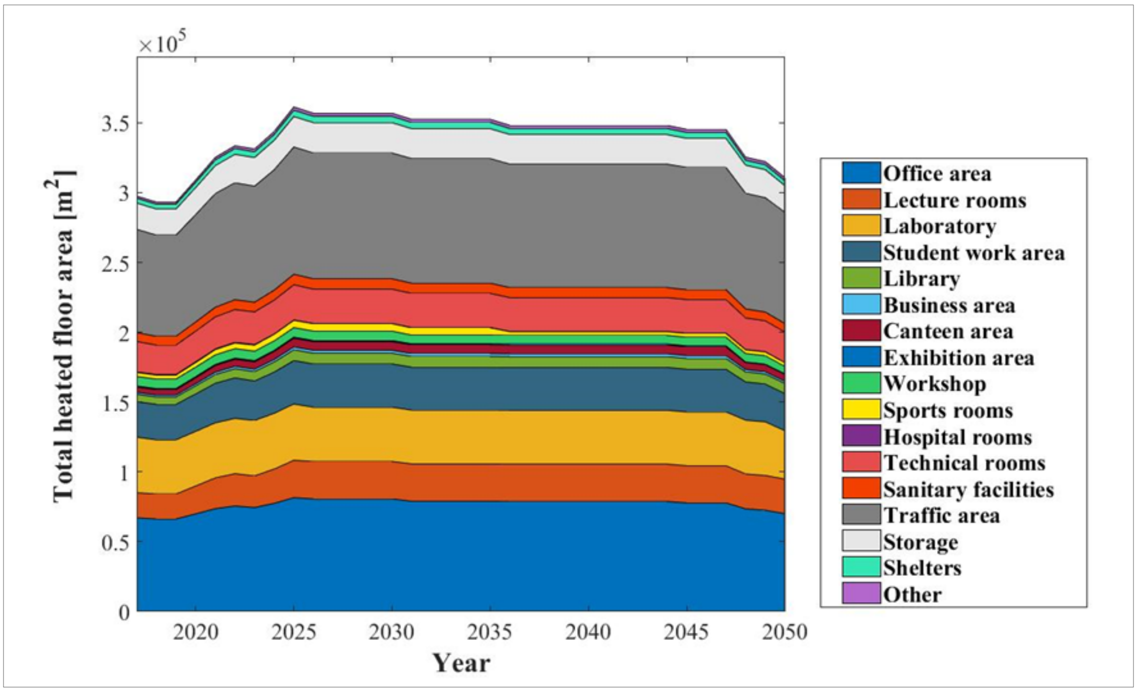

Figure D1. *Total heated floor area per floor area type*