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Optimal operating strategies of the micro-CHP for improved interaction between the electrical and thermal demand and supply

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MASTER THESIS

for

Student Kristin Folstad

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Optimal operating strategies of the micro-CHP for improved interaction between the electrical and thermal demand and supply

Optimale strategier for drift av mikro anlegg med kombinert varme og kraft produksjon (CHP) med tanke på bedre samvirke mellom behov og forsyning av elekrisitet og varme

Background and objective

Combined heat and power (CHP) system simultaneously produces the electricity and the heat and covers a large portion of heating in the low energy buildings. Until the recent focus on Net-ZEB, the potential advantage provided by electricity production of CHP has been largely untapped and has been considered as a by-product during the CHP appraisal. However, the CHP systems are considered as a potential solution in the Net-ZEB context as they can dampen or even avert the strong electrical exchanges that otherwise result in case of an all-electric Net-ZEB building.

The benefits offered by the CHP system can be availed using one or several of the strategies such as direct CHP power control, using the load management and the application of thermal or electrical storages. The opportunity associated with these strategies is so far not well-known. For example, the power control of the CHP system using heat lead or the electricity lead operation offers the advantage to shape the energy supply from the CHP according to the local demand; however, they at the same time can influence the energy performance of the system. However, the same effect or even better match can be found using the load management however; they require to the use the flexibility that is otherwise at the hand of occupants. The use of storage techniques are however considered the most flexible but involve large losses. Thus, the potential offered by these operating strategies is strongly dependent on their specific application.

The objectives of this work are therefore to simulate these strategies on a residential Net-ZEB and evaluate this building using different methodologies developed in the literature taking the energy performance and the demand-supply interaction indicators. The work shall eventually propose how these operating strategies can be suited in their Net-ZEB application and identify the needs for pilot projects.

This assignment is closely related to The Research Centre on Zero Emission Building at NTNU and SINTEF (FME ZEB) that has the vision to eliminate the greenhouse gas emissions caused by buildings. The main objective of FME ZEB is to develop competitive products and solutions for existing and new buildings that will lead to market penetration of buildings that have zero emissions of greenhouse gases related to their production, operation and demolition.

The following tasks are to be considered:

1. Define and simulate different operating strategies specific to the CHP and the building type
2. Assess the performance of the strategies using dynamic simulation and using different performance indicators in the Net-ZEB context
3. Propose the optimal control strategies in the Net-ZEB context and identify the needs for pilot projects in the area.
4. Make a draft proposal (8-10 pages) for a scientific paper based on the performed work in the master thesis.

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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.

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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, 24. January 2014

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Preface

This thesis was done the spring of 2014 at the Norwegian University of Science and Technology (NTNU), Department of Energy and Process Engineering. The work is closely related to The Research Centre on Zero Emission Buildings.

I would like to thank Usman Ijaz Dar for great guidance, help and support. I would also like to thank Natasa Nord for building model and good support with the simulation program EnergyPlus.

A scientific paper has been developed based on the main findings of the thesis, and can be found in appendix P.

Abstract

The research center of Zero Emissions Buildings (ZEB) has a goal of eliminating the greenhouse gas emissions associated with all phases of building development and use. This is achieved through more sustainable building construction and more efficient energy use. The Norwegian government has a similar goal of achieving zero energy buildings as a standard by 2020. This has led to proper investigation in technological solutions that can help to achieve these goals.

In a net-ZEB perspective, combined heat and power (CHP) is considered as a potential energy supply solution for buildings. CHP is seen as an emerging technology which has the potential to reduce primary energy consumption and the associated greenhouse gas emissions. This is achieved through concurrent production of electricity and heat using the same fuel. However, since the thermal output of CHP is substantially larger than the electrical output, the potential offered by CHP systems depend on their suitable integration with the thermal demand of the building.

In this thesis, a simulation model is used to investigate the performance of a CHP system compared to a conventional gas boiler system in a multi-family building that complies with the Norwegian building norm, TEK10. Different operational strategies are applied to the CHP model to investigate its optimal integration in domestic dwellings. Analyzing the simulation results indicates that the CHP system gives primary energy savings in all operational strategies, but operating the system in follow thermal mode represents the greatest savings. Applying load management resulted in further savings, and the fuel efficiency did increase, achieving a value of 75.1% on a higher heating value (HHV) basis. The CHP device is more capable of covering the electricity demand as peaks are shaved. This implies that CHP is better suited for buildings with stable electricity and heat demand. Electric demand following operation did however result in poorer primary energy savings and the corresponding CHP efficiency did decrease due to poorer heat recovery efficiency and frequent part load operation. Using renewable upgraded biogas as fuel in thermal following mode did result in the highest primary energy savings. Primary energy consumption was reduced by 34.3%, and the corresponding system efficiency based on primary energy was 70.7% on a HHV basis.

From an environmental perspective, it has been found that the CHP system is more favorable when the CO_2-emission factor for electricity is high. This is due to the reduction in electricity imports from the grid, and the part substituted electricity covered by the electricity exports from the CHP system. The greatest reduction in grid imports was seen when the CHP-device was set to follow the electrical demand of the building without restriction in thermal surplus. The CHP was able to cover 88.27% of the electricity demand, but the system efficiency decreased as significant amounts of heat was wasted due to overproduction. The highest amount of exports was seen when load management was implemented in thermal demand following mode, and represented 76.61% of the produced electricity. Using the current CO_2-emission factor for the UCPTE electricity mix, a reduction in CO_2 emissions was seen for all CHP configurations. The use of renewable fuel resulted in the greatest savings, and emissions were reduced by 71.91% compared to the gas boiler, representing a tremendous reduction. The use of natural gas as fuel resulted in significantly lower savings. The best case achieved a 26.58% reduction compared to the reference system. When using the net-ZEB definition, only CHP fuelled on renewable fuel did achieve CO_2-savings. This questions the environmental viability of today’s CHP systems as the CO_2-emission factor for electricity is expected to decrease over the coming years due to an expected increase in use of renewable fuels. Further research should therefore be done in order to enable an efficient CHP technology based on renewable fuels. This will decrease the emissions significantly, making CHP more competitive.

Sammendrag

Forskningssenteret for Zero Emission Buildings (ZEB) har som mål å eliminere klimagassutslipp knyttet til alle faser av bebyggelse og bruk av bygninger. Dette oppnås gjennom mer bærekraftige bygningskonstruksjoner og et mer effektivt energiforbruk. Den norske regjeringen har som mål å få null energibygg som en standard innen 2020. Dette har ført til grundig forskning i teknologiske løsninger som vil bidra til å oppnå disse målene.

Kombinert varme- og kraftproduksjon (CHP) er i henhold til ZEB ansett som en potensiell energiforsyningsteknologi for bygninger. CHP er sett på som en teknologi med potensial til å redusere primær energiforbruk og klimagassutslipp. Dette oppnås gjennom samtidig produksjon av elektrisitet og varme fra samme energikilde. Ettersom varmen produsert av CHP er vesentlig større enn den produserte elektrisiteten vil potensialet til CHP systemer avhenge av deres passende integrering med varmebehovet til bygningen.

I denne masteroppgaven er det brukt en simuleringsmodell for å undersøke ytelsen til et CHP-system sammenlignet med et konvensjonelt system med gasskjel i et bolighus som er i samsvar med norsk byggeforskrift, TEK 10. Ulike driftsstrategier er anvendt på modellen for å undersøke dens optimale integrering i bolighus. Analyse av simuleringsresultatene indikerer at CHP-systemet gir primærenergibesparelser i alle driftsstrategier, men oppnår de største besparelsene når den er satt til å følge byggets varmebehov. Bruk av laststyring resulterte i ytterligere besparinger, og CHP virkningsgraden økte til 75,1 % basert på øvre brennverdi. CHP-enheten klarer bedre å dekke elektrisitetsbehovet til bygget ettersom de høye toppene er unngått. Dette tilsier at CHP er bedre egnet for bygninger med mer stabilt elektrisitet- og varmebehov. Å la CHP-enheten følge bygningens elektrisitetsbehov resulterte imidlertid i dårligere primærenergibesparelser og CHP virkningsgraden ble også redusert grunnet dårligere varmegjenvinning og mer del-last drift. De høyeste primærenergibesparelsene ble oppnådd når oppgradert biogass ble brukt som energikilde og generatoren var satt til å følge byggets varmebehov. Det primære energiforbruket ble da redusert med 34,3 %, og systemvirkningsgraden basert på primærenergi var 70,7 % på øvre brennverdi basis.

Miljømessig vil CHP være mest gunstig når CO_2-utslippsfactoren for elektrisitet er høy. Dette er hovedsakelig grunnet reduksjon i importert elektrisitet fra kraftnettet, og den substituerte elektrisiteten dekket av eksportert elektrisitet fra CHP-systemet. Den største reduksjonen i import fra kraftnettet ble observert når CHP-enheten ble satt til å følge byggets elektrisitetsbehov uten begrensning i produsert overskuddsvarme. CHP var da i stand til å dekke 88,27 % av elektrisitetsbehovet, men systemets virkningsgrad ble redusert ettersom betydelige mengder varme ble tapt på grunn av overproduksjon. Eksport av elektrisitet var størst når CHP var satt til å følge byggets varmebehov med laststyring implementert, der 76,61 % av produsert elektrisitet ble eksportert. Ved å bruke dagens CO_2-produksjonsfaktor for UCPTE elektrisitetsmiks oppnådde alle CHP konfigurasjoner en reduksjon i CO_2-utslipp. Bruken av fornybart brensel resulterte i størst besparelser, og utslippet ble redusert med 71,91 % i forhold til den gassfyrte kjelen, noe som representerer en enorm reduksjon. Bruk av naturgass medførte imidlertid til betydelige lavere besparelser. Beste tilfellet oppnådde en reduksjon på 26,58 % i forhold til referansesystemet. Bruk av net-ZEB definisjon på CO_2 utslippsfaktor for elektrisitet førte imidlertid kun til CO_2-besparelser når CHP var drevet på fornybart brensel. Dette stiller spørsmål til den miljømessige gevinsten av dagens CHP systemer ettersom CO_2-utslippsfaktoren for elektrisitet forventes å avta i løpet av de kommende årene grunnet en forventet økning i bruk av fornybare energikilder. Videre forskning bør derfor gjennomføres for å muliggjøre en effektiv CHP-teknologi basert på fornybare energikilder. Dette vil redusere utslippene betydelig, noe som gjør CHP mer konkurransedyktig.

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1. Introduction

Generation of heat and electricity represented in 2010 41 % of the world's CO_2 emissions (IEA, 2012). The same year, the building sector represented 26.7 % of the final energy use in EU-27 (European comission eurostat, 2012), which shows that a significant amount of the energy produced is used in the building sector. According to UNs climate panel, it is in this sector that it is most economically viable to implement the actions for reducing the CO_2 emissions. Therefore the research and development of zero emission buildings (ZEB) is an important action to defeat the climate change (ZEB, 2014). A zero emission building is a building with no CO_2 equivalent emissions associated to its construction, operation and demolition. World business council for sustainable development has a vision of 50 % reductions of the total greenhouse gas emissions (GHG) by 2050 compared to 2005 – level (DiPiazza, Kreutzer, Mack, & Zaidi, 2010).

The building sector is today highly dependent on electricity for heating purposes. 99 % of the electricity generation in Norway comes from hydropower, which is a renewable energy source (Vannkraft. Statkraft AS, 2013). On a global perspective, on the other hand only a small part of the electricity production comes from renewable energy sources, which makes it beneficial to reduce the overall electricity use. Reducing the energy use in building will also lead to lower GHG emissions. This reduction can be achieved through more energy efficient systems, use of renewable energy sources and energy efficient building constructions (low energy buildings, passive house or plus buildings) which minimizes the energy demand. The government in Norway has agreed that passive house standard is to be required for new buildings from 2015 and nearly zero energy buildings as a standard from 2020 (Ministry of the environment, 2012). A zero energy building is a building with a greatly reduced energy demand which is only covered by energy from renewable sources. (Graabak & Feilberg, 2011)

The final energy consumption in buildings in EU27, Switzerland and Norway comes mainly from oil, gas and electricity (Buildings Performance Institute Europe (BPIE), 2011). This final energy consumption will likely continue, and therefore it is important to look at the potential of a more efficient use of these sources.

This master thesis is defined by The Research Centre on Zero Emission Building at NTNU and SINTEF (FME ZEB). The main objective of FME ZEB is to develop solutions for existing and new buildings, with the aim to achieve ZEB standard. An energy efficient supply and control system is a key element in achieving this goal. In this concept, different technologies of both building structure and energy supply solutions have been and will be considered. Some energy generations are considered to contribute to CO_2 emissions, while others contribute in reducing them. For example, energy imported from the grid accounts for certain emissions, while export of renewable energy from the building accounts for avoiding the similar emissions by other non-renewable energy producers connected to the same grid (Sartori, Andresen, & Dokka, 2010).

Combined heat and power (CHP) is seen as an emerging technology in using fossil energy sources more efficiently as it produces electricity and heat from the same fuel source. It has the potential to reduce primary energy consumption and associated greenhouse gas emissions. CHP is considered as a potential energy supply solution within a net-ZEB concept due to these potential effects (Alanne & Saari, 2003). CHP can run on renewable fuels, but fossil fuels are most commonly used. However, even though the devices are usually fuelled with natural gas, it is considered a low-carbon technology due to that it contributes to a more efficient use of the limited fossil resources (Day, Ogumka, Jones, & Dunsdonm, 2009).

The energy demand of a building can be divided into electrical and thermal, where the electrical demand goes to lighting and electrical equipment and the thermal demand to space heating, ventilation and domestic hot water. CHP has the potential to cover both demands, but problems around its dynamics hamper its market penetration. CHP systems have large thermal outputs, while the thermal demand of buildings decreases through better insulated building envelopes. The benefits of using a CHP device compared to the problems around its dynamics need to be analyzed in order to evaluate the potential of integration in buildings.

In this thesis, the CHP integration in a residential multi-family building (MFB) will be compared to a conventional gas boiler and different optimization strategies will be simulated and evaluated. The building complies with the Norwegian building norm, TEK10. Implementation of this technology in cooperation with other energy efficient solutions may help to reach FME ZEB's goal. First, the most relevant performance assessment methodologies in a net-ZEB context are defined through a literature study. Then, the effect of the CHP-implementations with the different optimization approaches versus the conventional gas boiler is evaluated in terms of these methodologies. The methodologies are formulated in order to evaluate the performance of the systems in an energetic and environmental perspective. Finally, results from simulations of the different operating conditions of the CHP are compared to the conventional gas boiler system and the effect of each implementation is discussed based on the methodologies defined. The different optimizing approaches reviewed are load management, different power control options and implementation of thermal storage. The possibilities and benefits of electrical storage will be discussed, but not simulated. At last, the possibility of using renewable fuel, such as upgraded biogas will be evaluated.

The scope for this thesis is to define an optimal control system for satisfying different energy demand variations in a multi-family dwelling. The energetic and CO_2 benefits for the implementation of a micro-CHP system depend heavily on the "non-CHP" reference situation. As in this thesis, the reference case is a condensing gas boiler which has high efficiency; the benefit of using CHP will depend on the system configuration of the CHP. It is important that the CHP device operates as efficient as possible, and that the power and heat output is produced in a rate that achieves net benefits on a future basis regarding primary energy, energy efficiency, reduced grid interaction and CO_2 emission.

Micro-CHP units are characterized principally by prime mover size (Poe), electrical efficiency and heat-recovery efficiency. The prime mover technology that is in focus in this thesis is the internal combustion engine. The tool used for analyzing the CHP system performance is the building simulation tool EnergyPlus. EnergyPlus is chosen as it is a well-developed simulation tool, and has an already existing CHP model integrated. The CHP model used is based on the international Energy Agency's Energy Conservation in Buildings and Community Systems (IEA ECBCS) Annex 42 for a Senertech internal combustion engine production unit.

2. Parameter definitions and abbreviations

Definition of parameters:

Case:	A specific installation with its data set on environment, building, demand profiles and cogeneration system.
Configuration:	A specific data set for individual cases in terms of cogeneration system and of components size/dimensions, and of the control strategy used.
Cogeneration:	Combined generation of heat and electricity.
Cogeneration device:	The cogeneration plant or appliance, as provided by manufacturer.
Cogeneration system:	The system providing heat and electricity. This includes the cogeneration device and other components such as storage, external pumps, auxiliary heater, and other supply components such as solar collector, heat pump etc.
Performance assessment:	Assessment of the performance of the system under investigation in regard to the selected performance criteria, by simulation.

Abbr.	**Description**
DHW	Domestic hot water
SH	Space heating
CHP	Combined heat and power (=cogeneration)
CO_2	Carbon dioxide
ICE	Internal combustion engine
HHV	Higher heating value
LHV	Lower heating value
SE	Stirling engine
ZEB	Zero emission building
El-Grid	Electricity supplied from the grid
El	Electric, electricity
El-NetGrid	Net amount of electricity exported to grid, or net amount of electricity delivered from grid
GHG	Greenhouse gases
RE	Renewable energy generated on the building premises
Del	Delivered
Exp	Exported
GB	Gas boiler
NG	Natural gas
El-Grid	Electricity supplied from/to grid

3. Micro-CHP

3.1 Technologies

Combined heat and power are devices that generate both heat and electricity, and can be produced off-site or on-site. Hence, the CHP- technology makes it possible to supply residential buildings with both electricity and heat. The electricity produced can either be used directly or exported to the grid. On the same hand, the heat generated can either be used directly or stored in a storage tank. CHP is an important technology for improving energy efficiency, security of energy supply and reduction of CO_2 emissions. It also reduces the dependence on non-renewable energy sources of the building while at the same time improve its interaction with the grid. CHP has been recognized by the European community as one of the first elements to save primary energy, to avoid network losses and to reduce the greenhouse gas emissions (Possidente, Roselli, Sasso, & Sibilio, 2006).

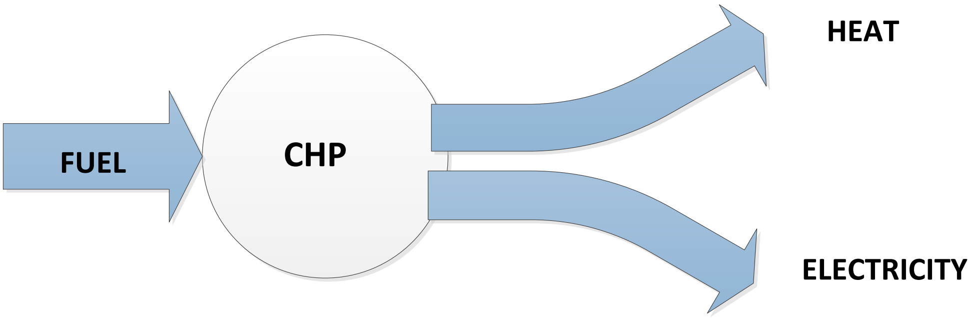

Figure 1: Basic illustration of CHP principle

Micro-cogeneration is the production of combined heat and power on a smaller scale. It has the same efficiency advantages as CHP plants, and has therefore a potential as an alternative to the conventional energy production today regarding reduced grid interaction and lower energy demand. This technology has become economically viable since year 2000 because of the rising energy prices (John Kopf, 2012). The European Cogeneration Directive defines micro-CHP as all units with an electrical capacity of less than 50 kW (Greenspec, 2013). Micro-CHP system used for single or multifamily dwellings are typically designed to provide electricity less than 10 kW and thermal heat less than 25 kW (Knight & Urgursal, 2005). The core benefits of micro-CHP are emission reductions, cost reductions, empowering consumers and security of supply. Energy production for buildings is one of the most promising targets for the appliance of CHP (Alanne & Saari, 2003). The reason why this technology is so interesting and applicable for single- and multifamily houses is due to their technical and performance features:

- High overall energy conversion efficiency.
- Low maintenance requirements equivalent to a domestic gas boiler.
- Very low noise and vibration levels for installation at home.
- Very low emissions of NOx, COx, SOx and particulates.
  (Kuhn, Klemes, & Bulatov)

In micro-CHP applications, the electricity is produced at the location where it is needed and the waste heat of generation is recovered and also used at the location. This leads to higher efficiency compared to central thermal generation stations which do not recover the waste heat, and transmission losses also occur when delivering the electricity from the station to the building.

A micro-CHP unit works as illustrated in Figure 2, converting the fuel, which is normally gas, and transforming it into heat energy for space heating and domestic hot water, and electricity for electrical appliances. In general >70 % is converted into heat, 10-25 % into electricity and 10-15 % are losses (Greenspec, 2013). These percentages will vary some depending on the CHP device chosen.

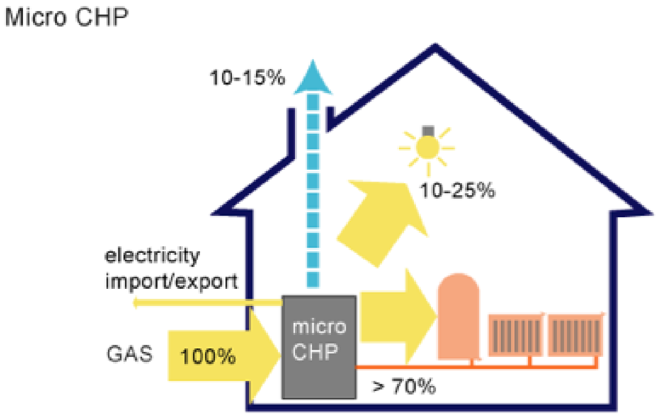

Figure 2: CHP installation in building (Greenspec, 2013)

Small- scale CHP devices have relatively low fuel- to- electrical conversion efficiencies compared to combined-cycle central power plants. Some existing prototypes have electric efficiencies as low as 5 %, although some fuel cell technologies have the potential to achieve efficiencies of 45 % (Beausoleil-Morison, April 2008). However, this has still not yet been achieved. Because of this relation, it is important that the thermal portion of the cogeneration device output is well utilized for space heating, space cooling, and/or domestic hot water heating. The residential cogeneration technologies cannot expect to deliver a net benefit relative to the best available central generation technologies if this thermal portion is not well utilized in the building.

The existing types of micro- CHP systems are reciprocating internal combustion engine (ICE) based systems, reciprocating external combustion Stirling engine (SE) based system, fuel cell based systems and micro- turbine based systems. The most common used are the ICE and SE based systems, but fuel cell is also an emerging technology with growing potential. In this thesis, an ICE based system will be considered.

Internal combustion Engine (ICE):

The most established micro-CHP appliance is the ICE. The typical characteristics for an ICE-based micro-CHP are its low cost, high efficiency, wide power range and ability to run on different fuels (Klobut, Ikäheimo, & Ihonen). It is based on the automotive engine, and possible fuels are diesel, biodiesel, gasoline, natural gas, biogas and landfill gas. The possibility of using renewable fuels makes it an interesting choice for energy supply, even though natural gas and diesel oil are the most common fuels. These engines are well proven, robust and reliable, and therefore are these systems usually the prime mover of choice for small-scale cogeneration applications (Hongbo, Weijun, & Yingjun). The ICE unit uses an internal combustion process to generate both heat and electricity. An ICE depends on combustion of a chemical fuel, typically with oxygen from the air. The combustion chamber of the engine is an integral part of the working fluid flow circuit. The typical benefits of ICE devices are that they have high electrical efficiency, large power range and have the possibility of using a varying range of fuels. The drawbacks are that they need service regularly, are noisy, which is not desirable for building application, and their emissions strongly depend on the fuel used (Alanne & Saari, 2003). These units are best applicable for buildings with smooth electricity and heat consumption profiles.

Internal combustion engines can be divided into two main categories: Diesel engines and spark ignition engines. For diesel engines the usage of biodiesel and rape oil can be included. The use of rape oil/biodiesel for the deployment of CHP plants has due to the excellent biodegradability and to its low ecotoxicity received major attention in ecological sensible regions. These systems do as well achieve high efficiencies, do not produce any direct CO_2 emissions and contribute to a sustainable energy supply in “green lodges” (Simader, Krawinkler, & Trnka, March 2006). A 100 % usage of biodiesel can be used in diesel engines without any problems. Rape oil can also be used. Biogas, however, can be used in both diesel engines and spark ignition engines. The market leader company to produce internal combustion engines is the Germany based company Senertec. The Senertec model – called Dachs – generates around 5.5 kW_{el} and a thermal power of 14 kW depending on the product model. This is the engine that Annex 42 bases its modulation in EnergyPlus (Simader, Krawinkler, & Trnka, March 2006). This device has a single-cylinder 4 stroke 580 cc special engine which is designed for a very long service (SenerTec AS, 2014). Figure 3 show the system configuration of a micro-CHP system based on combustion engine technology.

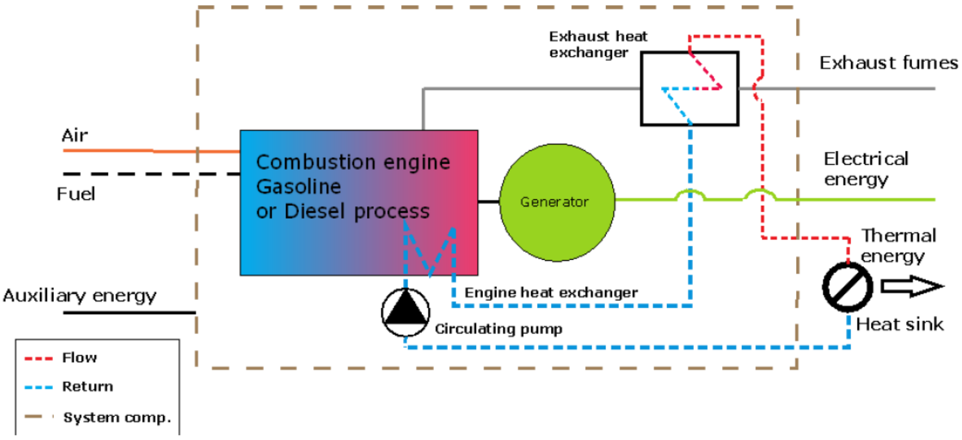

Figure 3: System configuration of a micro-CHP system based on combustion engine technology (Klobut, Ikäheimo, & Ihonen)

Micro-CHP appliances consume more fuel than condensing boilers, so the benefit of using CHP comes from the electricity generated (SEAI, 2011). If the engines do not run enough time to generate sufficient electricity, CHP can be more energy-and-carbon intensive than the condensing boilers they do replace. Therefore it is essential that the units are sized correctly, installed in the optimum location and configured with the correct control system. It is seen from previous studies that buildings with higher heat loads gives higher efficiency and use of the CHP units than buildings with lower heat loads. However, it is not good to artificially increase the heat loads to increase the operation of the micro-CHP. This will lead to higher CO_2 emissions and higher primary energy consumption even though the efficiency of the system will be better. Therefore it is better to develop an optimal control configuration and operate the CHP at best possible practice to meet the building loads, both electrical and thermal. ICE units operate most effectively when they run for extended periods of time with very few start-up cycles. This is because most of the wear on the engine occurs during start-up (SEAI, 2011).

Every micro-CHP uses in reality some electricity when in standby mode, which will affect the annual efficiency. This is because the system consumes imported electricity when the generator is in standby mode, which has high CO_2 emission factor in areas where CHP is of interest, instead of generating onsite electricity for electricity consumption (SEAI, 2011). As the electricity consumption of the micro-CHP is considered small compared to the amount produced, the standby power for the generator is set to be zero for the systems evaluated in this thesis. The corresponding factor for the gas boiler is also set to be zero, and this will therefore not affect the comparison in energy efficiency or primary energy consumption, which is the main focus for this work.

3.2 Integration of the CHP

The micro-CHP system can be implemented in residential buildings with various ranges of purposes. It can either be integrated to cover both thermal and electrical demand, the thermal demand and part of the electrical demand, the electrical demand and part of the thermal demand or part of the thermal demand and part of the electrical demand. Due to efficiency reasons of the plant, the most common is to use the micro-CHP unit to cover part of the electricity demand and part of the thermal demand (Knight & Ugursal, 2005).

Integration of micro- CHP systems into operating buildings may be challenging. This is because the loads are small and the load diversity is limited. The CHP device produces heat and electricity simultaneously, and in residential buildings there will be time where it requires one but not the other. Therefore it is difficult to define the best strategy for how it is optimal to use the micro-CHP for optimal efficiency and to cover the energy demand at the best rate possible. Factors like optimal sizing and control of the CHP system, how to meet peak loads (both electrical and thermal), need for and sizing of thermal storage, standardized technique for grid connection, ability to export electricity, emergency power operation (grid outage), safety, standards and code issues are important to look at when defining the system specifications and operating mode (Bell, et al., November 4, 2005).

How well the thermal energy produced by the generator is utilized in the building depends on the system control and operation as the generator produces both electricity and thermal energy at the same time, while the electrical and thermal demand of the building does not usually happen at the same time. For instance, if the cogeneration device is configured to cover the electrical demand of a house, this peak load does not necessary happen at the same time as the thermal peak load. Often, the electrical demand may peak late in the evening. This results in a large thermal output from the cogeneration device. At this time in the evening, the thermal demand might be low since the building is allowed to cool slightly during the night. This results in an overproduction of heat which is not utilized. To solve this problem, a storage tank should be integrated to store the overproduced heat for use when the thermal demand is higher than the thermal energy produced from the generator. The volume and thermal characteristics of the storage tank, the occupant electrical and hot water usage patterns, the thermal characteristics of the house and weather does all influence whether the thermal energy will be exploited or wasted. There are lots of different design possibilities for these factors, and a lot of research is necessary to determine the optimal design and utilization. To be able to analyze the performance of the cogeneration system and the influence of different parameters, it is necessary to use whole- building simulation programs (Beausoleil-Morison, April 2008).

4. Performance assessment methodologies for micro-CHP in the NET-ZEB potential

To get the reduction of the emissions related to the building sector to a sustainable level requires a tremendous effort in both increasing the energy efficiency in buildings and the share of renewable energies. Small combined heat and power systems may help to improve the situation on the energy supply side by cutting both the non-renewable energy demand for residential buildings and peak loads in the electric grid (Dorer & Weber, 2007). The performance assessment will be analyzed in terms of primary energy, energy efficiency, grid interaction and CO_2 emissions. The different system cases will be defined in section 6. Possible solutions would be to couple the cogeneration device with other devices, such as other components of cogeneration system (e.g. water storage) and other energy supply components such as heat pump and solar thermal systems.

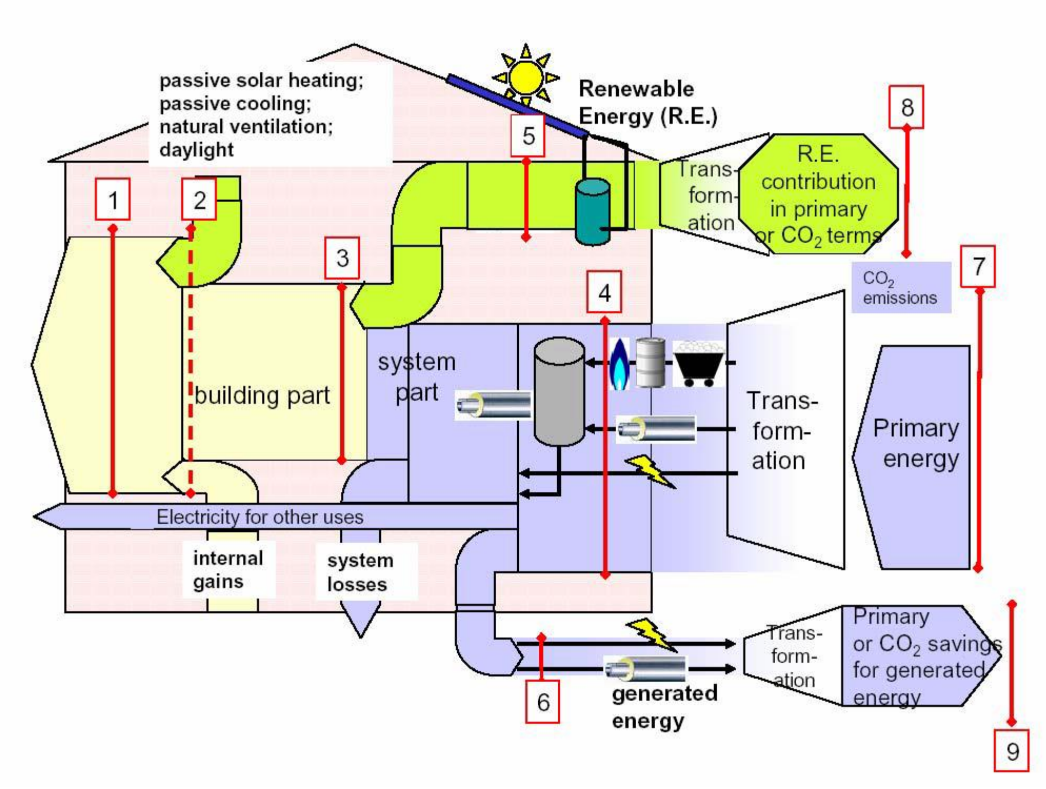

Figure 4: Example of energy conversion process and energy terms in a residential building (CEN/TC 89 N1016, 2005)

Figure 4 represents the energy conversion process and terms in a residential building. (1) is the energy demand, which is the amount of energy demanded by the building for heating and electrical appliances. (2) is the non-HVAC energy, which is the heat or cooling added to the building naturally through solar heating, daylight etc. (3) is the net energy, (4) is the delivered energy, (5) is the renewable energy, (6) is the exported energy, (7) is the primary energy, (8) is the primary energy equivalence locally generated renewable energy and (9) is the primary energy of the exported energy. The transformation process from primary energy to delivered energy depends on the type of energy delivered.

The primary energy related to the exported energy will be subtracted from the total primary energy delivered to the building, and will be seen as primary energy savings. Equally, it will account for CO_2 savings as well as explained later. In the system cases reviewed in this thesis there will be no on site renewable energy production. According to TEK10, 40 % of net heating demand should be covered by other energy supply solution than direct electricity or fossil fuels (Kommunal- og regionaldepartamentet, 2010).

The first three performance assessment methodologies consider the energy analysis of the system, while the fourth considers the environmental analysis. The objectives of the performance assessment are mainly to demonstrate application potential of models and building simulation tools developed and quantify the performance of selected cogeneration systems in terms of energy and emissions compared to the conventional system. From this, the most successful elements of individual cogeneration configuration can be documented for the case study, and promising applications field for cogeneration systems can be discussed.

Regarding energy, 3 types of energies are considered; Net energy demand, delivered energy and primary energy. *The net energy demand* is the energy demanded from the cogeneration, HVAC and the renewable energy systems to cover the demands for domestic hot water, space heating and for electricity. *The delivered energy* is the energy delivered to the building as fuel, heat or electricity. *The primary energy* is the energy source, which can be renewable energy or non-renewable energy (CEN/TC 89 N1016, 2005).

4.1 Based on primer energy savings

This assessment is based on primary energy consumption. The values will be derived in a post processing analysis based on the calculated values for the demand of delivered energy. The delivered energy demand (electricity and fuel), based on the net energy demand for space heating, domestic hot water, and electrical demand, for the whole simulation period will be calculated in EnergyPlus.

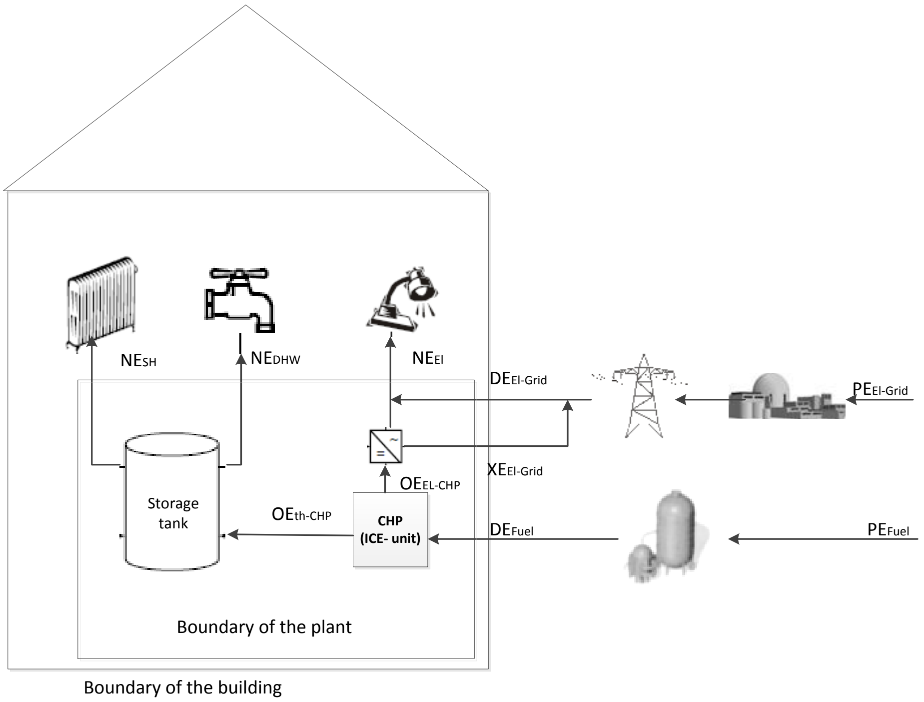

Figure 5: Control volumes and related energies. Based on drawing from (Dorer & Weber, 2007)

Primary energy represents the energy use associated with the embodied energy in natural resources such as crude oil, coal, natural gas, sunlight etc. It represents the delivered energy before any anthropogenic conversion or transformation. Primary energy can be divided into renewable and non-renewable energy, where natural gas for instance represents a non-renewable energy source. Primary energy rating makes possible to sum different types of energies (e.g. thermal and electrical) as they integrate the losses of the whole chain, which includes the losses outside the building system boundary (prEN 15203/15315, 2006). Figure 5 illustrates the control volumes and related energies for the micro-CHP system.

The primary energy consumption to generate electricity and heat will be considered for both micro-CHP and reference system. The primary energy demand is defined by equation 1:

$$PE = \sum\left(DE_i\, f_{prim,del,i}\right) - \sum\left(XE_i\, f_{prim,exp,i}\right) \tag{1}$$

where

PE	is yearly primary energy demand, in kWh;
DE_i	is yearly delivered energy for energy source *i* (electricity, oil, gas, district heating, biofuels or other energy source), in kWh;
XE_i	is the yearly exported energy for energy source *i*;
$f_{prim,del,i}$	is primary energy factor for energy source *i*, in kWh/kWh;
$f_{prim,del,i}$	is the primary energy factor for the exported energy source *i;*

(NS-EN 15603:2008, 2008).

In the primary energy factor, the following factors are included:

- Energy to extract the primary energy carrier.
- Energy to transport the energy carrier from production place to user location.
- Energy to process, store, generate, transfer and distribute, and all other elements that are necessary to deliver the energy to the building where the delivered energy is to be used.
  (NS 3031:2007+A1:2011, 2007/2011)

Primary energy factors can be divided between non-renewable and total primary energy factors. Both take into consideration the above mentioned parameters, but the non-renewable excludes the renewable energy component of primary energy (prEN 15203/15315, 2006). This may lead to lower primary energy conversion factor for renewable energy sources. For grid electricity, the non-renewable and total primary energy demand and respective CO_2-equivalent emission values depend on the generation mix of the electricity utility grid. For the consideration of the electricity mix, two electricity mixes will be considered, the UCPTE electricity mix and the net-ZEB definition.

The delivered energies to the building are natural gas and electricity. To convert this amount of delivered energy to primary energy, a primary energy factor has to be multiplied as seen in equation 1. The net energy and the energy output of the cogeneration device will not be exactly the same due to losses in the distribution system, mainly due to losses in the storage tank. The electricity on the other hand is assumed to be delivered without losses, and the delivered electricity OE_{El} equals the demand of the building plus exports minus imports.

When calculating the primary energy consumed by the cogeneration system, the amount of electricity produced and exported to the grid should be accounted for. This should be properly defined, and which primary energy factors to apply also needs to be determined. According to Annex 42, there are two approaches to consider this; as an additional demand or with the substitution principle (Dorer & Weber, 2007). In the first approach, the net amount of electricity delivered back to the grid is accounted for as an additional demand covered by the cogeneration system. In the second approach this amount is accounted for as a substitution to the same amount produced by the electricity mix of the grid. In this approach, the exported electricity is seen as delivered energy to the grid, and the primary energy factor for grid electricity is used to calculate the primary energy of the exported electricity. Using the substitution principle, the displaced primary energy ($PE_{EL\text{-}Dispaced}$) is given by equation 2.

$$PE_{El-Displaced} = f_{prim,del,El} \cdot XE_{El-Grid} \tag{2}$$

The substitution principle relates the energy input to the energy demand of the building only, and any surplus electricity produced is accounted for as a reduction in the energy input. Using this approach makes it more convenient to compare the CHP system directly to the conventional system in terms of primary energy consumption.

The different forms of delivered energy to the building are calculated by equation 3 and 4:

Delivered energy as natural gas: $$DE_{NG} = \frac{NE_{SH} + NE_{DHW}}{\eta_{DE}} \tag{3}$$

Delivered energy as electricity from grid: $$DE_{El-Grid} = NE_{El} - OE_{El,CHP} + XE_{El-Grid} \tag{4}$$

where,

DE_{NG}	is the yearly delivered energy of natural gas to the building;
$DE_{El\text{-}Grid}$	is the yearly delivered electricity to the building;
NE_{SH}	is the yearly net energy going to space heating;
NE_{DHW}	is the yearly net energy going to domestic hot water;
NE_{El}	is the yearly net energy going to electricity;
$OE_{EL,CHP}$	is the yearly electricity produced by the CHP;
$XE_{El\text{-}Grid}$	is the yearly exported electricity from the building to the grid;
n_{DE}	is the system efficiency based on delivered energy;

From this, the total primary energy demand for the system cases analyzed will be:

$$PE = DE_{NG} \cdot f_{prim,del,NG} + DE_{El-Grid} \cdot f_{prim,del,El} - XE_{El-Grid} \cdot f_{prim,del,El} \tag{5}$$

For comparison between the micro-CHP system and the conventional reference system, the primary energy savings (PES) will be evaluated. This is given by the equation 6:

$$PES = \frac{PE_{TOT,GB} - PE_{TOT,CHP}}{PE_{TOT,GB}} \cdot 100\ \% \tag{6}$$

where

$PE_{TOT,GB}$	is the primary energy of fuel and electricity consumed by the conventional system;
$PE_{TOT,CHP}$	is the primary energy of fuel and electricity consumed by the CHP system;

The main purpose of the conversion to primary energy is to quantify the total amount of energy including conversion, transmission and distribution losses. In this way, different system can be compared on the actual energy consumption in its primary form before conversion. Energy conversion that occur onsite, as in the case of both gas boiler and CHP, accounts for the losses from the conversion in site energy because the building is assessed based on the fuel that is purchased. In this case, the primary energy factor for natural gas only accounts for the transmission and distribution losses. While for electricity purchased, the primary energy factor includes both conversion factors for converting the primary energy from its primary source to electricity as well as the transmission and distribution losses (Energy Star, 2011).

For the amount of primary energy used for the CHP to produce electricity and heat to be less than the primary energy used for the gas boiler to produce heat, and electricity imported from the grid, the conversion efficiency has to be better. The CHP has to produce these loads more efficiently. As the primary energy factor for natural gas is lower than the primary energy factor for electricity, the reduction in electricity imported from the grid will be beneficial. The net benefit of the CHP installation in primary energy consumption depends on how efficiently the CHP operates.

4.2 Based on energy efficiency

The overall energy efficiency depends on several factors; the prime mover, the size of the plant, the temperature at which the recovered heat can be utilized and conditioning and operating regime of the cogeneration unit. It is a measure of how efficient the energy is produced, distributed, stored, converted and used (Dorer & Weber, 2007).

This assessment is based on an analysis of the building energy supply system (cogeneration and other HVAC components) in terms of net power. Both system size and storage devices will affect the efficiency of the cogeneration device and system. Energy performance factors are a measure of how efficiently the delivered or primary energy is utilized by the analyzed building and its cogeneration system to cover the annual electricity and net heat demand of the building (Dorer & Weber, 2007). These efficiency factors describe the whole system including the storage tank, and are given by equation 7 and 8:

$$\eta_{DE} = \frac{net\ energy\ demand}{consumed\ delivered\ energies} = \frac{NE_{SH}+NE_{DHW}+NE_{El}}{\sum DE_i} \tag{7}$$

$$\eta_{PE} = \frac{net\ energy\ demand}{consumed\ primary\ energies} = \frac{NE_{SH}+NE_{DHW}+NE_{El}}{\sum PE_i} \tag{8}$$

Where

n_{DE}	is the energy performance factor of the system based on delivered energies;
n_{PE}	is the energy performance factor of the system based on primary energies;
DE_i	is the delivered energy of source *i*;
PE_i	is the primary energy of source *i*;

Using the substitution principle for the exported electricity produced by the cogeneration system, the delivered and primary energy denominators in equation 7 and 8 will be ($DE_{El\text{-}Grid} - DE_{El\text{-}Displaced}$) +

DE_{NG} and $(PE_{El\text{-}tGrid} - PE_{El\text{-}Displaced}) + PE_{NG}$, respectively. When evaluating the system performance it is better to use the efficiency based on primary energy as this takes into consideration the energy quality.

Efficiencies regarding the specific efficiencies of the CHP unit and the reference case of a condensing gas boiler are defined by equations 9-12, and are based on equations from EN 15316-4-4:2007 (NS-EN 15316-4-4:2007, July 2007).

CHP efficiency:
$$\eta_{CHP} = \frac{CHP\ System\ output}{CHP\ System\ input} = \frac{OE_{th,CHP} + OE_{El,CHP}}{DE_{Fuel}} \tag{9}$$

CHP thermal efficiency:
$$\eta_{th} = \frac{CHP\ thermal\ output}{CHP\ System\ input} = \frac{OE_{th,CHP}}{DE_{Fuel}} \tag{10}$$

CHP electrical efficiency:
$$\eta_{el} = \frac{CHP\ electrical\ output}{CHP\ System\ input} = \frac{OE_{El,CHP}}{DE_{Fuel}} \tag{11}$$

Boiler efficiency:
$$\eta_{boiler} = \frac{Boiler\ energy\ output}{Boiler\ energy\ Input} = \frac{OE_{th,boiler}}{DE_{Fuel}} \tag{12}$$

Where

$OE_{th,CHP}$	is the thermal output of the CHP device;
$OE_{El,CHP}$	is the electrical output of the CHP device;
$OE_{th,boiler}$	is the thermal output of the boiler;
DE_{Fuel}	is the gross input to the generator;

When evaluating the annual performance of the system, the following parameters should be taken into account:

- Water temperature (return/flow)
- Start/stop effects
- Part load operation
- Air inlet temperature
  (NS-EN 15316-4-4:2007, July 2007)

4.3 Based on reduced grid interaction

This assessment is based on an analysis of the building related to the reduced grid interaction. In this context, reduced grid interaction means reduced grid imports as exported electricity is assumed beneficial for CHP. This is only an assumption, and in reality a grid structure has to be organized to make electricity export feasible economically as well as environmentally. A feasibility analysis should be done in this context. However, this is not the main objective of this thesis, and the assumption of an existing electricity structure is considered as an appropriate approach for the comparison.

The annual electricity generated by the cogeneration unit $OE_{el,CHP}$ can either be demanded by the building or exported to the electricity grid, as illustrated in Figure 5. The amount exported or imported electricity depends on the demand of the building NE_{EL} compared to what is produced by the cogeneration device. If the electricity demand is higher than what is produced, electricity is imported. Likewise, if the electricity demand is lower than what is produced by the cogeneration device, electricity is exported.

The exported and delivered electricity from/to grid can be explained by equation 13 and 14, respectively:

$$XE_{El-NetGrid} = \begin{cases} XE_{El-Grid} - DE_{El-Grid} & if \quad XE_{El-Grid} > DE_{El-Grid} \\ 0 & if \quad XE_{El-Grid} \leq DE_{El-Grid} \end{cases} \qquad (13)$$

And

$$DE_{El-NetGrid} = \begin{cases} DE_{El-Grid} - XE_{El-Grid} & if \quad DE_{El-Grid} > XE_{El-Grid} \\ 0 & if \quad DE_{El-Grid} \leq XE_{El-Grid} \end{cases} \qquad (14)$$

Where,

$XE_{EL-NetGrid}$	is the net amount of electricity exported to the grid;
$DE_{EL-NetGrid}$	is the net amount of electricity delivered from the grid;

For the electricity produced locally from the CHP unit, delivered into the grid and consumed later on again from the grid, a grid loss factor, $fl_{El-Grid}$ may be considered. Then the electricity exported back to the grid can be defined by equation 15.

$$XE_{El-Grid} = \frac{OE_{El-Grid}}{(1+fl_{El-grid})} \qquad (15)$$

The loss factor is normally set to 10 % (Dorer & Weber, 2007).

4.4 Based on CO_2 savings

The last performance assessment methodology is based on CO_2 savings. Each of the case systems will be evaluated and compared with the reference system, and the corresponding $C0_2$ savings will be considered.

The CO_2 emissions are calculated by the equation 16:

$$m_{CO2} = \sum(DE_i \cdot K_{del,i}) - \sum(XE_i K_{exp,i}) \tag{16}$$

where,

m_{co2}	is the yearly CO_2 emissions, in kilograms;
DE_i	is the yearly delivered energy for the energy source *i*, in kWh;
XE_i	is the yearly exported energy for the energy source *I*, in kWh;
$K_{del,i}$	is the CO_2 factor for the delivered energy source *i*, in kg/kWh.
$K_{exp,i}$	is the CO_2 factor for the exported energy source *i*, in kg/kWh.

The coefficients $K_{del,i}$ and $K_{exp,i}$ can be the same value (NS-EN 15316-4-4:2007, July 2007), and this is assumed for the electricity in this report.

The performance criterion regarding emissions is the amount of CO_2 emitted by the CHP unit during the simulation period. For the CHP system, equation 16 reduces to equation 17:

$$mCO_2 = DE_{NG} \cdot K_{del,NG} + DE_{El} \cdot K_{del,El} - XE_{El} \cdot K_{exp,el} \tag{17}$$

The CO_2 factors of each unit delivered energy will be set. The CO_2 factor is the amount of carbon dioxide that is emitted to the atmosphere per unit delivered energy (NS 3031:2007+A1:2011, 2007/2011). In order to compare the CO_2 equivalent emissions by the CHP system and the reference system, equation 18 is used.

$$\Delta mCO_2 = \frac{mCO_2^{GB} - mCO_2^{CHP}}{mCO_2^{GB}} \cdot 100\ \% \tag{18}$$

Where,

ΔmCO_2	is the CO_2-savings using the CHP system, in % ;
mCO_2^{GB}	is the CO_2-emissions for the reference system, in kg/kWh;
mCO_2^{CHP}	is the CO_2-emissions for the CHP system, in kg/kWh;

This parameter gives us the avoided CO_2 emissions by implementing the micro- CHP system. The environmental impact is an important parameter when choosing one technology over another. As CHP is considered a low carbon technology, this assessment is an interesting point of view in evaluating the reliability of this statement. The emissions from an ICE generator depend on the operation and the fuel used. For an optimal operation regarding CO_2 emissions, a renewable fuel should be used, such as biogas and biodiesel.

5. CHP modeling:

The main objective with CHP modeling is to predict the thermal and electrical outputs of a cogeneration device as precise as possible. An ICE- plant consists of a generator linked to an engine, and a gas-to water heat exchanger and other system components such as circulation pumps and control configurations (Alanne, Söderholm, & Sirén, 2009).

The internal combustion engine used in this thesis is a Senertech ICE, which is based on an Otto cycle (Thomas, 2008). This unit is chosen because it exists already calibrated data for this engine in the simulation tool used, EnergyPlus. Since this engine is one of the market leading micro-CHP appliances, an evaluation of its optimal performance is of interest. In the simulations, the ICE cogeneration model consists of two sub-models:

1) An engine/generator unit model that predicts the heat production and the electrical generation in response to changing building energy demand.
2) A thermal storage model that predicts the energy and mass flows in all other portions of the ICE cogeneration systems.

A thermal storage is included as this ensures a more stable and secure operation of the CHP.

5.1 Model control volumes

The control volume of the model is illustrated in Figure 6.

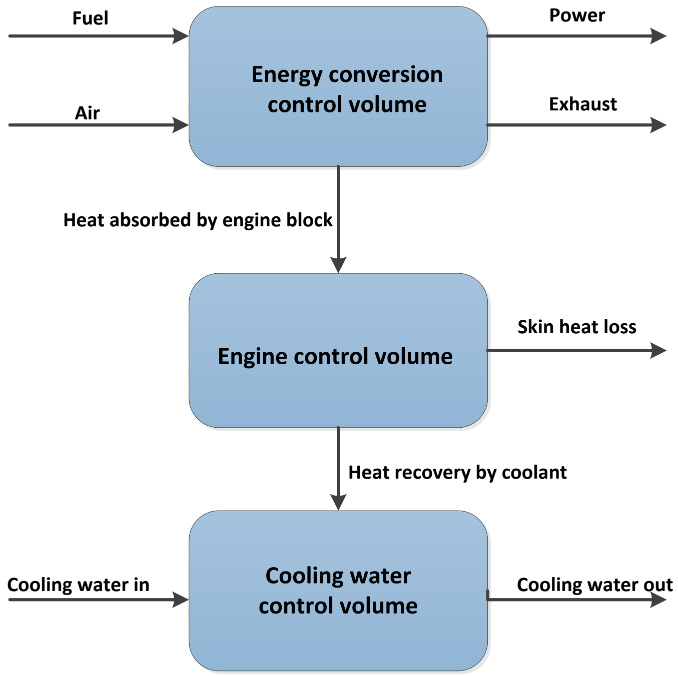

Figure 6: Control volume micro CHP

The model used is based on the generic ICE/Stirling engine model developed by Annex 42, and represents any combustion-based cogeneration device (Ian, Ferguson, Griffith, Kelly, & Weber, 2007). It represents 3 basic control volumes, the energy conversion control volume, the engine control volume and the cooling water control volume. The energy conversion control volume represents the

combustion process taking place within the cylinder of the engine unit. This expresses the conversion of fuel to electricity and heat in the engine under steady state conditions. This control volume uses generic polynomial performance equations derived by Annex 42 to relate the fuel consumption and the fuel heat release (heat absorbed by the engine block and exhaust gases) to the electrical power production of the device (Beausoleil-Morison, April 2008).
The efficiencies that relate useful energy production to fuel energy consumption are modelled as functions of the electrical output, coolant flow rate and coolant temperature. This modelling leads to more simplicity, ease of calibration, and reduced data collection burden (Beausoleil-Morison, April 2008). The drawback of this method is that the model must be calibrated using empirical data which results in that each set of model inputs only is applicable to one engine type, capacity and fuel type.

The engine control volume models the thermal transients in combustion engines. The energy balance is represented by a first order differential equation. This equation accounts for the thermal storage within the engine, skin losses of the engine and heat exchange between the engine and the cooling water control volume. The cooling water control volume represents the heat uptake from the engine to the cooling water. The equations behind the CHP model in EnergyPlus can be found in appendix F.

5.2 Simulation tool: EnergyPlus

As it was desired to use a simulation program with an already developed model of micro-CHP, EnergyPlus was chosen. EnergyPlus is chosen as it is a well-developed simulation tool, and the CHP model integrated is based on the international Energy Agency's Energy Conservation in Buildings and Community Systems (IEA ECBCS) Annex 42 for a Senertech internal combustion engine production unit. As the model is not normalized, and data on different micro-CHP units are limited, this model will be used in all evaluations of this thesis. Different system control and configurations will be applied to this model within a multifamily building to evaluate its performance in regard to the methodologies defined in section 4. Micro-CHP models have been implemented in the modelling platforms TRNSYS, ESP-r, EnergyPlus and IDA-ICE in order to be available to as broad a user base as possible (Beausoleil-Morison, April 2008). As EnergyPlus had available models of fuel cell, internal combustion engine and Stirling engine, this simulation tool was considered as a good fit for the work of this thesis. IDA-ICE was also considered, but since it here only was developed a model for fuel cells it was not used. This, because it was desired to evaluate today's most developed and market entered technology of the CHP, which is the internal combustion engine. Also it is noted that the existing models on fuel cells currently only calculate the steady-state performance at a particular simulation step, while the combustion engine based models account for thermal transient effects in cooling water outlet temperature as well (Beausoleil-Morrison, Ferguson, Griffith, Kelly, Maréchal, & Weber, 2007).

EnergyPlus is a collection of many program modules that works together to calculate the energy required for heating and cooling a building by using a variety of systems and energy sources. The program simulates the building and associated energy systems when they are exposed to different environmental and operating conditions. The tool receives inputs from text files in an .idf format, which makes it possible to define all necessary input values.

EnergyPlus enables the simulation of various buildings performances. It simulates dynamically the energy use and corresponding emissions in buildings. It makes it possible to simulate a building, the technical installations in buildings and the energy supply system within the building at the same time. In this way the output result for the energy demand of the building will be more realistic and exact than it would have been if the simulations of each part had been done separately.

The three system cases that will be simulated are defined in section 6, and EnergyPlus makes it possible to compare the energy demand of the energy supply solutions, and gather an understanding of the impact and benefits of choosing a micro-CHP system compared to the conventional system with a gas boiler and electricity imported from the grid. The possible operating strategies which will be applied to these models are defined in section 7.

5.3 Building

The building construction model used for simulation is drawn in ScetchUp, a 3D drawing tool to build buildings. The building model is based on the building made by bachelor students of Natasa Nord, and has 3 floors (Rausand & Iordache, 2012). The total floor area is of 450 m^2, each floor having 150 m^2. Each floor represents one thermal zone, which makes the total building structured with 3 thermal zones. Each floor has the same temperature levels as it is assumed to be three identical apartments. Therefore, the three zones made are gathered together to represent one united zone for the whole building. This is done to make it easier to check temperature levels and calculate the demand of the building. Also, the simpler the building model is, the easier it is to identify possible sources of errors. The building is shown in Figure 7 and Figure 8.

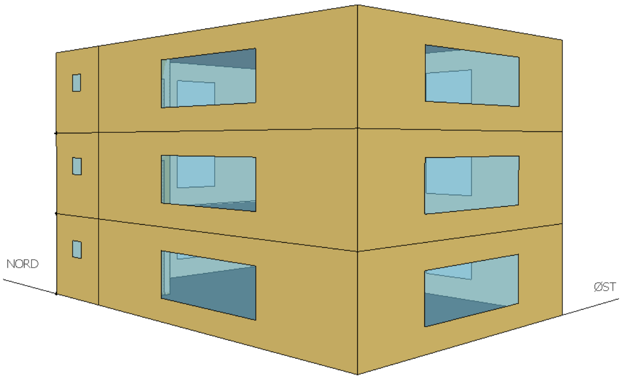

Figure 7: Building model seen from north

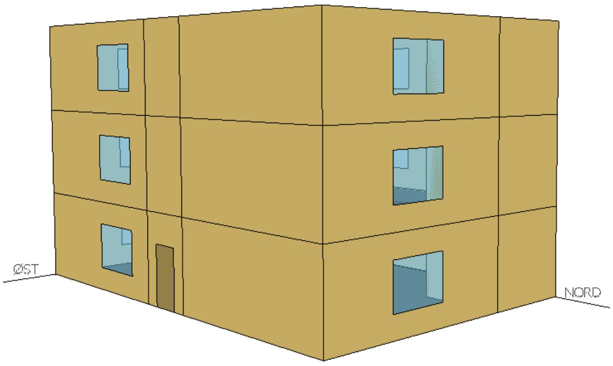

Figure 8: Building model seen from south

When making a building more energy efficient, one has to consider the following actions; reduce the energy demand of the building through efficient building construction, then apply energy efficient management of energy equipment within the building and energy recovery, and then choose the best energy supply technology.

	U – values (W/m2 K)				
	Walls	Ground floor	Roof	Window	Door
Building	0.16	0.145	0.113	1.016	1.181
TEK 10 measures	0.18	0.15	0.13	1.2	1.2

Table 1: U-values building shell

To reduce the energy demand of the building, the model has been built in a way that complies with the requirements in TEK10. As can be seen in Table 1, each building part fulfils the requirements (Kommunal- og regionaldepartamentet, 2010). The building is tight and compact, which makes the building shell robust and the transmission losses small.

The floor elevation of the building is 3 m, and the windows cover 63.36 m^2 of the walls. In TEK10 there is a requirement that the windows should not cover more than 20 % of the heated floor area of the building. Since the floor area of the building is 450 m^2, the windows cover 14.08 %, and the building therefore complies with the requirement (Kommunal- og regionaldepartamentet, 2010).

The energy demand of the building depends on the building construction and the external and internal loads. The external loads are affected by the weather, and therefore a weather file is used for the energy simulation of the building. EnergyPlus uses weather files with the format .epw to collect the necessary weather information for the location. The location of the building simulated in this project is Oslo Fornebu and the weather file is taken from EnergyPlus official website (U.S Department of Energy, 2013). The internal loads are defined as loads from people, electrical devices, lights and hot water equipment. The sizing of these loads depends on the type of building and the number of people living there. In this project there were assumed to live 4 people in each apartment, lights were defined to be 1.95 W/m^2, electric equipment of 1.80 W/m^2 (NS 3031:2007, 2007), and hot water equipment is supplied by a stratified hot water tank supplied with heat from either a gas boiler or the micro-CHP unit as will be mentioned later in the report. The size of these loads depends on the actual use of a room or a building. Some assumptions were therefore necessary to estimate these values in order to do the energy simulation of the building. The occupancy and activity profiles for the people in the building are based on the reference report of task 32 from IEA and can be found in appendix H (Heimrath & Haller, 2007).

5.4 Energy demand

The energy demand and heat balance of the building will be dynamically calculated by EnergyPlus. This means that it takes into consideration the changing outdoor climate over the simulation period, and the changing use thereafter. The use of each load is defined by schedules, and EnergyPlus uses differential equations to describe time varying conditions. The heat balance in the building is described by equations that form an algorithm. This algorithm calculates the heat energy condition at one point in time by taking basis on the previous point in time. Each period of time is one hour, and EnergyPlus makes it possible to define how many steps you would like to have in the period of time. Sixty steps are the maximum, where each minute is simulated. Normally six steps are sufficient and recommended to avoid errors in complex building calculation (EnergyPlus- US Department of Energy, 2013). Since the micro-CHP model developed by Annex 42 is not recommended to use with half-hourly or hourly time-step since their accuracy can be compromised, a minutely time-step (60 time-step per hour) is used for optimal accuracy in results (Beausoleil-Morrison, Ferguson, Griffith, Kelly, Maréchal, & Weber, 2007).

The building is made with simple balanced constant air ventilation (CAV) system predefined by EnergyPlus and water based floor heating as heat distribution system. A simple balanced CAV is implemented in the three main rooms, while the bathrooms are designed with a simple exhaust CAV using the outdoor air. For balanced ventilation an appropriate amount of fan heat is added to the stream of air entering. Both an intake and an exhaust fan are assumed to co-exist, and have the same flow rate and power consumption. The balanced ventilation system consumes twice the fan electricity than the exhaust ventilation as it employs two fans instead of one (EnergyPlus- US Department of Energy, 2013). Balanced ventilation is the most common form of ventilation used in buildings (Novakovic, Hanssen, Thue, Wangensteen, & Gjerstad, 2007).

Space heating and hot domestic tap water are supplied by a condensing gas boiler, a micro-CHP unit or a combination of both, depending on the system configuration used. This is the thermal demand of the building. The electrical demand goes to lighting in each room, electrical equipment and the electrical fan for ventilation. This is supplied by electricity imported from the grid in the case of a gas boiler system, and partly or fully by the ICE- generator in the case of a micro-CHP system.

The electrical demand of the building is modeled by taking basis on data from CREST domestic electricity demand model. The CREST model was downloaded from Loughborough University's homepage (Richardson & Thomson, 2010). The model provides a high-resolution model of domestic whole house electricity demand. It is possible to choose month, number of people in the dwelling and if it is a weekday or weekend. For the profiles made and used in the model, no differences are made between weekdays and weekends. This is done to ease the implementation of the load profiles in EnergyPlus, and it is considered that these differences will not have too much impact on the yearly electricity use. One yearly profile was made for the lighting appliances and another one for the electrical appliances. For comparison of the user profiles, the master thesis by Eline Rangøy is used (Rangøy, 2013). The electricity use of the electrical appliances depends on which electrical appliances that exist in the building. For the building model made in the master, the electrical appliances within the building are shown in Table 2.

	Mean cycle power
TV	128 W
Dish washer	1264 W
Microwave	1250 W
Washing machine	2056 W
Washer dryer	2500 W
Freezer	190 W
Fridge	112 W
PC	147 W
Hob	2125 W

Table 2: Mean cycle power of electrical appliances in the building (Richardson & Thomson, 2010)

Activity schedule are made on an hourly basis based on the daily consumption profiles made in the CREST domestic electricity demand model. It is assumed that the use of the electrical appliances is the same during the year. Daily profiles for each appliance is made, and thereafter weekly profiles based on the daily profiles are made. At the end, the yearly profiles are made based on the weekly profiles. Some appliances, which will not be used each day, have two options for the daily schedules. One option is when the appliance is not utilized, and the other when it is utilized. The use of each appliance can be seen in appendix J. These activity schedules are made based on the minutely power values for each appliances calculated in CREST model. The power output is then divided by the mean cycle power to get the fraction to be used as a schedule in EnergyPlus.

For the electrical appliances it is assumed that each week will be have the same load profiles. For the lighting, the demand profiles will be separated into four periods. One is defined from December to February (winter), one from March to May (spring), one from June to August (summer) and one from September to November (autumn). The lighting demand is taken from CREST domestic electricity demand model, doing one simulation for January to get the winter profile, one for May to get the spring profile, one for July to get the summer profile and then one for October to get the autumn profile. This approach is considered to give a sufficient lighting profile throughout the year. In reality there are slightly differences from day to day and month to month, but moreover this approach will represent the buildings lighting demand sufficiently. The lighting profiles can be found in appendix I.

When making the reference load profiles for electricity in EnergyPlus, schedules had to be made to represent the usage pattern from the CREST domestic electricity model. As the values from the model were on a minute basis, these had to be converted to hourly values to be implemented in EnergyPlus. From these hourly values, schedules were made for a day, and from this day schedule for a month were made, and then for a whole year. The schedules objects in EnergyPlus allows the user to influence scheduling of many items (such as occupancy density, lighting, thermostatic controls, occupancy activity etc.) (EnergyPlus- US Department of Energy, 2013).

The day schedules perform the assignment of pieces of information across a 24 hour day. This can occur in various fashions including a 1-per hour assignment, a user specified interval scheme or a list of values that represent an hour or portion of an hour. The day schedules made in the models are based on hourly values to represent the demand. The week schedule object(s) perform the task of assigning the day schedule to day types in the simulation. As some devices may be used some days, but not others, a week schedule has to be made. Then a combination of the daily profiles for each device is set together on a weekly basis. The yearly schedule is used to cover the entire year using references to week schedules (which in turn reference day schedules). If the entered schedule does not cover the entire year, a fatal error will result (EnergyPlus- US Department of Energy, 2013).

For flexibility, a schedule can be entered in “one fell swoop”. Schedule:Compact object are used to model all the features of the schedule components in a single command. Each schedule made as compact must cover all days of the year (EnergyPlus- US Department of Energy, 2013). The schedule for hot water usage, activity schedules for people etc. are made based on this schedule form and can be seen in appendix H.

6. Description of system cases

6.1 Energy Supply system

In the case of micro-CHP system, the total energy supply system is illustrated in Figure 9. For the reference case, a gas boiler is coupled to the cylindrical hot water storage tank instead of the CHP device. Space heating water for the low radiant floor heating is tapped directly from the storage tank, while domestic hot water is heated by a heat exchanger from the storage tank. Electricity demand, which is not covered by the CHP unit, will be imported from the grid. A controller is placed in the storage tank to assure that the tank temperature is acceptable and the deliver from the supply device corresponds to the demand of the building.

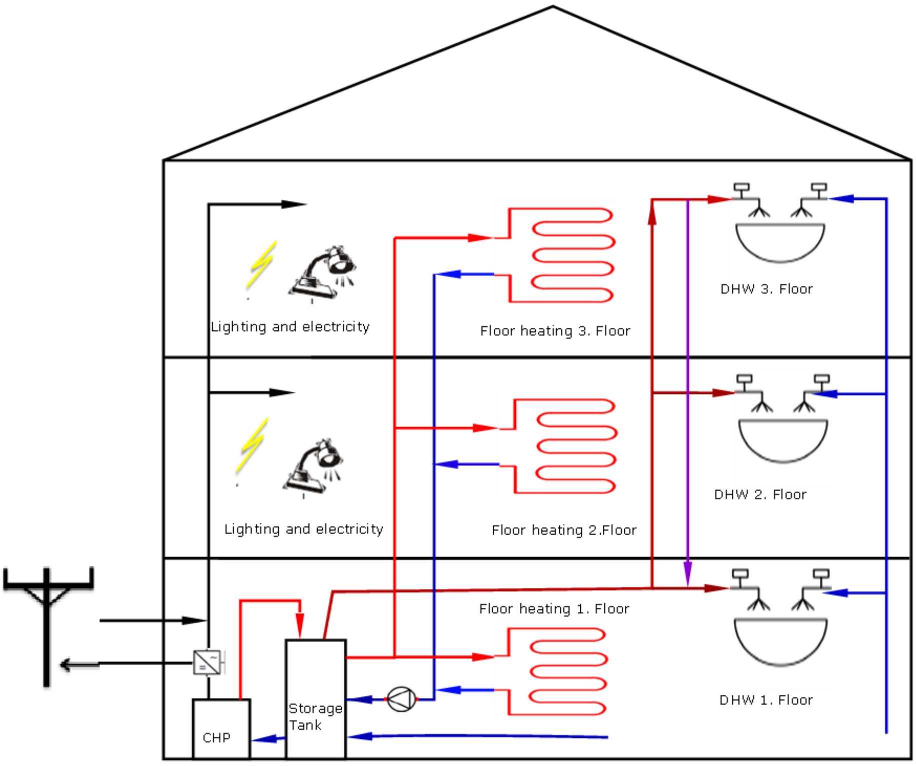

Figure 9: Supply system in simulation model.

As it can be seen, the thermal demand of the building is the domestic hot water heating and the radiant floor heating in each floor. Hydronic radiant floor heating system represents a better choice for low energy buildings as it brings higher exergy efficiency and increases thermal comfort (Hugo, Zmeureanu, & Rivard). The floor heating system is set to have a supply temperature of 40°C and a return temperature of 35°C based on the heating system parameters from Task 32 from the IEA (Heimrath & Haller, 2007). A circulation pump is implemented in the system to make the water circulate. Floor heating is schedule to be on during the heating season and off during the summer. The heating season is assumed to be from 20/09 to 01/06, which is a little longer than the heating season defined in Hugo, Zmeureanu and Rivards work (Hugo, Zmeureanu, & Rivard), as the weather properties is Oslo climate. The domestic hot tap water is designed with a supply temperature of 55 °C and cold water supply with a temperature of 7°C. The target temperature at which the cold and hot water is mixed to attain is 38°C. The amount of heat needed for space heating in comparison with domestic hot water during a year depends on the building size, the thermal insulation, ventilation, passive solar use, internal heat loads as well as the number of people in the building (IEA, 2000). To be able to supply the two heat consumers (DHW and space heating), the supply water needs to be available at two different temperature levels. This can be done either by implementing two separate storage tanks, or implementing one single storage tank with stratification. In a stratified storage mixing is avoided, and there will be different temperature levels in the tank. Hot water has a lower density than cold water, and therefore will the hot water always be located in the upper part of the storage tank, and the colder water will be found at the bottom. The stratification in the tank can be built up by adding heat to the tank (charging) or removing heat from the tank (discharging). This can be done either indirectly or directly. If it is done directly, water is added to or removed from the storage via water inlets/outlets of the tank. If it is done indirectly, heat exchangers are placed inside the storage surrounded by water. The indirectly charging/discharging has higher possibility of destroying existing stratification in the tank as it tend to create zones of uniform temperature above (in the case of charging) or below (in the case of discharging) the heat exchanger. The direct charging/discharging can create good stratification, but this requires that the inlets and outlets are placed correctly according to the desired temperature levels (Suter, Weiss, & Letz, 2000). As the stratified water heater does only have the possibility to model one use side outlet and one source side outlet, the loop set point temperature will be based on the domestic hot water as this has the highest temperature level. The loop temperature is therefore set to have a flow temperature of 55°C and a temperature difference of 40°C, where each load has the set temperatures defined in the design specifications.

As the building simulated is placed in Oslo climate, it is assumed that no cooling is required during the year. Since no cooling device will be implemented in the model, slightly high room temperatures may happen during the summer since the building envelope is well insulated.

6.2 System configurations

Different system configurations:

I. Reference case: gas boiler system with heat storage.
II. ICE- based micro- CHP system with heat storage.
III. ICE-based micro-CHP system with heat storage and gas boiler as auxiliary heater.

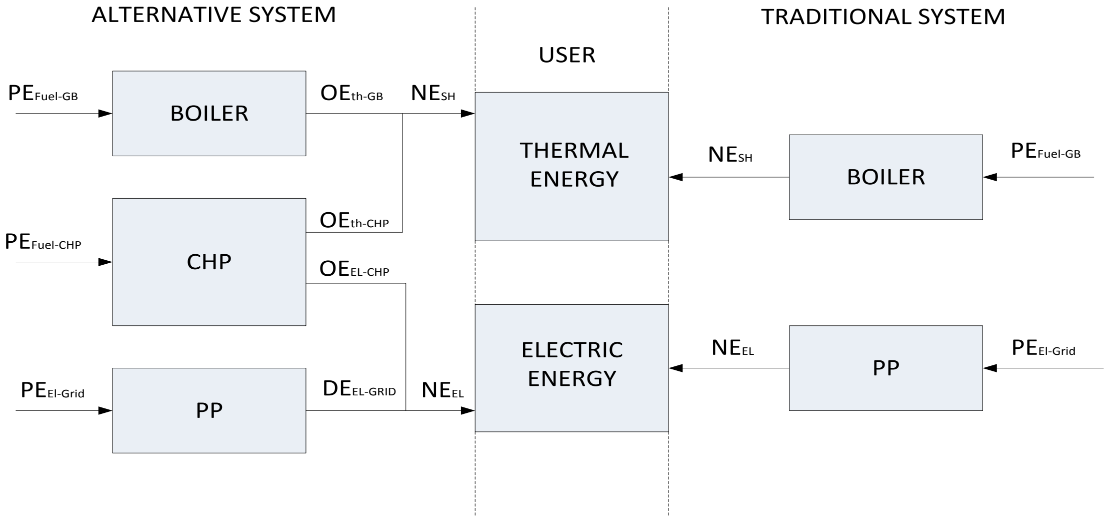

Figure 10: Energy flows of compared system (I and III)

Figure 10 show the basic principle of the comparison between the traditional system of a gas boiler and grid electricity and the alternative system with a CHP device, gas boiler and grid electricity.

To be able to compare the effect of micro-CHP integrated in a residential building, a model for a conventional system with a gas boiler has been developed. To be able to compare the systems properly, it is important that the reference case uses the same model for the building and the respective heat distribution and ventilation system, the same level of detail considering parasitic losses and distribution losses, the same DHW and electrical load profiles and the same weather files (Dorer & Weber, 2007). As no changes will be done to the building or the distribution system within the building, these requirements are fulfilled. The systems will be compared after the methodologies reviewed in section 4. All cases are modeled with thermal storage to assure a more continuously operation of the gas boiler and the CHP device.

For the CHP case, another possibility would be electrical storage to store the surplus electricity generated. This could be stored in fuel cells or batteries for use when the electricity demand is higher than the generated electricity. However, in this study this type of storage is not considered, and all electricity surplus generated by the cogeneration system is directly delivered to the grid.

All pipes in the system models are made adiabatic, which means that there will be no heat losses though the piping of the system. In real life, there would however be some losses through the piping.

6.2.1 Definition of storage tank

As a large part of the building sector is characterized by a highly variable demand, the system cases are modeled with a storage tank. This eases the operation of the plant, as it meets the mismatch between production and demand (Celador, Odriozola, & Sala, 2011). The tank used for hot water storage is a vertical stratified cylindrical tank. The tank shape is chosen to be vertical cylindrical in EnergyPlus because this describes best residential water heaters (EnergyPlus- US Department of Energy, 2013). Having a thermal storage tank in cooperation with CHP prolongs the yearly operation time and allows the CHP-unit to operate more continuously. This avoids the frequent occurrence of transient behavior during start-up and shutdown (Rosato, Sibilio, & Ciampi, February 2013).

Micro-CHP appliances are often installed with buffer tanks to reduce cycling and increase the likelihood of long periods of operation (SEAI, 2011). This is desired as it maximizes the electricity produced, and wear on the engine is reduces as there will be less frequent stop/start cycles. A buffer tank of 1 m3 can buffer 23kWh between 80°C and 60°C, which says that it can store about 2 hours of operation for the micro-CHP device with a thermal output of 12kW (SEAI, 2011). Larger tank sizes may lead to higher operating times of the CHP as this makes it possible to store more produced heat in the buffer tank. However, if buffer tanks are oversized, the standing heat losses can become large, especially if the tank is located outside the heated part of the building. Therefore, the tank used in the simulation is placed inside the heated part of the building to avoid large losses and the skin losses of the water tank will contribute to the internal gains of the building. It is also modelled with good insulation to minimize tank losses. The level of insulation of the tank and the system characteristics have an impact of how the losses in the system will be. The tank's U-value is calculated based on the following equation taken from PhD. Student Usman Ijaz Dar's work (NTNU, 2014):

$$U_{Tank} = \frac{0.042}{thk} \times \max(1.2, \left(2 - \frac{V_{tank}}{10}\right)) \qquad (19)$$

Where,

U_{Tank} is the uniform skin loss coefficient per area to ambient temperature, in W/m^{2}K;

thk is the thickness of insulation, in m;

V_{tank} is the volume of the tank, in m^3.

The uniform skin loss coefficient accounts for the tank insulation and applies during both off- and on cycle operation. In the tank modelling, it is assumed that this represents the only tank losses and no overall losses at any particular node to account for thermal shorting due to pipe penetration, water heater feet or any loss effects are included (EnergyPlus- US Department of Energy, 2013). The equation shows that for increased tank sizes the uniform skin loss coefficient (U-value) of the tank becomes smaller due to that the thermal bridges become smaller with increased tank size. The off-cycle losses are set to zero in the design specifications for the tank, and the following insulation thickness is set to 15 cm to give the tank a good U-value. There are assumed no losses due to pipe connections on supply and demand side, and it is therefore likely to believe that the corresponding tank losses would have been higher in real life installations.

The heat loss from a storage tank is usually expressed through the product of the heat loss coefficient of the storage and the temperature difference between the storage and the surroundings (Departmant of Civil Engineering Technical Univercity of Denmark, 2013). The tank used in the modelling will have more stable temperature throughout the storage, and therefore it is assumed that the thickness of insulation in the tank is the same for the side, the top and for the bottom. If there were to be larger differences in temperatures in the tank, a thicker insulation should be used in the top of the tank as the heat losses would have been greater here.

The tank height depends on the volume, and is calculated by the following formula, also given from PhD. Student Usman Ijaz Dar's work (NTNU, 2014):

$$H_{Tank} = \max(\min(2.2, 1.78 + 0.39 \cdot \log(V_{Tank})), 0.8) \qquad (20)$$

In EnergyPlus the water heater objects are components for storing and heating water. The stratified water heater used in the simulations is coupled to a plant loop simulation. The water heater applications are for domestic hot water heating, low-temperature radiant space heating, and energy storage of waste heat recovery from the gas boiler or the micro-CHP unit (EnergyPlus- US Department of Energy, 2013).

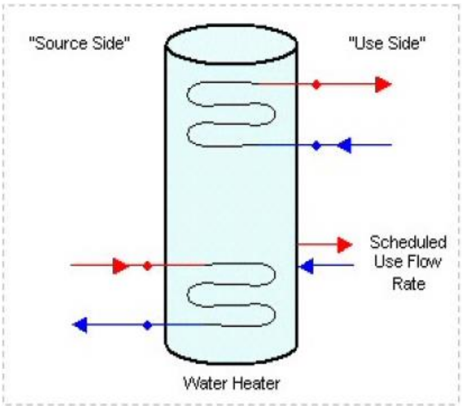

Figure 11: Water heater configuration

In both configuration systems, the water heater is coupled together with the corresponding plant loop. When the water heater is coupled in this way, it has an inlet node and an outlet node on the "source side" and an inlet and outlet node on the "use side" as seen in Figure 11. On the "source side", cold water is drawn from the tank and warmer water is returned. On the "use side", hot water is taken from the tank, and cooler water is returned from the outlet of the heating system or from the cold water supply mains (EnergyPlus- US Department of Energy, 2013). The source side is towards the CHP or gas boiler, while the use side is toward the heating loads of the building.

A stratified water heater is used because it has the advantage of giving a better modeling of thermal storage applications, which rely on stratification to improve heat transfer performance. Thermal stratification increases the performance of the heat storage in hot water tanks. This is because of the different density of hot and cold layers of water within the tank, which makes the hot water remaining on the top and the cold water on the bottom. This makes it possible to have higher temperatures sent to the load and lower ones to the heat source (Celador, Odriozola, & Sala, 2011).

The stratified water heater is divided into 10 nodes of equal volume. These nodes are coupled by vertical conduction effects, intermodal fluid flow, and temperature inversion mixing (EnergyPlus- US Department of Energy, 2013). The model solves the differential equations governing the energy balances on the nodes simultaneously using a numerical method. The object allows simulation of two heating elements. These two elements can cycle on and off to maintain the node temperature within the dead band. The dead band tells the sensor how many degrees the indoor temperature is allowed to decrease below the set temperature. It reflects the maximum temperature difference between the set point and the cut-in temperature for water heater 1 and 2, respectively.

The tank volume is the actual volume of the fluid in the tank, measured in m^3. For the systems, the heat storage tank size used is 500 liters, which equals 0.5 m^3. The parameters for the water heater is taken from the existing example file for micro-cogeneration based on annex 42 in EnergyPlus with modification in tank size, height and U-value based on equation 19 and 20, and can be found in appendix A. The engineering description of the stratified tank can be found in appendix G.

To model the stratification in the tank, the inlet mode of the entering fluid from the use and source sides can either be set to fixed or seeking. If it is set to fixed mode, the fluid will enter at the fixed height specified. If it is set to seeking mode, the fluid “seeks out” the stratified node that is closest to the inlet temperature and adds all flow to that node. Maximum stratification is provided in the seeking mode (EnergyPlus- US Department of Energy, 2013). Seeking mode is therefore chosen for the stratified tank used in this thesis.

6.2.2 Definition of reference system with condensing gas boiler

The reference system consists of a condensing gas boiler coupled together with a stratified storage tank to produce heat, and electricity is directly imported from the grid. The system is illustrated in Figure 12.

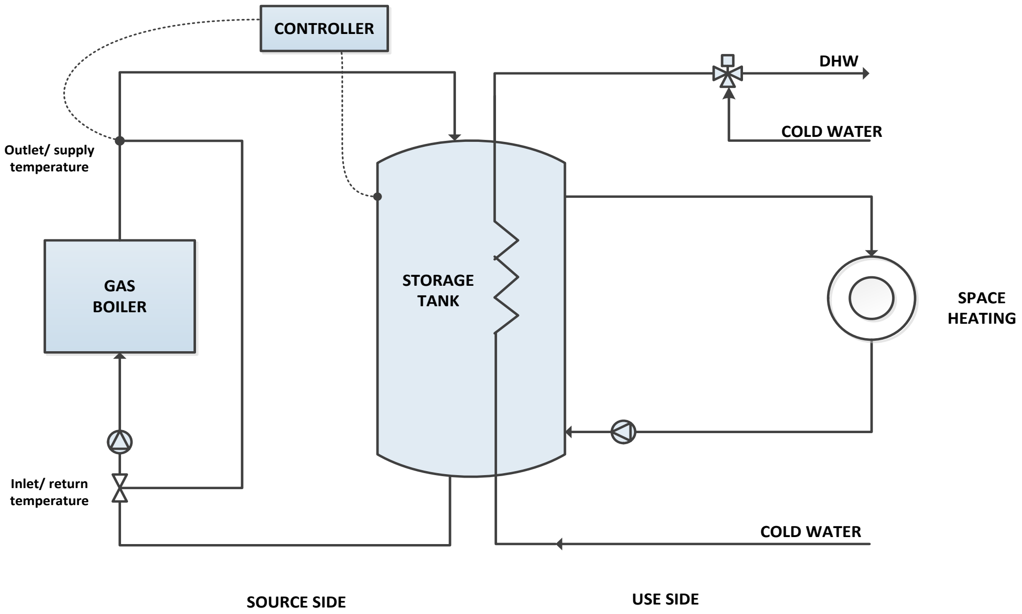

Figure 12: Configuration system with gas boiler

The space heating illustrates the floor heating in the main rooms and the bathrooms in the three floors of the building. When energy is delivered to different heat loads, EnergyPlus uses a concept of a splitter and a mixer to divide and mix the stream of heat from the heat supply source. The condensing gas boiler has a nominal efficiency of 0.89 and a capacity of 25 000 kW and is fuelled with natural gas. The gas boiler is designed to cover the entire heat demand. All the electrical devices in the building are covered by electricity imported from the grid.

The efficiency of the boiler is based on nominal thermal efficiency. This nominal efficiency input is based on higher heating value, and efficiencies from manufacturer based on lower heating value have to be converted to an efficiency based on higher heating value. For a more accurate representation of the performance, a normalized efficiency performance curve can be used, but it is not a required input. To modulate the condensation effect of the gas boiler, a normalized efficiency curve was therefore chosen. Using only the nominal efficiency, the fuel consumption output will be the theoretical fuel use. The fuel used by the boiler model is calculated by equations 21 and 22:

$$TheoreticalFuelUse = \frac{Boiler\ Load}{Nominal\ Thermal\ Efficiency} \tag{21}$$

$$FuelUsed = \frac{TheoreticalFuelUse}{Normalized\ Boiler\ Efficiency\ Curve\ Output} \tag{22}$$

The nominal thermal efficiency of the boiler is the heating efficiency of the boiler’s burner, and relative to the higher heating value of the fuel at a part load ratio(PLR) of 1.0 and the temperature entered for the Design Boiler Water Outlet Temp (EnergyPlus- US Department of Energy, 2013). A normalized boiler efficiency curve is used to describe the normalized heating efficiency of the boiler’s burner as the efficiency is not constant and depends on factors such as the PLR and the boiler outlet water temperature (T_w). A biquadric curve is used to model the efficiency of the condensing gas boiler. The biquadric curve uses the equation 23 to model the efficiency:

$$BiQuadric \rightarrow Eff = A_0 + A_1 PLR + A_2 PLR^2 + A_3 T_w + A_4 T_w^2 + A_5 PLR\ T_w \tag{23}$$

The specifications of the boiler and the efficiency value used are given in appendix B. These values are based on the condensing gas boiler example in the input/output reference of EnergyPlus (EnergyPlus- US Department of Energy, 2013).

6.2.3 Definition of ICE- based micro-CHP systems

The existing system model for micro-CHP developed in EnergyPlus is applicable for both internal combustion and Stirling cycle engines. Since an example file with already existing parameters was developed for an ICE engine device, this is used. The calibration parameters are taken from measurements conducted by the IEA/ECBCS Annex 42 for a Senertech internal combustion engine production unit (EnergyPlus- US Department of Energy, 2013). The model might be used for other types of residential CHP devices as well, but since it was developed for the two earlier mentioned technologies, no modifications in the model parameters will be done. This is because the model is not normalized, and therefore performance coefficient developed for one type and capacity of CHP device cannot be used for a device with a different capacity.

In the model, both the electrical efficiency, η_e, and the thermal efficiency, η_q, is a function of the cooling water mass flow rate, m_{cw}, the temperature of the cooling water at the inlet, $T_{cw,}$ and the steady-state net electrical power produced, $P_{net,ss}$. The ICE-generator has a rated electric power output of 5500 W, and a rated thermal to electrical power ratio of 2,444. This implies that the maximum rated thermal output is 13 450 W. The generator has a rated thermal efficiency of 0.66 and an electrical efficiency of 0.27. These efficiencies are based on the lower heating value of the fuel, while for the evaluation of the systems compared to the conventional system are based on higher heating value of the fuel. This will result in slightly lower efficiencies than it would be if the lower heating value of the fuel where to be used. Higher heating value is used as the standard output of EnergyPlus. The system will first be analyzed in a heat-demand-following operation scheme as the generator is designed to cover the entire energy demand of the building. Then load management will be applied to this system configuration. Load management will be further discussed in section 7.1.

For real life installation, the micro-CHP device would have been placed in a technical room in the basement of the building. As the building model used in the project is not designed with a technical room, the generator is placed inside the building. This result in some skin losses from the generator to the building, which will result in a slightly reduced energy demand compared to gas boiler. However, this amount is small and will not result in dramatically changes. In theory, according to the input/output reference of EnergyPlus (EnergyPlus- US Department of Energy, 2013), the field zone name could be left blank if the cogeneration device would be wanted outside or not to add skin losses to a zone. However, during the modeling this was not possible as the simulations would not run without this specification.

EnergyPlus uses nodes to connect systems together. The micro-CHP device is modeled with water nodes and air nodes, which couple the generator together with the rest of the system. The cooling water inlet node and a cooling water outlet node connect the generator to the plant loop that receives heat, in our case to the stratified water heater. The cooling water inlet node is where the cooling water for the CHP device enters, and the cooling water outlet node is where it exits. The cooling water inlet node is connected to the storage tank source side outlet node, which draws cooling water from the tank. The cooling water outlet node is connected to the storage tank source side inlet node, which supplies the tank with hot water.

The air inlet node supplies the CHP unit with air for use inside the generator, while the air outlet node receives the exhaust from the CHP unit. The predefined specifications for the micro-CHP unit used can be found in appendix C.

The system is illustrated in Figure 13.

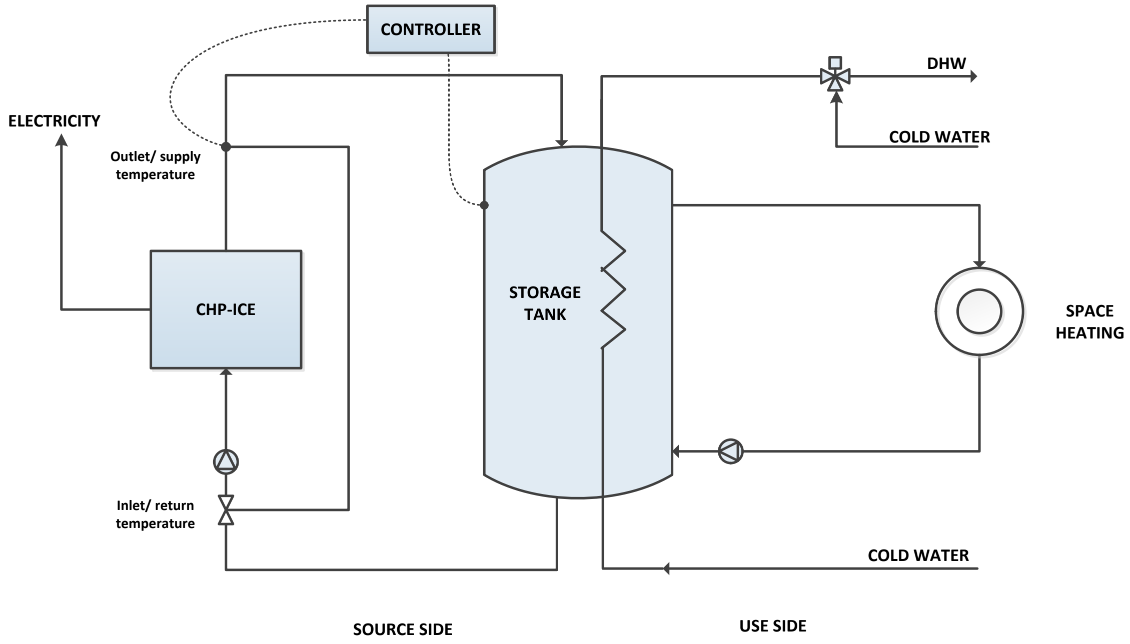

Figure 13: Configuration system with CHP.

In the specifications of the model, maximum and minimum electrical power restrictions are set. If the electrical demand is higher than the maximum electrical power defined, the unit will restrict its output to this level. If the electrical demand is less than the minimum electric power, the unit will hold its output to this level. The maximum restrictions will be the rated thermal output of the device, as it is modeled in a follow thermal mode. The minimum cooling water flow rate is defined to protect the device from overheating. This is the minimum flow rate of cooling water that must be available for the unit to operate, and if the flow is less than this, the generator will shut down. As will be seen in the configurations later in the report, this factor will have its impact on the system in follow electrical mode. Also there is set a maximum cooling water temperature at the inlet or outlet to protect from overheating. This maximum value is set to be 80°C in all cases simulated and is taken from the existing example file in EnergyPlus (EnergyPlus- US Department of Energy, 2013). If the generator exceeds this limit, the generator will shut down. This is connected to a controller in the storage tank, which controls the cooling water outlet. In appendix I, the implementation of the model in EnergyPlus can be seen with all the connecting nodes. The cooling water temperature is measured at node 2.

In the modeling of the combustion micro-CHP device model in EnergyPlus, an enhanced system- level approach was deployed. This means that the device is represented as a single functional element. However, when the governing balance equations were formulated, the physical processes in each control volume where considered. Due to a lack in internal details of the device, empirically derived expressions has been used to represents these processes (Beausoleil-Morison, April 2008).

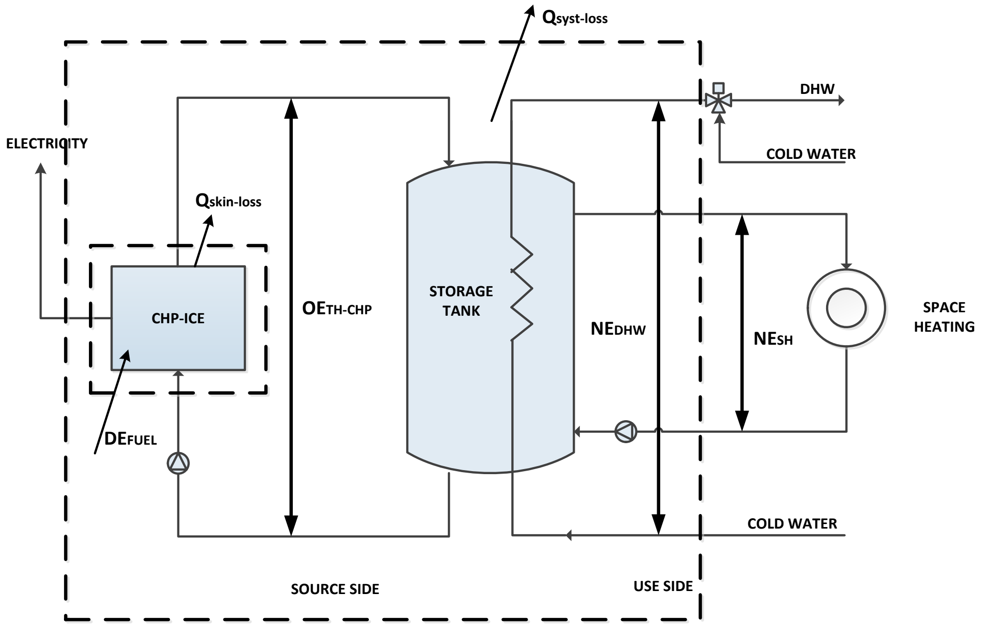

Figure 14: Control volumes of the CHP system

Figure 14 shows the control volumes of the CHP system, with the corresponding energy input and outputs in the system as defined in section 4. The energy supplied to the loads equals the thermal output of the generator minus the energy loss of the storage tank. In this illustration the skin losses of the CHP device and the total system losses are included. The system losses include the storage loss and the distribution loss. It is desirable that these losses are as low as possible to achieve a high allover performance. In this study the heat dumped from the tank is considered as losses, which will affect the system performance.

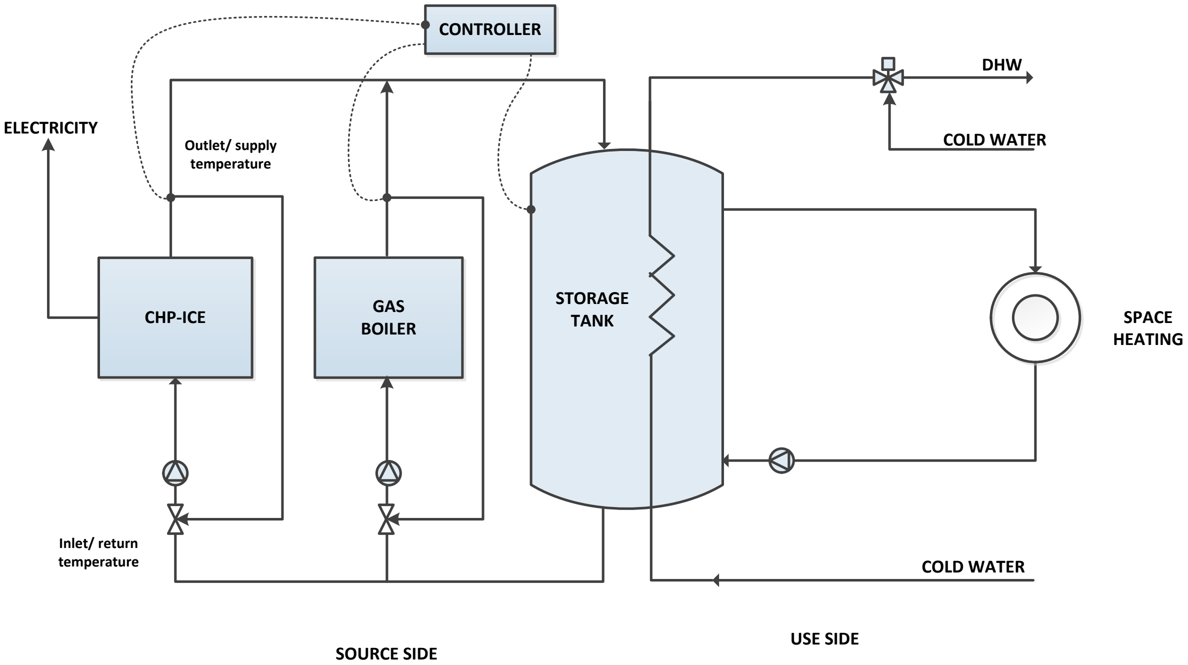

Figure 15: Configuration system with CHP and gas boiler

The system illustrated in Figure 15, has an auxiliary boiler coupled in the supply side of the system. The gas boiler and the CHP is coupled in parallel due to that it is used a condensing gas boiler and the design system has low return flow temperature. Parallel integration is often used for larger micro-CHP units and more complex heating systems (Simader, Krawinkler, & Trnka, March 2006). This is done to make it possible to let the gas boiler cover the peak loads, and ensure a more stable operation of the CHP as it can produce the same amount of electricity and heat during the whole day. The implementation of a gas boiler is relevant if the CHP device is set to follow the electrical demand instead of the thermal demand. This is because the thermal demand of the building used in the simulations has higher thermal demand than electrical demand throughout the year, except for some peaks, which makes it necessary with an auxiliary boiler to cover the thermal demand not covered by the CHP. This system scheme is therefore applied to all cases simulated without follow thermal mode. Operational strategies reviewed in section 7.2 will be applied to this model. In EnergyPlus, this is modeled by a plant equipment list in the supply loop. The first equipment defined in this list has the highest priority and will run whenever available. When the first equipment is not available or has produced its upper capacity, the next equipment in the list will be applied to cover the rest (EnergyPlus- US Department of Energy, 2013). In this way, a modelling of using the CHP to cover base load and the gas boiler to cover the peaks is enabled. A sketch of the model implementation with the following node placements can be seen in appendix M. The operation of the CHP and gas boiler will be based on the supply loop temperature at node 8. When the CHP device is not able to keep the desired supply temperature, the gas boiler cut in to ensure that the desired temperature is set for the loop. Similarly when the temperature exceeds its upper limit, the generator shut down to protect from overheating.

6.3 Control configurations

Boiler control:

How the boiler operates depend on the boiler flow mode chosen. There are three choices for operating mode of the expected flow behavior. These are “NotModulated”, “Constant flow”, and “leavingSetpointModulated”. The first option can be used for both variable and constant pump arrangements, and the boiler is passive in the sense that it can operate at varying flow rates although it makes a nominal request for its design flow rate. The “Constant flow” is used when there is a constant speed pumping. The “leavingSetpointModulated” makes the boiler model to internally vary the flow rate so that the temperature leaving the boiler matches a set point (EnergyPlus- US Department of Energy, 2013). The chosen flow mode in the system models is “NotModulated” as there is placed a variable speed pump at the inlet of the boiler loop. For the gas boiler coupled with the CHP as an auxiliary boiler, it is activated when the CHP device is not able to meet the heat demand of the loop.

Micro- CHP control mode:

For the micro-CHP systems analyzed, a heat- demand-following and an electric-demand following control mode is used. These control modes and further adaptions of these will be reviewed in section 7.2. For the CHP system without auxiliary boiler, heat-led operation is the only supply option for heat as it has to be integrated to cover the whole thermal demand.

Control for the micro-CHP generator:

The generator is modeled as always on for all cases, meaning that the device is available any time the value is greater than zero. This means that the generator might consume standby power at times when there is no power requested from the electric load center.

To control the cooling water mass flow rate, an internal control is chosen. This indicates that the flow of cooling water is controlled inside the CHP device, similarly to an automobile's thermostat (EnergyPlus- US Department of Energy, 2013). The maximum cooling water temperature is set to be 80°C, as can be seen in the model specifications in appendix C. With the internal control, the generator turns off when the internally-measured return temperature (generator sensor) exceeds the set value (SenerTec UK- GB, 2014). The minimum cooling water flow rate is set to be 0.055 kg/s to protect the generator from overheating. If the cooling water flow rate is low, the system may overheat and must be deactivated (Beausoleil-Morrison, Ferguson, Griffith, Kelly, Maréchal, & Weber, 2007).

Stratified heat tank storage control:
To avoid overheating of the storage, a maximum temperature limit is set for the storage tank. This is the temperature where the tank water becomes dangerously hot and is vented through boiling or an automatic safety. Any extra heat added to the tank after this maximum temperature is immediately vented. This temperature is set to 98°C.

Pump control:
Both pumps in the plant loops (supply loop and demand loop) are modeled with intermittent control type. This means that if there is no load on the loop, the pumps can shut down. Otherwise, the pumps will operate and select a flow which is somewhere between the minimum and maximum flow limits defined. The pumps will try to meet the flow request made by the demand side components. In the supply loop (loop between the CHP device and the stratified tank), the stratified tank will be the demand side component. Similarly for the demand loop (loop between the stratified tank and the space heating and domestic hot water components), the demand side components will be the space heating and domestic hot water (EnergyPlus- US Department of Energy, 2013). The pump specifications can be seen in appendix E.

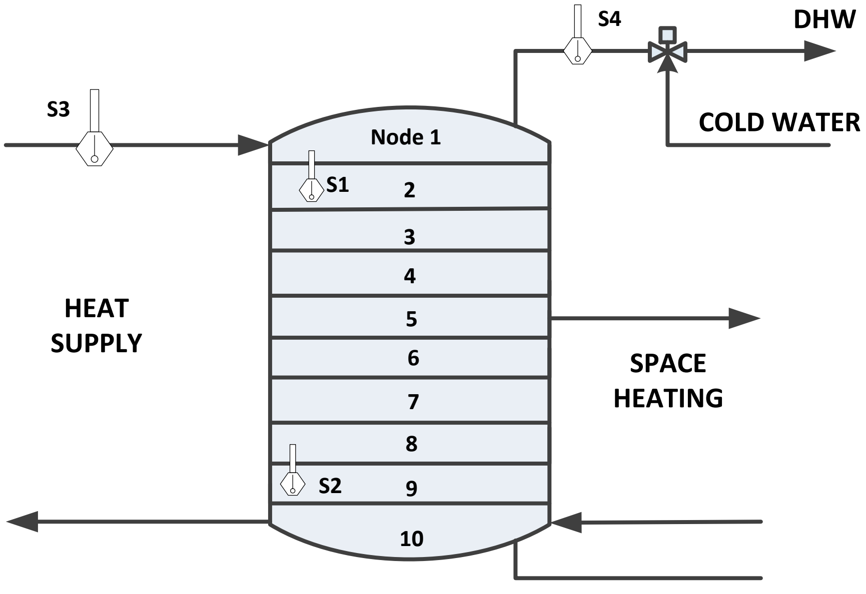

Figure 16: Temperature control system configurations

To control the system configurations, temperature sensors are placed on the supply water from the heat source equipment, in the storage tank and on the supply water to domestic hot water to ensure acceptable temperatures in the system. In EnergyPlus, the modelling of the controls is based on temperature sensors on certain points in the supply loop and the demand loop. Also, the tank is controlled to not exceed its maximum temperature limit, and does also have a set point temperature to follow. Sensor S3 in Figure 16 ensures that the supply water is set to have a temperature of 70°C until the storage tank sensor S1 is heated up to its temperature set point of 60°C. The supply temperature in the supply loop is set to be 70°C to fit the specific DHW user's set temperature of 55°C. If the supply equipment does not provide sufficient heat to keep the set point temperature level, a heater device in the tank is turned on to provide the rest. Sensor S1 is set to have a set point temperature with a dead band of 10°C, which means that if the temperature in the tank sinks below 50°C, water heater 1 is turned on. Similarly if the temperature exceeds 70°C, the supply equipment is turned off. Sensor S2 has a set point temperature of 50°C with a dead band of 10°C. This means that if the temperature falls below 40°C heater 2 is turned on. This sensor is however just a back-up and the heater capacity of heater 2 is 0 as it is assumed that heater 1 at sensor S1 is sufficient as back-up. Sensor S4 ensures that the domestic hot water is provided at a minimum temperature of 55°C to avoid legionella. From this, cold and warm water is mixed to attain its target temperature of 38°C. For the electrical follow operation with thermal surplus restriction, a supplementary control is set on sensor S1 to avoid overheating of tank as the operation is not controlled by the tank sensors but of the electrical demand of the building. In this operation, the heat supply from the supply equipment will be forced off if the temperature at sensor S1 is measured to exceed 75°C. In EnergyPlus, this will correspond to the temperature at node 1 in the tank. The minimum and maximum allowable return temperature to the CHP device is set to 10°C and 70°C, respectively, based on Senertech instruction document for installation (Dachs Senertec UK, 2014).

Theoretically, the domestic hot water supply will be taken from the top of the tank, while supply water for floor heating will be taken from a node placed lower in the tank. This is the purpose of the stratification effect of the tank, to achieve different temperature levels in the tank (Streicher, Heimrath, & Bales, 2007). However, the stratified tank in EnergyPlus is only constructed with one possible outlet and inlet on the demand side of the tank, where in real life constructions multiple outlets of the tank are possible. This is because of the concept of a mixer and a splitter who splits the supply water to the different loads depending on the heat requirement demanded by each of the loads. Therefore, the supply temperatures to the low radiant heating system will be higher than what was predicted in the design requirements. However, as the simulation program is constructed in this way, the elevated temperatures will not affect the space heating demand. The demand demanded by the floor heating equipment will be the same as the mass flow of water is changed depending on the water inlet temperature and the heat demanded by the device. The ΔT value is the same, and that is the parameter of interest for the energy demand calculation. The floor heating demands the heat required to meet is operating floor surface temperature of 18°C. Further description of the modelling of the plant loops in EnergyPlus can be found in appendix N, with corresponding sketches of configuration II and III in appendix L and M, respectively.

7. Optimizing system configurations

How the micro-CHP system is integrated with the rest of the buildings HVAC system has an effect on its performance, and control strategies that ensure optimum running pay a high importance regarding achieving primary energy and emission savings compared to the reference system. Also, the appliance of buffer tanks helps to ensure steady and consistent operation of the appliance (SEAI, 2011).

It is uncertain which types and sizes of prime mover, and which configurations and operating modes of micro-CHP system that will penetrate the market most in the long term. Therefore an increased focus on research is needed to identify strategies that will maximize the long-term benefits of the micro-CHP approach with respect to CO_2 emissions, energy costs for consumers, and demand-side management in the electricity industry (Peacock & Newborough, 22. June 2005). Technical features of micro-CHP technologies are in general well documented, but the published evidence of their performance in meeting transient heat and electrical load profiles is limited. To make CHP an attractive option compared to the commonly used conventional gas boiler, research has to be done to enable an operation as optimal as possible for the CHP device.

A micro-CHP technology has essential characteristics (e.g. operating efficiency, load following capability, set back capability, stop-start characteristics, servicing requirements, life expectancy) that will influence its supply and demand matching performance. To enable better performance of the CHP and make it better match the building’s demand, CHP systems may often include a thermal storage, an auxiliary boiler, and even electrical storage/reconversion equipment (Peacock & Newborough, 22. June 2005). This was more specifically reviewed in section 6. The operation of the system can be regulated by controls based on the home’s changing requirements for heat and power, and external factors such as the import and export price for micro-CHP generation. Since micro-CHP units are often not able to cover a dwellings entire demand, most systems are designed with an auxiliary boiler, a thermal storage and a network connection. The CHP-system analyzed in this thesis is able to cover the entire thermal demand of the building if operated in heat-led operation, but a storage tank is implemented in all system configurations to ensure a stable supply.

Accordint to a study by N.J Kelly, J.A Clarke, A.Ferguson and G. Burt, recent studies have shown that the CO_2 savings of the CHP system depend on different factors such as the operation and control of the unit, the prevailing climate, the behavior of the building’s occupants and the size of the heat and power demands (Kelly N. , Clarke, Ferguson, & Burt, 2008). These issues will be further investigated in this thesis and how to optimally operate the CHP device depending on the buildings thermal and electrical loads will be discussed.

Studies by Peacock and Newborough (Peacock & Newborough, 22. June 2005) and Cockroft and Kelly (Cockroft & Kelly, 19 January 2006) showed that under certain circumstances CO_2 emissions may increase with the installation of micro-CHP. These studies did, however, rely on static models of both building and CHP device. Dynamical modelling is more appropriate to use as evaluation method due to the temporal variations in demand and the operational characteristics of the CHP device. The model does then provide an appropriate platform to evaluate not only likely carbon savings from the micro-CHP but also to explore specific factors of performance such as rates of on/off switching, temporal variations in efficiency and interactions with thermal storage and other balance of plant, all under realistic operating conditions (Kelly N. , Clarke, Ferguson, & Burt, 2008).

From end-user perspective, the main requirement of a micro-CHP model is to predict accurately the varations in thermal and electrical outputs and their interaction with the building's envelope, thermal plant and control system. The important parameters to simulate are therefore those that couple the CHP device together with other parts of the building simulation model, specifically, the heat output, electrical power output, and heat losses. From an environmental perspective, the fuel input/consumption does also need to be predicted. Mode of operation, the season and insulation levels will have an impact on the temporal characteristics of the micro-CHP system's heat and power output. Minimizing the cycling frequency is also beneficial for the durability of the micro-CHP device and will reduce maintenance (Kelly N. , Clarke, Ferguson, & Burt, 2008).

Further in this section the different operating strategies that can be applied to improve the operation of the CHP device coupled to the building envelope will be presented. The different operational strategies reviewed are load management, power control, thermal and electrical storage and the use of renewable fuels.

7.1 Load management

Load management or demand management is a method to adjust the electrical demands rather than the output of the plant. This can be done by for example forced switch-off of large power consumers such as sauna stoves and ovens or by limited simultaneous use of electrical appliances (Alanne, Micro-Cogeneration-I: Introduction). Today, demand management usually concerns the demand for electricity, but in the future demand management for other utilities such as natural gas or water might be possible. The main principle with the demand management controls is to shut off or reduce the power to non-essential loads. This is done in order to reduce the overall building demand, which will be beneficial for the CHP device as it can cover a larger part of the building's demand, and thus reduce the amount of imports from the electricity grid. Typical controls are:

- Shut off or dim electric lights, equipment, or HVAC systems
- Reset the thermostatic set points on HVAC systems (if electrical)
- Reduce the load of a set of similar components by rotating one or more components "off" for a short time interval
- Turn on generators to meet some or all the building's demand
  (EnergyPlus- US Department of Energy, 2013)

In EnergyPlus, the demand limiting controls implemented are intended to model some of the more common demand limiting strategies. One of the objects to use is called DemandManagerAssignmentList, and is a high level control that makes demand limiting decisions based on a list of possible demand limiting strategies. Each of the demand limiting strategy will be described in a separate object called DemandManager. Each DemandManager object will control a group of similar load objects of same type, such as lights, electrical equipment or thermostats (EnergyPlus- US Department of Energy, 2013). The Demand Manager is built into the overall solution method for the program. Three major segments of code are executed by the program for each time step:

- Exterior energy use
- Zone heat balance (surface heat balances, internal gains and air flows).
- HVAC system simulation (air and plant loops).

The exterior energy use is independent of the zone heat balance and the HVAC system simulation. This energy use handles energy use regarding exterior lights and exterior equipment that are placed outside the building, and which do not contribute to the zone's heat balance. In the building model used in this thesis, there is no exterior energy use as there are no exterior lights or equipment. *The zone heat balance* includes all of the surface heat balances, internal heat gains and airflows. *The HVAC system* simulation includes air and plant loops with their associated HVAC components. The HVAC system's behavior depends on the results of the building's heat balance at each timestep. During the simulation, the DemandManager is called after each HVAC simulation step. First, the DemandManagerAssignmentList object is evaluated and the DemandManager then decides if demand limiting is required depending on the current load of the building. If it is required, the demand limiting objects are limited after priority. Based on the Demand Manager Priority selected, the Demand Manager then decides which DemandManager objects should be activated. In turn, the activated DemandManager objects limits the respective load objects. As one or more of the DemandManager objects has been activated, a time step has to be re-simulated as the load conditions have changed (US Department of Energy, 2013).

There are two options for the DemandManager Priority; sequential Priority or all priority. *For sequential priority*, each DemandManager in the list is sequentially activated from first to last until the demand is reduced below the limit or until all managers are activated. A DemandManger is skipped if it is not possible to reduce the demand. Reasons that make it impossible to reduce the demand are that there is not enough load to limit, the demand is not available because of is on-schedule defined, or it is already activated because it reached its load limit during a previous time step. *For All Priority*, all DemandManagers in the list are activated simultaneously to achieve the maximum demand reduction. Using this priority option, only one final re-simulation is required after all DemandManagers are activated (US Department of Energy, 2013). Sequential priority is chosen for the load management applied in this thesis as some loads of the building are considered less essential than others.

The first approach in the load management will be to reduce the electricity demand below the standard values for yearly electricity in NS 3031:2007+A1:2011 (NS 3031:2007+A1:2011, 2007/2011). This value is in total 28.9 kWh/m2 a. The building is implemented with relatively low energy demand for lighting, while the energy demand for electrical appliances are high. Therefore, the majority of the demand management should be done here.

The load management is implemented such that the CHP generator can be able to cover the whole electricity demand. The maximum electricity demand limit is therefore set to be 4000 W. This is implemented with a safety fraction of 0.8, which implies that electricity demand over 3200W is adjusted by a damand manager assignment list as was explained in the previous paragraphs. This is under 5500 W, which is the amount of electricity possible to produce by the generator. Avoiding the high peaks will make it possible to reduce the dependence on the electricity grid as the CHP unit can produce a larger amount of the buildings demand, especially since the thermal and electrical peaks often do not happen at the same time. Load management will be tried implemented in both heat-led and electricity-led operation to see where the effect of the load management will have greatest impact on the operation of the CHP. When implemented in electricity-led operation, the demand limit is set to be 5500 W, instead of 4000 W since it is expected that the generator is more capable at meeting peaks when it follows the buildings electrical demand. However, since high electricity production is followed by high heat production, it is expected that high electricity peaks may result in overheating of storage tank.

7.2 Power control

In order to achieve an optimum match between demand and supply it is possible to implement the CHP with several operation modes. The control of the micro-CHP device defines the basis on when the prime mover is activated, deactivated or turned down. The device can be set to operate in a heat following mode, electrical follow mode, a time-led mode or a hybrid approach may be adopted (Peacock & Newborough, 22. June 2005). This thesis will focus on heat following and electrical following mode, but the other possible modes are also briefly described in this section.

For the heat following operation mode, start and stop control decisions will be based on temperature differences between the indoor and outdoor temperature. The micro-CHP device will operate to cover the whole thermal demand of the building, and electricity will be produced thereafter. This can, however result in a more frequent on-off operation of the device, at least in periods when the thermal demand of the building is not stable. The benefit is that the whole thermal demand will be covered by the CHP device, and a supplementary boiler is not necessary as long as the thermal output of the generator is large enough to cover the peak.

The electrical excess produced by the CHP in the case of thermal load following mode is stored in batteries or fed into the grid. It is assumed that the exports from the CHP incur negligible distribution losses before it reaches its point of use. Electrical shortage is covered by grid electricity or by discharging the battery storage. In the system cases reviewed in this thesis, only grid electricity will be an option in the simulated cases. However, the concept of battery storage will be presented in section 7.3.

For electricity following mode, the cogeneration device is operated to cover the electrical demand of the building as far as possible. This will reduce the amount of imports significantly, but thermal surplus may be generated at times when it is not needed. Also, when the electricity demand is low, the CHP device will then not be able to cover the thermal demand of the building. This makes it necessary to have a large enough storage tank to store the surplus heat, and a supplementary boiler to cover the thermal demand at times when the CHP-device is unable to cover the demand. If it is not possible to store the surplus heat, it is dumped to the environment. For this operating mode, the electrical demand will be the controlling variable for the power output from the CHP system.

In general, three operations will be possible for the electrical load following control: parallel power applications, grid independent applications and back-up power applications. In parallel power applications, the CHP system is working in parallel with other systems. Then the CHP system will supply the consumer until it reaches it maximum electrical output. The part not covered by this output is imported from the electricity grid. For parallel power applications, the micro-CHP and utility grid can operate simultaneously, and power can be supplied into the utility grid (Klobut, Ikäheimo, & Ihonen). For grid independent applications, the CHP has to cover the consumer's demand on its own. In this case, the CHP system is often coupled in combination with a battery system or multiple CHP devices is coupled in parallel. For back-up power application, the CHP system is operated as a stand-by power supply system to improve reliability. In this case, grid electricity is typically as primary source and CHP is the supporting source (Klobut, Ikäheimo, & Ihonen). In these cases, the thermal output produced simultaneously should be used as well as possible. Here, appropriate heat storage tanks or other measures may be used to store the surplus heat (Simader, Krawinkler, & Trnka, March 2006). For the cases simulated in this thesis, the case were micro-CHP and grid power are coupled in parallel will be of interest. The thermal output of the system will be used whenever possible, and

rejected to the atmosphere otherwise. If biomass is used as fuel, the rejected heat can also be used to dry the fuel (Klobut, Ikäheimo, & Ihonen).
For the follow electrical mode two different control options will be investigated for the ICE:

1. Unrestricted thermal surplus, ICE. In this case, the operation of the micro-CHP system depends on the electricity demand of the building, and heat is produced thereafter independent on the thermal demand of the building. Thermal surplus is allowed, and will get stored in the storage tank as far as possible and wasted when the tank exceeds its upper limit.
2. Restricted thermal surplus, ICE. The CHP system is set to follow the electricity demand as in (1), but only if $(NE_{SH}+NE_{DHW})>OE_{th,CHP}$, or if $(NE_{SH}+NE_{DHW})< OE_{th,CHP}$ and $T_{store}<T_{max}$. Applying this control ensures that the thermal output of the micro-CHP system will better match the thermal demand of the building, and thermal surplus is avoided. However, this may result in more start/stop events of the device (Peacock & Newborough, 22. June 2005).

T_{max} = maximum temperature setting of thermal storage, °C.

For time-led operation, the users will set the start and stop times for space and hot-water heating, and the supply device will follow the heat demand during these specified periods. Then the CHP device will only be on during these specified "on" periods. The advantage of this method is that the user can specify the amount of start-up cycles, and limit the use. The disadvantage is that it is not necessarily easy to know exactly when space heating and DHW is demanded. This can lead to overproduction in some period, while in other periods the demand will not be covered as the device is off. Due to that the CHP-device used in this thesis produces general more heat if operated at full power than the demand of the building, and that for time-led operation the CHP will operate at constant power output during its operation, such operation mode is not implemented. If the CHP model were not normalized, the capacity could have been reduced, and the CHP could have been set to operate at constant full-load output during the specified on periods and off else. This could have led to better efficiency as the generator would have operated the whole time at full-load, which optimizes the efficiency. An auxiliary gas boiler has to be implemented for this operation mode to ensure supply in the specified off periods.

Other control approaches may also be considered. Operation at constant power (base load) is one option. In this case, the CHP system is operated to only cover the base load, and thermal and electrical storages, heat sink, auxiliary boiler and grid is employed when needed. It is also possible to apply a combined operation mode. Example of such operation modes are (1) heat driven with peak-electricity function; (2) maximum electricity and/or heat demand, and (3) minimum electricity and/or heat demand (Simader, Krawinkler, & Trnka, March 2006). A last possible approach is to develop a hybrid function to attempt to improve the supply/demand matching performance. This can for example be done by including some measure of the predicted demand (Peacock & Newborough, 22. June 2005).

The operation of the CHP device may also be controlled by the temperature of the buffer storage. The purpose of the buffer storage is to deliver heat to the hydronic heating system and to shave the peak thermal demands. By using the storage tank as the basis of control, the operation of the CHP device can either be controlled by letting the set point temperatures for the storage determine the on/off-operation of the micro-CHP plant or controlling the temperature of supply water to the radiator network by mixing supply and return water according to the outdoor temperature.

It is also possible to let the generator operate after power requirements in the public grid. This operation supplies power to the network to counteract for a drop in the network voltage, and stops the supply to the network to counteract a network rise. For this to be possible, some control configurations has to be set to ensure the thermal comfort of the building. According to (Kelly N. , Clarke , Ferguson, & Burt, 2008), three responses to external request for control are possible:

1. *Positive participation*: In this mode, the CHP device can be switched on to provide power to the network (to counteract a drop in the network voltage) if it is off and the buffer tank temperature is below its upper limit. Then the generator can operate until the buffer tank's upper limit is reached.
2. *Negative participation:* For this operation, the CHP device can be switched off to counteract a network rise if the device is on and the buffer tank temperature is above its lower limit. Then the generator can be off until the buffer tank temperature falls below its lower limit.
3. *Unavailable:* The device will be unavailable for use in network control if the generator is on with a buffer temperature below its lower limit and off with a tank temperature of above its upper limit because the thermal demand of the building has priority.

In EnergyPlus, the Electric load center distribution objects are used to include on-site electricity generators in the simulation. Depending on the operation scheme chosen, the electric load center dispatches the generator and tracks and reports the amount of electricity generated and purchased. A net electricity report is then reported with values to an excel file where it can be seen how much the total electricity purchased from the grid is reduced by the on-site power generation. Generators which follows the thermal demand uses internal load calculations from the plant simulation (EnergyPlus- US Department of Energy, 2013).

Different generator operation scheme types are available in EnergyPlus. The available schemes are base load, demand limit, track electrical, track schedule, track meter, follow thermal and follow thermal limit electrical. *Using the base load scheme*, the generator will operate at their rated electric power output when the generator is scheduled on. The base load scheme will request all generators which are schedule to be on to operate, even if they exceed the electricity demand of the facility. *Using the DemandLimit Scheme*, the amount of purchased electricity from the utility will be limited to the amount specified in the input object. This scheme tries to let the generator meet all of the electrical demand that exceed the limit of purchased electricity which is set by the user. Using the TrackElectrical scheme, the generators will try to meet the entire electrical demand of the building. *Using the TrackSchedule* scheme, the generator will try to meet the whole electrical demand determined in a user defined schedule. *Using the trackMeter* scheme, the generators will try to meet the electrical demand from a meter. This meter can also be a user-defined custom meter. Using the DemandLimit, TrackElectrical, TrackSchedule, and TrackMeter schemes, the available generators will sequentially be loaded. The demand which is not met by the available generators will be purchased from the electricity grid. If the electrical demand is small and less than the minimum part load ratio of the generator, the generator will operate at its minimum part load generator, and the excess will either reduce the demand or be exported to the electric grid. *Using the follow thermal and follow thermal limit Electrical scheme*, set the cogeneration device to meet the thermal demand of the building. Using follow thermal scheme, electrical excess is allowed to be exported to the grid. For follow thermal limit electrical, the thermal output of the generator is restricted to a maximum of the building's current electricity demand, and no electricity will be exported. The electrical load center converts the thermal load to an electrical load using a nominal ratio of the thermal to electrical power production for the generator (EnergyPlus- US Department of Energy, 2013).

The baseload operation scheme was considered, but cannot be applied to the system configuration and building analyzed in this thesis due to that the micro-CHP model is not normalized. For baseload operation, the generator would operate at full load (5.5 kW electric output) whenever scheduled on. If the generator operates in this mode in the building analyzed, it will produce more heat and electricity than required by the building. The generator should therefore be sized differently if this mode were to be applied. As the model is not normalized, it is more difficult to change its capacity as all the parameters only works for the capacity specified. Due to lack in existed calibrated data, this mode was therefore not implemented.

Another operational strategy is to let the generator only run during daytime. Then the generator is only allowed to operate during daytime, but has the possibility to store heat during this period for use during the night time. In this mode, the cogeneration device operates at full load continuously until it has to stop at the end of the day or when the storage tank is fully heated. When the generator is off, heat is primarily taken from the storage tank. The rest of the heat is supplied by the auxiliary boiler. This mode can be designed to deliver peak demand and only part of the peak demand. For the modelling in EnergyPlus, this strategy would have been done by setting the generator to meet baseload and then define the availability schedule of the cogeneration device. A control device which shut down the generator when the tank is fully heated has to be implemented as well to ensure acceptable temperatures in loop and storage tank. This strategy will not be implemented, but is included as an interesting possibility for further investigation in future studies.

7.3 Thermal and electrical storages

This thesis only evaluates the implementation of buffer tanks, which represents short-term thermal storage, and electricity feed-in to the public grid. However, the concept of seasonal thermal storage and electrical storage are also presented in this section.

One common form for short-term storage is the usage of buffer tanks in the system configurations. The buffer tank utilized in this thesis is the stratified storage tank represented in section 6.2.1. Stratification in a storage tank depends mainly on the volume of the tank, the size, location and design of the inlets and outlets, and the flow rates of entering and leaving streams. Stratified tanks are useful for maximizing the thermal energy efficiency of non-continuous and semi-continuous processes. Liquid at two or more different temperatures is stored within the same tank to provide a buffer for variations in heating and cooling loads. Control of the thermocline between the hot and cold fluid regions is needed to minimize thermocline growth and maximize operation of the storage tank (Walmsley, Atkins, & Riley). Two storage tank sizes will be analyzed in this thesis: 500 l and 1000 l. Buffer storage integrated in a building's heating system helps reducing the peak demand and energy consumption, especially when energy costs during peak periods are much higher than those in off-peaks periods (Nelson, Balakrishnan, & Murthy, 24 September 1998). Thermal storage tank is used to provide greater operational flexibility during transient load demands.

However, the use of buffer storage does not help the variation between production in cold and warm season as it cannot store heat over seasons. It is seen that thermal surplus during warm season often occurs in micro-CHP systems when the plant can be operated close to constant power only and shutdowns are not preferred. This is most typical for fuel cell plants (SOFC plant). This leads to significantly thermal losses, which again leads to poor annual efficiency. To avoid this, seasonal thermal storage may be implemented. Different thermal storage technologies available are mass storage, phase change materials (PCM) and thermo chemical energy storage (Alanne, Micro-Cogeneration-I: Introduction). The applicability of seasonal thermal storages depends on the operational environment, the inlet temperature of the heating system and the trade-off between storage capacity and storage losses. Regarding the operational environment, the climatic conditions and the geological structure of the building site are factors of interest. Here parameters like ground temperature and if the ground is covered by snow affect the implementation of seasonal heat storage. The temperature level of the heat storage is also a parameter of interest which affects the storage capability. For instant seasonal storage for low temperature heating system at 40°C are more efficient than for conventional radiator heating at 70°C. This is because a heat storage to supply 40°C heating systems are less sensitive for tank losses than a storage at 70°C (Alanne, Micro-Cogeneration-I: Introduction). Thermal storage is, compared to electrical storage in batteries, much cheaper, but has a slightly lower energy storage density (Klobut, Ikäheimo, & Ihonen).

Electrical storage enables the possibility to cover the whole electrical demand of the building only by the micro-CHP device, and thus eliminate the dependence on grid electricity. The basic requirements for electrical storage is that it has large charge-discharge quantities, must tolerate high discharge power, has minor service requirements, is safe, longevity and has high energy density. Some electrical storage alternatives that are already on the market are lead-acid battery, NiMH-battery, and $LiFePO_4$-battery. The lead-acid-battery has good availability at low price (4-6Wh/€), but has low energy density (60-75 Wh/L). The NiMH-battery has high energy density (140-300 Wh/L) and high self-discharge, is already in the market but has a high price (1Wh/€). The LiFePO4-battery has high energy density (170

Wh/L) and low service requirement, but is still an emerging technology at high price (<1 Wh/€) (Alanne, Micro-Cogeneration-I: Introduction).

In EnergyPlus, there are two models for storing electrical energy, a simple mode that is not intended to represent a specific type of storage technology but rather a general concept, and a battery model that represents the kinetic battery model originally developed by Manwell and McGowan (US Department of Energy, 2013). The simple model is like a constrained bucket with energy losses, and the bucket holds a quantity of Joules of electrical energy. Losses and limits to storing and drawing are specified, but otherwise the bucket just holds the electricity. Constrains on the rates of charging, $P_{stor\text{-}charge}$, max, and drawing, $P_{stor\text{-}draw,max}$, efficiencies for charging, ε_{charge}, and drawing, ε_{draw} are specified by the user. The kinetic battery model is primarily used to model hybrid energy systems. It is called kinetic due to that it is based on chemical kinetics process to simulate the battery charging and discharging behavior. This model is used to model the electrical storage module of hybrid and distributed power systems. In other words, the kinetic battery model illustrates better real life electrical storage appliances, but the modelling is also more detailed than the simple electrical storage model in EnergyPlus.

Another option for surplus electricity is to feed it into the electricity grid. To make this work, some sort of arrangement has to be done. The monetary compensation for the electricity fed into the grid may be based on feed-in tariffs, net- metering or time- of use metering. The feed- in tariffs makes the utilities obliged to buy electricity from small producers at rates set by the government (buyback rate). To make this possible, a two-directional electricity metering is required. This is applied in many European countries, for instance Germany. Net-metering works such that both electricity imported and exported from/to the utility are metered. The amount of electricity produced onsite and fed into the electricity grid is deducted from the metered energy inflow and compensated through a retail credit by the utility. Time-of use metering is a two-directional metering strategy that allows rate schedule depending on peak demands hours (Alanne, Micro-Cogeneration-I: Introduction). Grid electricity is expensive in peak demand hours, while it is less expensive otherwise. Using time-of use metering, imports in peak hours can be avoided and thus reduce the energy cost. However, for all these methods of coupling small-scale producers to the grid, the stability of the grid limits the amount connected.

7.4 Using renewable fuel: Upgraded biogas

To lower the CO_2 emissions, the use of biogas as a fuel instead of natural gas has been reviewed as an option. Biogas is considered as a more renewable fuel than natural gas, and since it comes from sources which naturally would have contributed to CO_2 emissions, the contribution of CO_2 emissions will be remarkably smaller. Principally biogas can be produced from household waste and agrifood industry. During the processing of biogas, generally approximately 65% methane (CH_4) and about 30% carbon dioxide (CO_2) is produced (Malik & Mohapatra, 2012).

The global issues regarding sustainable energy and greenhouse gas emissions set the use of biomass as a potential source for power generation in increased focus. Biomass is a non-fossil biogenic organic-inorganic product which is generated by both natural and anthropogenic processes. It is also considered as the most profitable renewable energy source after hydropower. Some examples of biomass are wood, herbs and agricultural, aquatic, animal and human (bones, manures) and charcoal. For gasification, charcoal and wood are the most preferred fuels. For use in internal combustion engine the biomass has to undergo biomass gasification. Since any biomass material can undergo gasification, this process is much more attractive than ethanol production or biogas where only selected biomass materials can produce the fuel (Rajvansh, 2014). Biomass gasification means incomplete combustion of biomass resulting in production of combustible gases consisting of Carbon monoxide (CO), Hydrogen (H_2) and traces of Methane (CH_4). This mixture is called producer gas (Rajvansh, 2014). This would be a sustainable option, and researches have concluded that the use of producer gas from biomass gasification in internal combustion engines is a viable option, and can contribute in a lower use of fossil fuels which will results in lower CO_2 emissions and lower primary energy consumption. When the efficiency of an internal combustion engine is accounted for, 1 kWh of electricity needs about 2.4 m3 of wood gas as fuel. Wood gas has a much smaller energy content that biogas, 5 MJ/m3 compared to 18-26 MJ/m3. Biomass gasifiers combined with internal combustion engines are commercially available. An existing technology using wood, chips, pellets or bio-waste as fuel for gasification+ ICE produces 50-500 kWh electrical output and 100-1000 kWh thermal energy (Klobut, Ikäheimo, & Ihonen). However, it is not possible to modulate the producer gas for micro-CHP in EnergyPlus, as the possible gas mixtures do not include carbon monoxide (CO).

Another option is to upgrade the biogas as it can be upgraded to be a substitute for natural gas. As it has the same characteristics as natural gas, this can easily be applied to the simulation model. No change in the simulation parameters is therefore necessary as the heating value of the fuel will be the same. Normal biogas consist roughly of 60 % CH_4, 39 % CO_2, <1% N_2+O_2, between 50-3000 ppm H_2S and Saturated H_20. The upgraded biogas (biomethane) consist of 98 % CH_4, 1 % CO_2, about 1 % N_2+O_2, <1ppm H_2S and <1ppm H_20 (Mezei, 2010). To produce upgraded biogas from raw biogas, a process where CO_2 and CH_4 is separated is necessary. Normally components with high carbon dioxide absorption capacity are used to separate the CO_2 from the CH_4 in the biogas. Upgraded biogas, also called biomethane, can be interchangeable with natural gas and is also superior to natural gas is several aspects. Biomethane is cleaner as it does not contain hydrocarbons heavier than CH_4. Biomethane does also offer the opportunity for a carbon negative fuel, not just carbon neutral, as it is a renewable source of CH_4 and the biogas source can be from waste (Mezei, 2010). From the efficiency and economical aspect, the upgrading of biogas to natural gas quality is a vital criterion for its optimum utilization. The biogas production and upgrading processes are according to Bioferm energy systems proven technologies. They are reliable, efficient and safe and have the advantage of full integration into new and existing power and heat generation plants (Bioferm energy systems, 2014). The upgraded biogas can be supplied to the already developed natural gas grids and delivered to households and industry. The expected energy requirement for a single produced cubic meter of natural gas substitute (upgraded biogas) is equal to around 0.3 kWh (Makaruk, Milthner, & Harasek, 2010).

According to SEAI report on biogas upgrading and utilization (Persson & Wellinger, 2006) biogas from AD has a lower heating value of 6.5kWh/nm3 and from landfill gas 4.4kWh/nm3. Natural gas on the other hand has a lower heating value of 11kWh/nm3. In the upgraded biogas, the carbon dioxide is removed. Removing CO_2 from the biogas increases the heating value and the required Wobbe index of the gas is reached (SEAI, 2014). To upgrade the biogas to natural gas standard, some restrictions has to be set to assure the quality of the gas. Exemplary limits from an Austrian natural gas standard can be seen in Table 3.

Gas components	Limit	Unit
Oxygen	≤0.5	% m/m
Carbon dioxide	≤2.0	% m/m
Nitrogen	≤5.0	% m/m
Hydrogen sulphide	≤5.0	mg/m3
Total silicon	≤10	mg/m3

Table 3: Exemplary limits natural gas standard (Makaruk, Milthner, & Harasek, 2010)

In the modeling of the case of using biogas as a fuel instead of natural gas it is assumed that upgraded biogas is used. This biogas is upgraded to have the same calorific value as natural gas, and thus the primary energy factor and emission factor for biogas will be applied. The energy of upgrading the biogas to natural gas standard will not be considered. Therefore it is reasonable to believe that the CO_2 emissions and the primary energy usage will be higher than what is presented in this master if all phases where included.

8. Results

To investigate the impact of the different operating strategies presented in this thesis, different cases have been simulated. The main findings of the simulations are the following cases:

Case number	Description
1	Reference case: GB, storage tank with reference parameters
2	CHP only with storage and follow thermal mode
3	CHP only with storage, follow thermal mode and load management
4	CHP and GB with storage and follow thermal, limit electrical surplus mode
5	CHP and GB with storage tank size 0.5 m^3 and follow electrical mode with restricted thermal surplus
6	CHP and GB with storage tank size 0.5 m^3 and follow electrical mode with unrestricted thermal surplus
7	CHP and GB with storage tank size 0.5 m^3 , follow electrical mode as in 5 and with load management
8	CHP only follow thermal mode tank size 1.0 m^3
9	CHP only with storage, follow thermal mode and upgraded biogas as fuel

Table 4: Cases simulated

8.1 Energy Demand building

As can be seen in Figure 17, the building has high space heating demand during the heating season depending on the outdoor temperature, and peaks in the coldest winter months. The demand for hot water and electricity remains constant, and are defined by schedules in the modelling phase. As it can be seen, the thermal demand represents the major part of the building's energy demand during the coldest months.

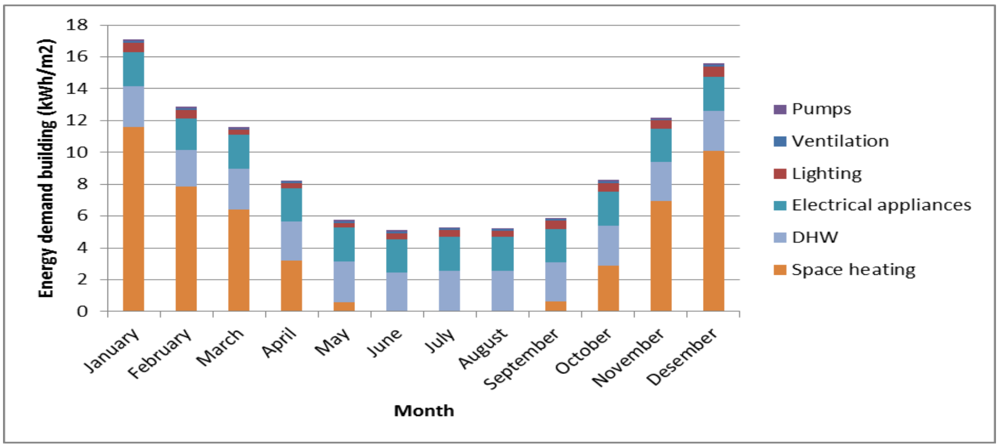

Figure 17: Monthly energy distribution of reference building

	Electricity	Domestic hot water	Space heating	Total
Specific energy demand GB case (kWh/m2)	31.93	29.95	58.75	120.63
Specific energy demand CHP case (kWh/m2)	31.93	29.95	50.33	112.23

Table 5: Specific yearly energy demand by end user

As it can be seen by Table 5 and Figure 17, the space heating demand reduces some when implementing CHP. This is due to the skin losses of the CHP that contributes to some heating of the zone. As can be seen for the CHP case, the total yearly specific energy demand of the building is 112.22kWh/m^2. Space heating, domestic hot water and electricity represents 45%, 27% and 28% of total energy demand, respectively. The space heating demand could have been lowered if heat recovery in ventilation was implemented. One of the energy measures in TEK 10 implies that the heat recovery should be ≥70 % for building built after 2010 (Kommunal- og regionaldepartamentet, 2010). Since this was not included in the ventilation predefined by EnergyPlus, this was not implemented. The domestic hot water represents well the standard value of NS3031, which is 29.8kWh/m^2 (NS 3031:2007+A1:2011, 2007/2011). The amount used for electricity is close to the standards value of NS3031, which is 28.9kWh/m^2 (11.4kWh/m2 and 17.5kWh/m2 for lighting and electrical appliances, respectively).

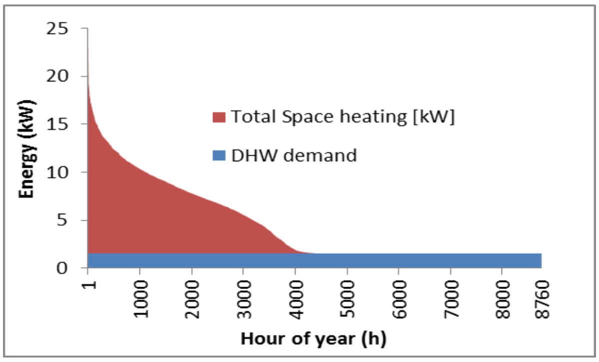

Figure 18: Duration curve heating

Figure 18 shows the duration curve for heating for the building. The total energy demand for heating peaks at a value of 19.97 kW. This leads to a problem for the micro-CHP, as it has a rated thermal capacity of 13.45 kW. This implies that it will not be able to cover the peaks. However, since it is coupled with a storage tank, these peaks may be covered by the heat stored in the tank from periods where the demand is low.

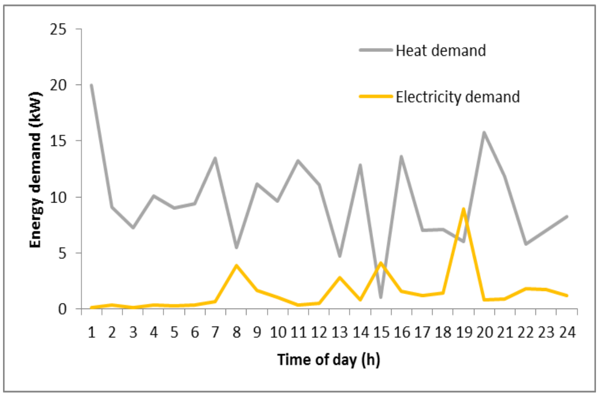

Figure 19: Power and heat demand for a cold day when the temperature reaches its minimum

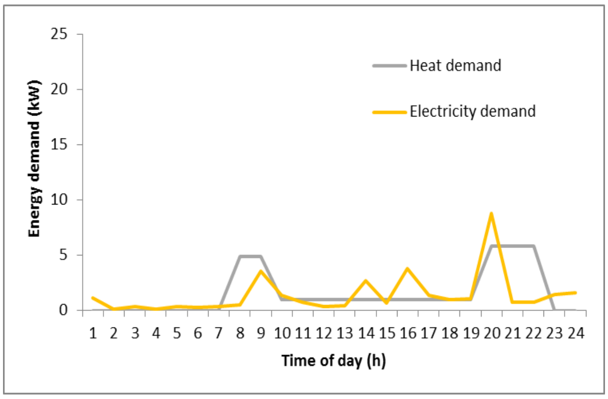

Figure 20: Power and heat demand for a warm day when the temperature reaches its maximum

As it can be seen from Figure 19 and Figure 20, the electricity production is moreover constant during the year with some small variations, while the heating demand is much smaller during the summer compared to the winter. It is therefore important to try to integrate the CHP at best possible practice to meet the variations in demand without decreasing the efficiency of the device to much. For some buildings, the building is allowed to cool during the night time, and the building has a set point temperature lower than during the day time. However, for the building simulated this is not considered and the room set point temperature remains constant during day and night at a temperature of 20°C. Therefore it can be seen that the space heating demand depends on the outdoor temperature and remains high during night time as well. Compared to former studies of M. Howing, R.R Negenborn and B. De Schutter, these heat profiles present the heat demand of a domestic building well. As the building in these studies was allowed to cool during the night, the heat demand was lower during these hours compared to the building used in this study (Howing, Negenborn, & De Schutter, Jan 2011).

8.2 Implementing load management

The aim of implementing load management is to lower the electrical demand peaks and thus lower the amount of electricity imports. This can be done by lower the use of controllable electrical appliances such as washing machine, dishwasher, TV, microwave, washer dryer and PC. Fridge, freezer and hob are considered as uncontrollable loads and do therefore remain the same. When load management is implemented in case 3, the demand for space heating increases slightly due to the fact that the internal gains from the electrical appliances will be reduced. The electricity demand is set to have a limit of 3200 W, which means that the electricity use never exceeds this value (schedule 4000 W, with a security of 20 %).

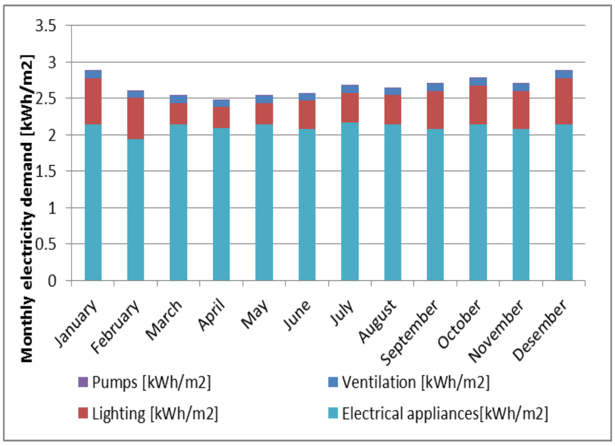

Figure 21: Monthly electricity demand by user base case

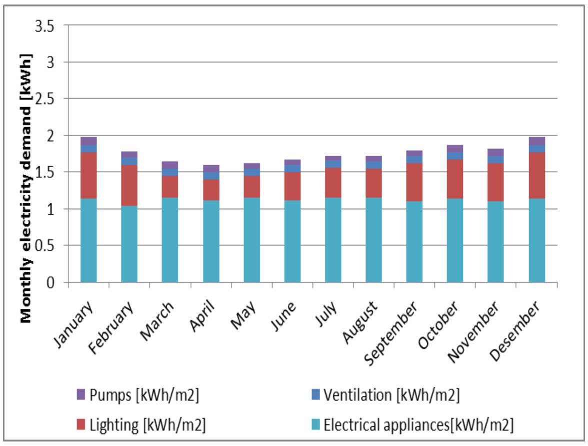

Figure 22: Monthly electricity demand by user case 3

As can be seen from Figure 21 and Figure 22, the electricity use for electrical appliances is significantly reduced by implementing load management. The electricity demand is relatively stable during the season and the only user who varies some is lighting. Electrical appliances represent the largest part of the total electricity demand, and it is therefore here the largest load management is done. The reduction is done by the load manager shaving the electricity peaks according to the scheduled control which can be found in appendix K.

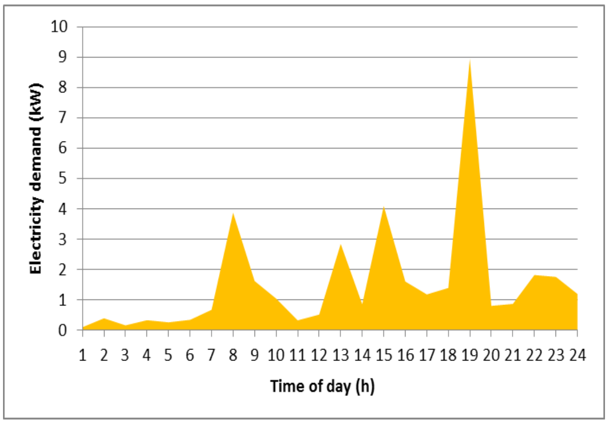

Figure 23: Electricity demand without load management, base case

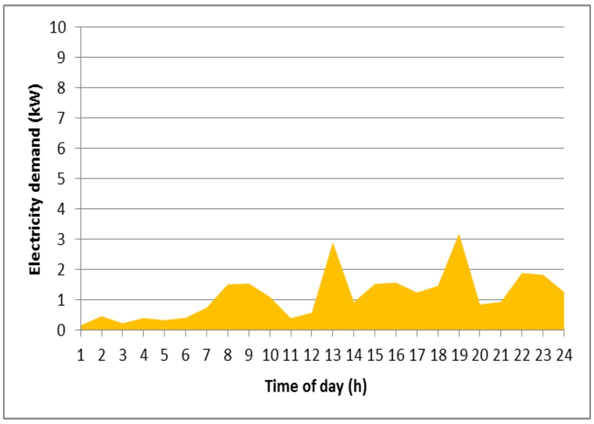

Figure 24: Electricity demand with load management, case 3

As seen from Figure 23 and Figure 24, the electricity peaks are shaved significantly by implementing the load management. This will affect the amount of exports and imports as the electricity produced by the CHP device is more or less the same as before, or even higher as the thermal demand of the building increases. This makes the CHP able to cover a higher amount of the electricity demand, which leads to a significant reduction in imports and an increase in exports.

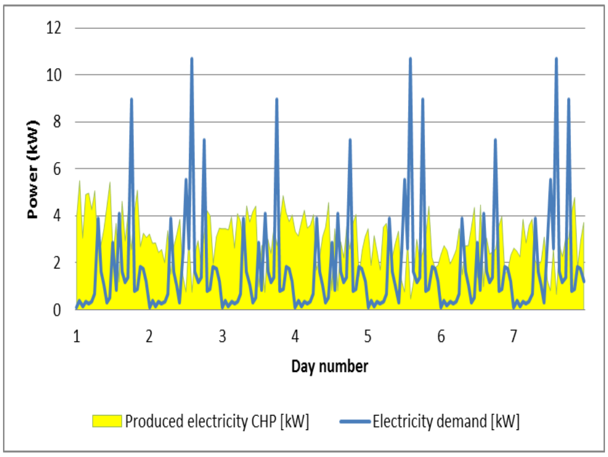

Figure 25: Electric demand versus produced CHP cold period, case 2

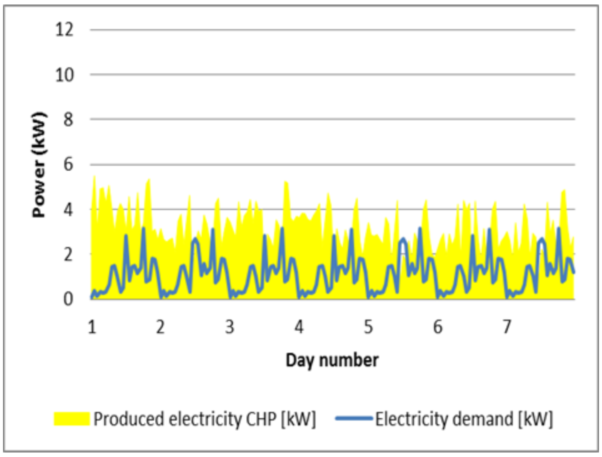

Figure 26: Electric demand versus produced CHP cold period, case 3

As the generator is set to follow the building's heat demand, the electricity production will be high during the cold period. Figure 25 and Figure 26 represents the electricity demand versus the produced electricity from the CHP for a cold period for case 2 and 3, respectively. For case 2 without load management, it can be seen that the CHP is not able to cover the peak demands of electricity, while electricity surplus is seen when the demand is low. For case 3 with load management, the CHP will be able to cover all peak demands during the winter period, but a large amount of surplus electricity is seen. As electricity surplus is exported to the grid and thus avoids electricity production from larger power plants with higher emission, it is seen beneficial to export electricity in a micro-CHP context. As long as there will be an integrated system for electricity feed in to the grid, this will not be a problem and is beneficial as it reduces the dependency of large central power stations to supply the grid with electricity.

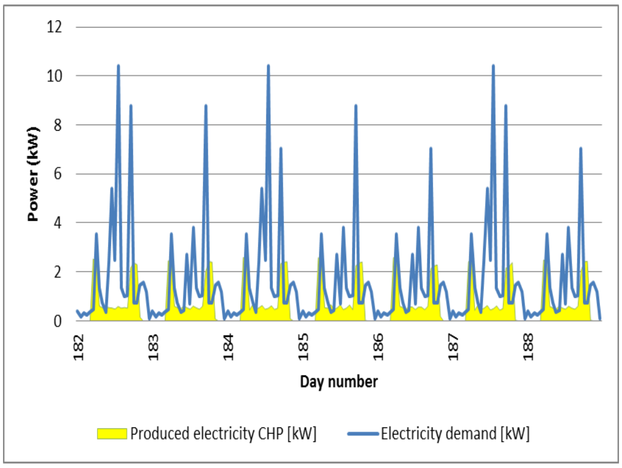

Figure 27: Electrical demand versus produced CHP warm period, case 2

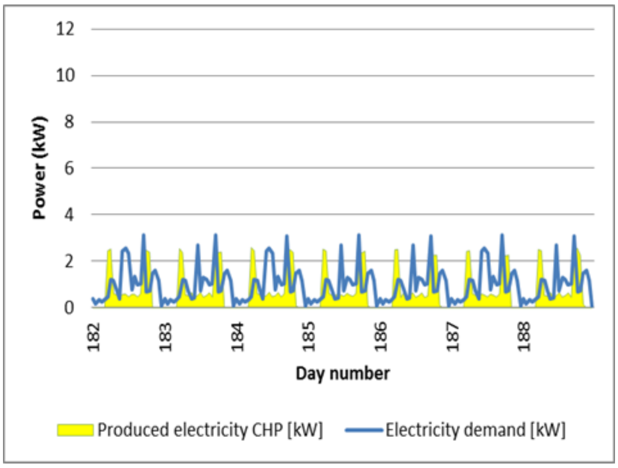

Figure 28: Electrical demand versus produced CHP warm period, case 3

As it can be seen from Figure 27 and Figure 28, the CHP device is more capable of covering the electrical demand of the building with the implementation of load management as the electricity peaks are shaved. However, since the thermal demand of the building is low during the summer months, the amount of electricity produced is also low and therefore even with the implemented load management; the generator is still not able to cover the entire demand during periods with low heat demand.

8.3 Implementing power control

The aim of power control is to make the CHP device able to better meet the electrical demand of the building without affecting the thermal supply demand matching remarkably. This may be difficult as micro-CHP produces heat and electricity simultaneously, while the thermal and electrical demand of the building do often not happen at the same time. For the evaluation of power control, two operating mode is considered: follow thermal and limit electrical surplus, and follow electrical. Both operating modes will be applied to the system configuration with CHP and auxiliary gas boiler to ensure heat supply. For the follow electric mode, three cases are evaluated; one with restricted thermal surplus (case 5), one with unrestricted thermal surplus (case 6) and one with restricted thermal surplus and load management (case 7).

8.3.1 Implementing follow thermal mode with electrical surplus limit

To evaluate the operation of the CHP, the temporal characteristics of the building's demand is of interest, especially when the generator is set to operate in a follow thermal mode. The difference in temporal variations for both case 2 and case 4 is reviewed to see the effect of implementing electrical surplus restriction on the generator in follow thermal mode. How the generators operates in follow thermal mode depend on the outdoor temperature, the internal loads of the building and thereafter the space heating and DHW demand.

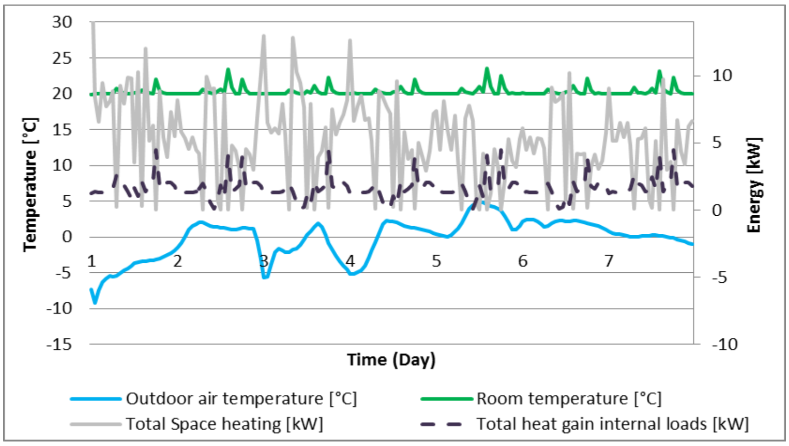

Figure 29: Building room temperature, outdoor temperature, internal gains and SH demand during a cold period.

Figure 29 show the characteristics of the space heating demand and the internal gains versus the indoor- and outdoor temperature for a cold period. As it can be seen, at times when the internal gains from electrical appliances, people etc. are high, the space heating demand becomes lower. It can also be seen that the space heating demand varies and does not have a stable demand rate. Due to this, the storage implementation has an important impact as it shaves the peak and assures a more stable and continuously supply. As the generator follows the thermal demand of the building in this operation mode, the tank temperature is dependent on this operation. For the case with the electrical surplus restriction, the tank temperature is affected differently than for case 2 without the restriction as can be seen in Figure 30 and Figure 31.

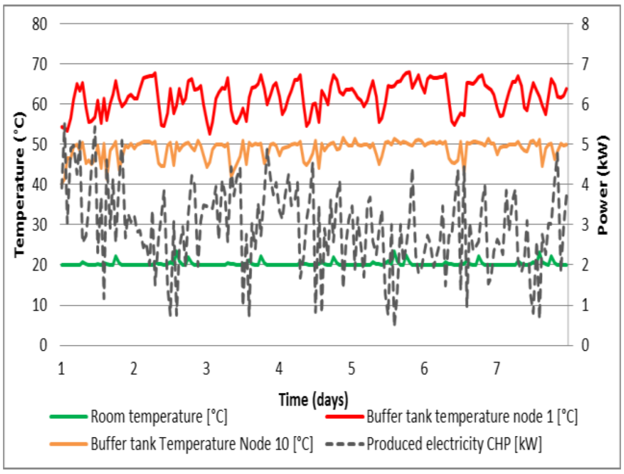

Figure 30: Temperature versus power produced during a cold period, case 2

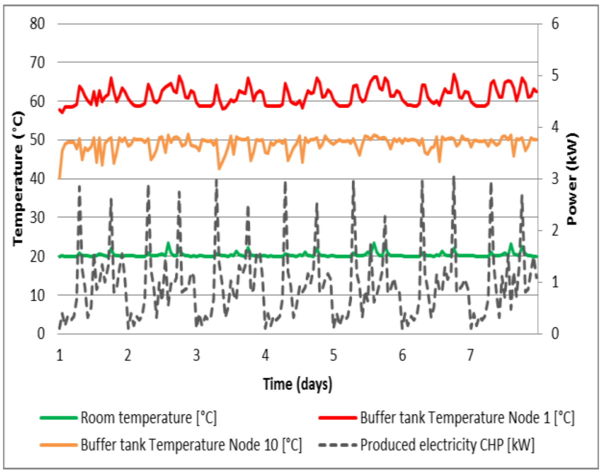

Figure 31: Temperature versus power produced during a cold period, case 4

The buffer tank temperature is lower when the thermal output of the generator is lower. This represents a peak in demand for space heating and domestic hot water, and more heat is withdrawn from the tank than what is supplied. However, the temperature remains at an acceptable level, which means that the generator supplies sufficient heat to keep the tank temperature within its dead band. If exports are not possible, the device should be implemented to follow the thermal demand of the building as long as it does not exceed the electrical demand of the building, which is done in case 4. In this case, the system has to have a gas boiler to ensure stable heat supply. As can be seen in Figure 30 and Figure 31, the storage temperature reaches a higher temperature in case 2 when the surplus restriction is off. This is because less heat is supplied from the generator to the tank. For case 2, the temperatures remain within an acceptable range, but the auxiliary boiler is frequently used due to deficit of heat supply from the CHP during the cold period. Comparing to the temperature of case 2, it can be seen that the storage temperature in case 4 with the limitation in electric surplus varies more depending on the demand. This is because the generator is not allowed to produce heat if this exceeds the electrical demand of the building, and therefore more heat is withdrawn from the tank in these periods. The connected gas boiler does however ensure a stable supply temperature to the tank.

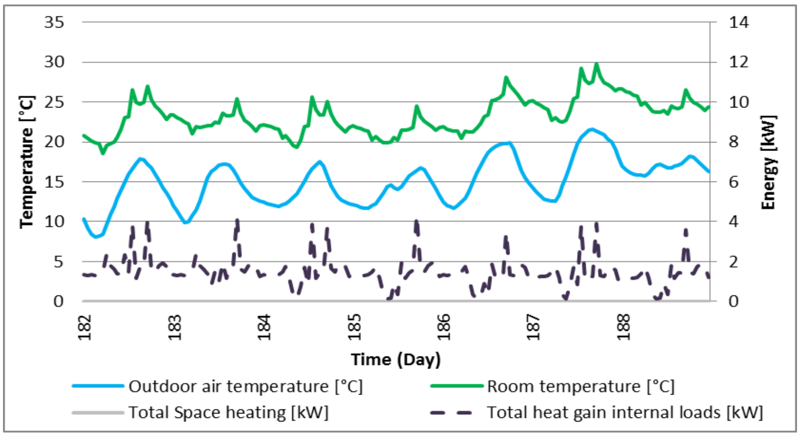

Figure 32: ***Building room temperature, outdoor temperature, internal gains and SH demand during a warm period.***

As can be seen from Figure 32, the room temperature depends on the outdoor temperature and the internal gains. Some cooling demand could be implemented as the temperature reaches 30°C when the outdoor temperature is highest. However, it is assumed that this could be naturally ventilated by opening windows, and therefore no cooling equipment is implemented in the model as the evaluation is regarding micro-CHP which only supplies heat and electricity. There exists generators that provide both cooling and heating, and this could be an option for places with higher cooling demand.

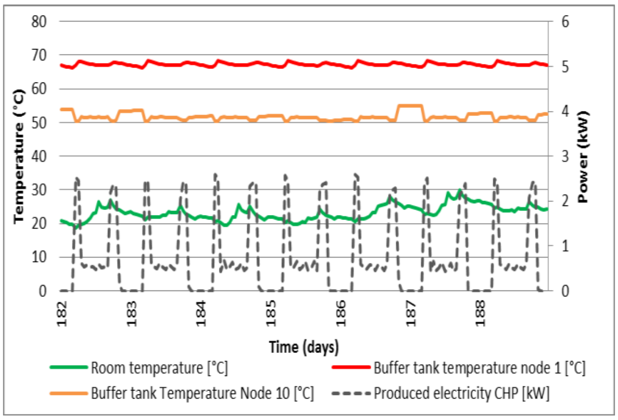

Figure 33: Temperature versus power produced during a warm period, case 2

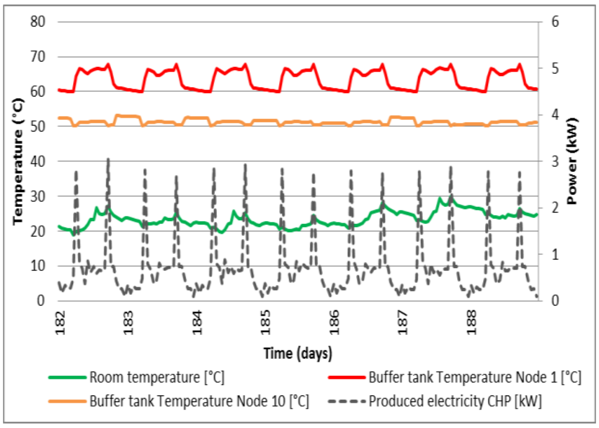

Figure 34: Temperature versus power produced during a warm period, case 4

Since there is no space heating demand during the warmest period of the year, the only heat demand is domestic hot water. Since the total thermal demand is significantly lower than during the cold period, it can be seen in Figure 33 for case 2 that the hot water storage remains relatively stable at its upper temperature limit. The tank temperature at node 1 (top of tank) remains stable below its upper temperature limit of 70 degrees. The small variations in tank temperature indicate that the supply equipment generally supplies sufficient heat to the tank compared to the heat withdrawal from the demand side loads. For case 4 it can be seen in Figure 34 that the upper tank temperature varies more. This is because the electric demand restricts the thermal output of the generator slightly, which result in higher heat withdrawal from the tank when no heat is supplied to the tank. The tank temperatures depend heavily on the heat supply and the supply is remarkably different in the two cases due to the surplus restriction.

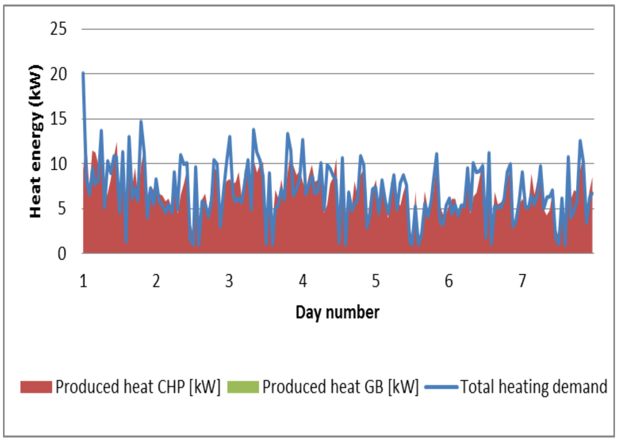

Figure 35: Heating demand versus thermal output CHP and GB during cold period, case 2

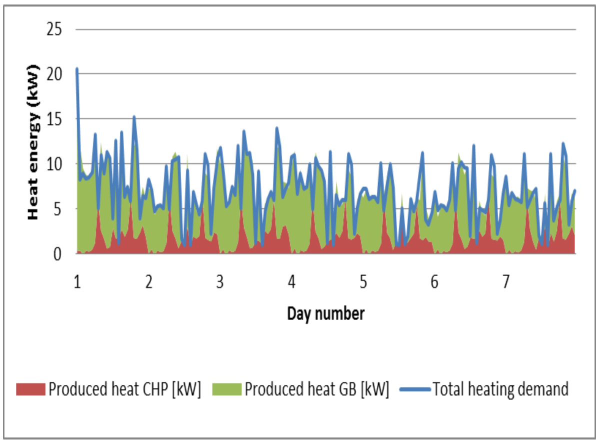

Figure 36: Heating demand versus thermal output CHP and GB during cold period, case 4

As shown in Figure 35 and Figure 36, the electric surplus limitation restricts the thermal output of the generator, which makes the generator less able to cover the thermal demand of the building during cold periods. An auxiliary gas boiler coupled to the loop is compulsory for this operation. This is especially necessary during the heating season when the heating demand of the building is high.

During the warm period, it was seen that the electrical limitations did not affect the operation of the CHP as much as during the cold period. The CHP was then able to cover the major part of the heat demand, which made the dependence on the auxiliary gas boiler smaller. This is because the heat demand is substantially smaller during the warm period compared to the cold period. Limiting the electrical output to not exceed the electrical demand of the building does limit the CHP device possibility to produce sufficient heat to cover the demand, and therefore the auxiliary gas boiler is frequently used. The amount of heat produced by the CHP has decreased with 66 %. The CHP and tank losses have however decreased some, but compared to the thermal output of the CHP, the losses pays a larger part of the total output. This has its impact on the efficiency, which is reviewed later.

With the electrical surplus restriction, the generator will better meet the electricity demand. As no exports are allowed, this will however result in a frequent use of the auxiliary gas boiler, especially during the heating season. The electricity demand met by the CHP has increased significantly as exports are not allowed. The main reason for this is that when exports are allowed, the model exports more electricity to the grid than only the surplus electricity. To demonstrate the effect of the implementation, the electricity production versus demand is presented for a cold period for each of the cases. The cold period is chosen due to the fact that this is when the heating effect is highest. During the summer months there were less electricity surplus in case 2, and therefore the effect of the implementation was less remarkable.

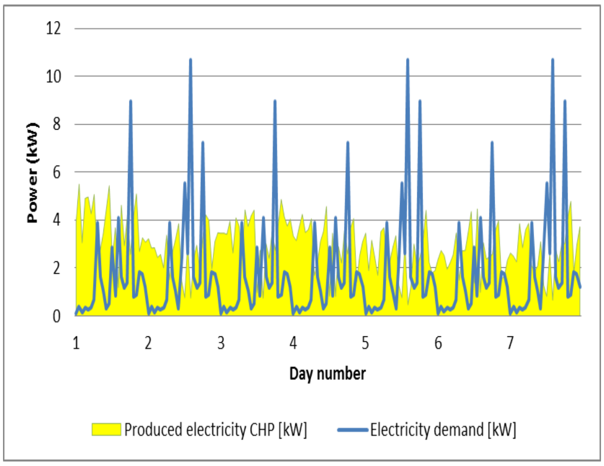

Figure 37: Electricity produced versus demand cold period, case 2

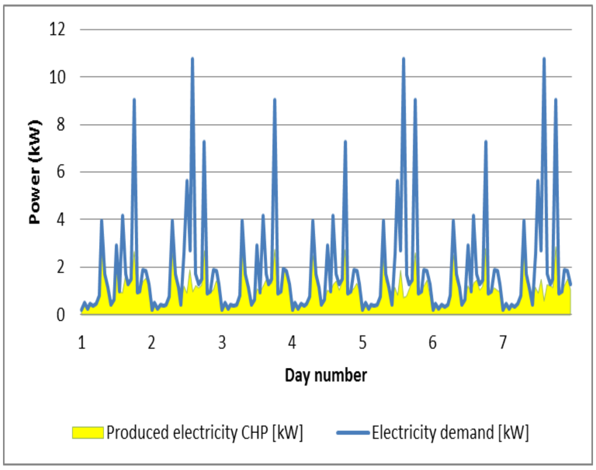

Figure 38 Electricity produced versus demand cold period, case 4

As it can be seen from Figure 37 and Figure 38, the electricity produced matches better the electricity demand in case 5 where electricity surplus is limited. However, if it is possible to export electricity and there is an existing infrastructure for this, this would be more beneficial for the CHP, as it can cover a larger part of the thermal demand of the building as well as it can operate more frequently at higher partial loading.

8.3.2 Implementing follow electrical mode

To avoid overheating of the tank, and thus surplus heat that will be wasted, control sensors has to be implemented. This will ensure an acceptable supply temperature to the radiant heating and the domestic hot water. A temperature sensor has been set on the supply water from the tank to the thermal loads of the building. To enable the generator to meet a larger part of the electricity demand, the supply temperature limit is set to be in the range of 55-75°C. If the supply water in the tank exceeds its upper limit of 75°C, the generator is forced to shut down. If the temperature is below its lower limit of 55°C, the supply equipment is turned on. In this mode an auxiliary gas boiler is coupled to the loop to ensure heat supply when the electricity demand is low. The restriction is implemented in both case 5 and 7, and results in lower usage of the CHP compared to the gas boiler. To view the effect of the implementation, a case where thermal surplus is allowed is presented in case 6. The tank is then allowed to exceed 75°C until it reaches the boiling temperature of 98°C. At this point heat is vented from the tank and thus wasted.

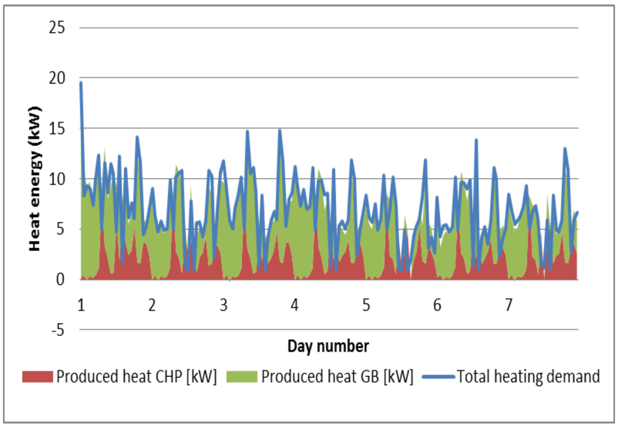

Figure 39: Heat production versus demand cold period, case 5

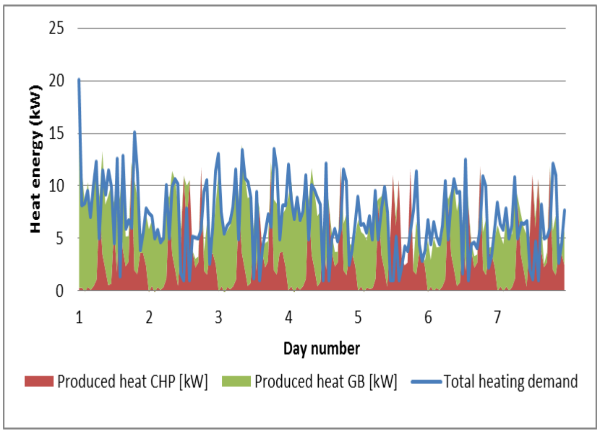

Figure 40: Heat production versus demand cold period, case 6

As can be seen from Figure 39 and Figure 40, the thermal output from the CHP device is restricted according to the thermal demand of the building in case 5. In case 6 on the other hand, it can be seen that the thermal output of the generator exceeds the thermal demand of the building occasionally. However, as the demand is relatively high during the cold period, the impact of the thermal surplus restriction is not that present. Also, since the relation between the electrical demand and thermal demand of the building is during major parts of time lower than the heat to power ratio of the CHP, the auxiliary gas boiler is frequently used.

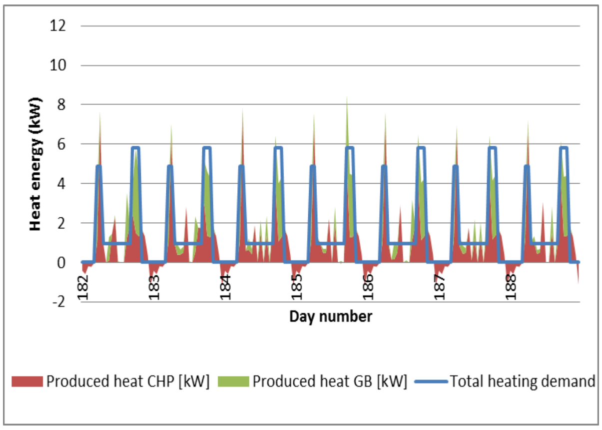

Figure 41: Heat production versus demand warm period, case 5

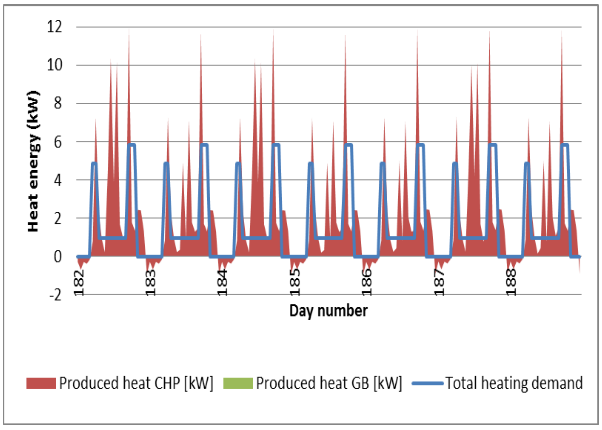

Figure 42: Heat production versus demand warm period, case 6

As can be seen from Figure 41 and Figure 42, thermal surplus is present in case 6, while remarkably avoided in case 5. The impact of the restriction is more present during the warm period, as the thermal demand of the building is lower. In the graphs, negative values of the heat produced are seen. This does probably represent times when the skin losses of the generator makes a larger part than the useful heat produced, which make the total value negative. These values are seen when the electricity production is low due to low electricity demand (lower than 1kW). For many CHP generators, when operating at low part load ratio they may be unable to recover the heat. Some manufacturers therefore restrict the minimum allowable electricity output of the generator to be over 1kW, while others research studies have stated lower restrictions, typically being 5% of the device's rated output (Annex 42, 2007). This will however, lead to either surplus electricity production or decrease the operation time of the generator as it is not allowed to operate at lower power output.

Thermal surplus results in high temperatures in the tank since significantly more heat is delivered to the tank without being a demand that is withdrawn from the tank. Implementing thermal surplus restriction, these high tank temperatures are avoided and also less heat is vented from the tank. The temperatures versus the electricity produced for case 5 and 7 were similar as the thermal restrictions were applied to both cases. However, with load management implemented, the generator is expected to meet a higher proportion of the electricity demand of the building. In case 6, the tank temperatures were higher since no control restriction was implemented. The largest impact on the tank temperature is seen during the warm period when the outdoor temperature reaches its maximum. Since the electricity production remains fairly constant throughout the year, while the heat demand varies, there is remarkably overheating of the tank in warm periods. Some elevated temperatures were seen for the cold season as well, but only the warm season is presented since this is where the influence of thermal surplus restrictions had greatest impact.

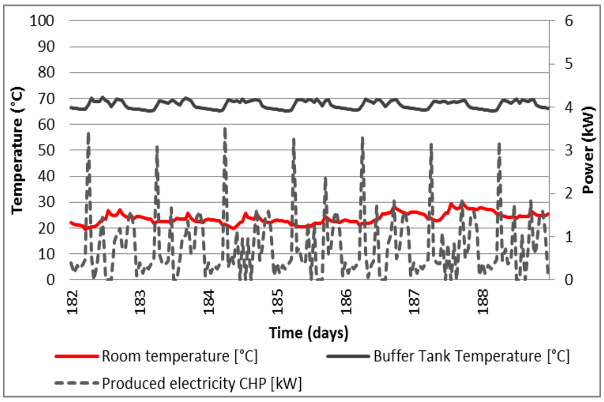

Figure 43: Room temperature, tank temperature versus electricity produced warm period, case 5

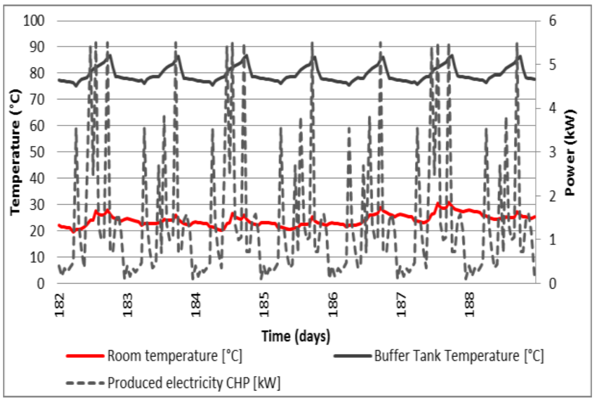

Figure 44: Room temperature, tank temperature versus electricity produced warm period, case 6

As shown by Figure 43 and Figure 44, the tank temperatures in case 5 remains within an acceptable temperature limit in the most critical period of the year due to the temperature restriction implemented in the tank. This does however affect the electricity production. In case 6, it can be seen that there is produced substantially more electricity than in case 5. However, the temperatures in the tank increase significantly in periods where the electricity production is high. This is because substantially more heat is produced by the CHP and delivered to the tank than what is demanded. During the cold season, more heat is required from the tank, and the temperatures are therefore not as elevated.

Since the thermal surplus restriction has an impact on the amount of electricity produced, the demand coverage in the period where the production is most restricted is of interest. As the thermal demand is lowest during the warm period, the electricity coverage by the CHP production of a typical warm day during summer is presented from the three cases in Figure 45-Figure 47.

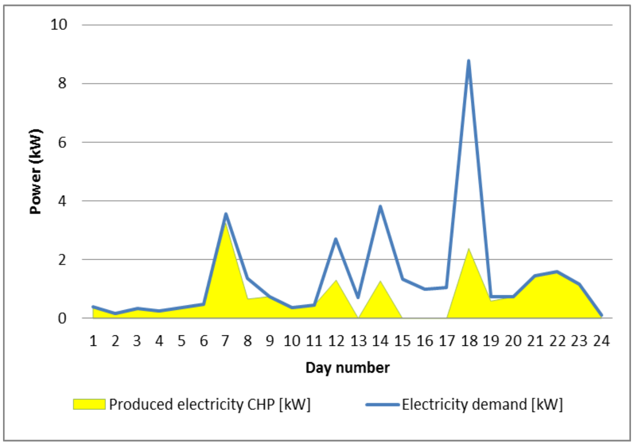

Figure 45: Electricity produced versus demand warm day, case 5

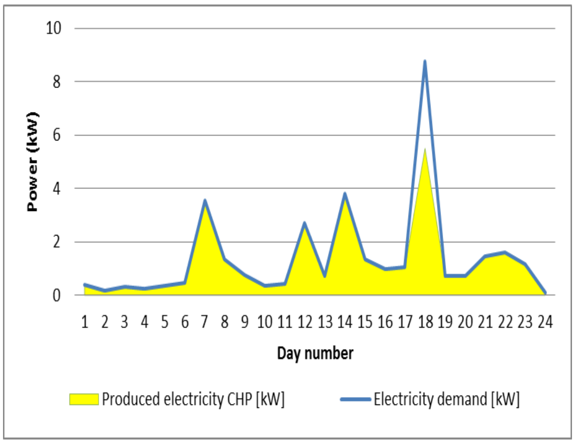

Figure 46: Electricity produced versus demand warm day, case 6

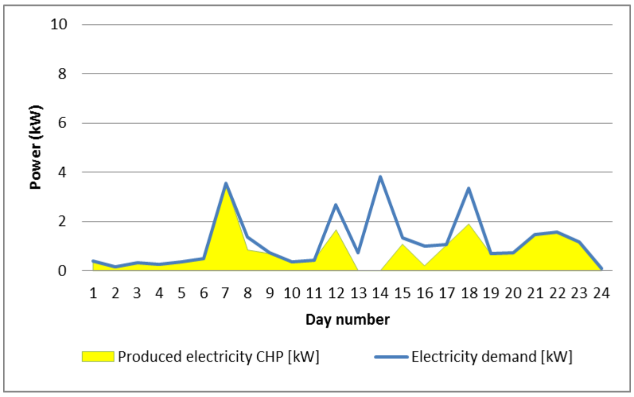

Figure 47: Electricity produced versus demand warm day, case 7

It can be seen that case 6, without thermal surplus restriction, covers the electricity demand in the best manner. However, it is desirable to avoid wasted thermal surplus. In case 7, it can be seen that the CHP is more capable in meeting the electrical demand than case 5 due to the implemented load management. Implementing load management reduces the demand, which makes the CHP more capable of meeting the electrical demand.

8.4 Primary energy consumption

The primary energy used in each of the configurations is found by multiplying the primary energy factor to the delivered energy to the building as defined in section 4.1. The results for each of the cases are represented under.

	Primary energy factors f_P	
	Non-renewable	Total
Natural gas	1.36	1.36
Biogas	1.092	1.092
Electricity mix UPCTE	3.14	3.31

Table 6 Primary energy factors from (NS-EN 15603:2008, 2008)**, biogas from** (Pout & BRE, 2011)

All simulated cases are viewed and compared to the reference case in order to determine which proposed methods that achieve greatest primary energy savings.

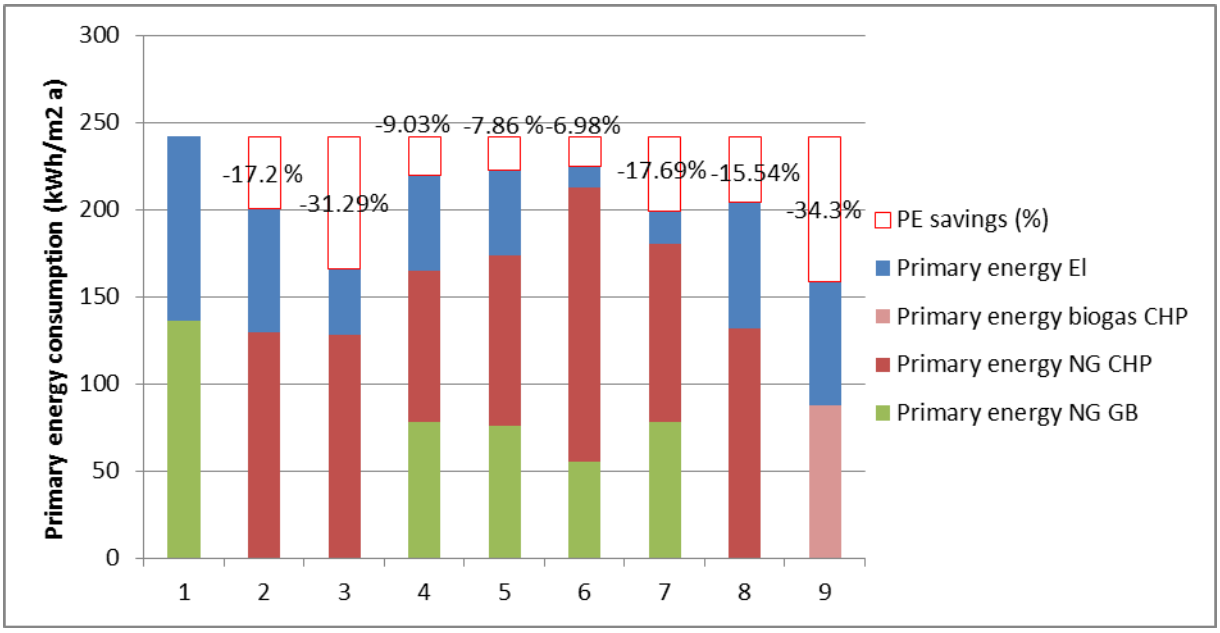

Figure 48: Primary energy savings

	PE biogas (kWh/m^{2}a)	PE NG (kWh/m^{2}a)	PE El (kWh/m^{2}a)	PE total (kWh/m^{2}a)
Case 1	-	136.02	106.687	241.7
Case 2	-	129.26	70.906	200.167
Case 3	-	128.223	37.851	166.07
Case 4	-	164.66	55.218	219.88
Case 5	-	173.715	48.993	222.709
Case 6	-	212.424	12.403	224.82
Case 7	-	179.92	19.02	198.947
Case 8	-	131.61	72.533	204.145
Case 9	87.909	-	70.906	158.815

Table 7: Specific primary energy consumption

Figure 48 shows the primary energy savings for all the cases simulated in this thesis. In Table 7 the corresponding yearly primary energy consumption for each of the cases can be seen.

For case 2 in follow thermal mode, the CHP achieves primary energy savings of 17.2% compared to the condensing gas boiler. For the values of primary energy for natural gas in the CHP cases, the exported electricity is substituted from the total amount using the methodology presented in section 4.1. The thermal storage supplies heat to the building at peak demands hours. The implementation of thermal storage shaves the peak and ensures a more stable operation of the CHP. For CHP operating in follow thermal mode, no auxiliary boiler is required since the CHP coupled to the storage is able to cover the entire demand on its own and ensure acceptable temperature levels in the building and the tank.

The primary energy savings increase when implementing load management as was done in case 3. Compared to the reference system the primary energy savings are 31.29 %. Managing the electricity loads helps the building to cover a larger part of its electricity demand, which reduces the dependency on electricity imports from the grid. The primary energy consumption from grid imports has been reduced from 70.9kWh/m^2 to 37.8kWh/m^2 by implementing load management, which represents a reduction of 47% compared to case 2 and 65 % reduction compared to the reference case 1. This implies that buildings with a larger heat to electricity ratio achieve higher primary energy savings than buildings with lower heat to electricity ratio.

For case 4, on the other hand it is seen that the resulting primary energy savings are less than for case 2. This is mainly because there are no exports in follow thermal limit electrical mode. Exports are seen beneficial in a PE context and therefore substituted from the amount of fuel delivered. For exports to be possible, an infrastructure on the grid needs to be established. This is not well developed in many areas, and therefore an operation that limits the electrical output of the CHP-device to what is demanded by the building might be necessary in some cases. This may result in insufficient heat produced at times when the heat demand is high and the electrical demand is low as was seen for the case study reviewed in this report. This is solved by the auxiliary gas boiler to cover the resulting heat demand which is not covered by the CHP. A stand-alone CHP system is not able to have this operation as it will not deliver sufficient heat to the building on its own.

For case 5, 6 and 7 where electrical following mode were implemented, it is seen that case 7 who also have load management and thermal surplus restriction implemented, achieves the greatest primary energy savings. Case 6, without thermal surplus restriction, achieves the poorest primary energy savings. This is mainly because of the amount of wasted heat production due to overheating.

Increasing the tank size as was done in case 8 did not lead to increased primary energy savings, and a reduction of 1.66% is seen compared to case 2.

Using upgraded biogas as fuel instead of natural gas as was done in case 9, 34.3% primary energy savings are achieved compared to 17.2% in case 2. However, as the primary energy factor for biogas is used, the energy usage for the upgrading process is not taken into account. It is therefore believable that the savings would have been slightly lowered if this process was included. According to the literature study reviewed in 7.4, approximately 0.3kWh/m^3 energy was required to upgrade biogas to natural gas substitute. The yearly amount of fuel delivered in case 9 (and 2) is 4.75 m^3. This means that the energy required to upgrade the biogas is 1.425 kWh. Per m^2, this will only represent 0.00316kWh/m^2, which represents a small part compared to the total consumed fuel energy.
The use of upgraded biogas is used to demonstrate how the savings could be if a renewable fuel was used instead of natural gas. As the process of upgrading biogas to natural gas quality is not included, the benefits of using biogas represented in this report will be higher than what would be the case in reality as a larger amount of biogas at its original form would be required as its heating value is lower than for CHP. However, it is assumed to give a picture of its potential and the whole process should be

further analyzed in pilot-projects. The upgraded biogas case is applied to case 2, and therefore has the same operational characteristics.

The highest primary energy savings are achieved in case 9, when upgraded biogas is used as a fuel. Closely followed is case 3 where the generator operates in follow thermal mode and load management is implemented. Here, a reduction in primary energy of 31.29% is achieved, closely to the 34.3% achieved by using upgraded biogas as fuel. It can be seen that the poorest primary energy savings are achieved in the cases where the generator is set to follow the electrical demand of the building, or restricted to not have electrical surplus generated. However, implementing load management combined with follow electric mode results in higher primary energy savings as is seen for case 7. If load management is not to be implemented, the follow thermal mode of the generation gives best operation based on achieved primary energy savings.

8.5 Energy efficiency

The efficiencies are based on higher heating value to do the comparison to the reference system (case 1), which represents a best practice case of a condensing gas boiler with high efficiency. The efficiencies are calculated based on the equations found in section 4.2.

	1	2	3	4	5	6	7	8	9
Thermal efficiency	-	0.521	0.524	0.423	0.394	0.440	0.405	0.523	0.521
Electrical efficiency	-	0.226	0.228	0.238	0.238	0.243	0.241	0.220	0.226
CHP efficiency	-	0.747	**0.751**	0.662	0.633	0.684	0.646	0.744	0.747
Gas boiler efficiency	0.902	-	-	0.941	0.941	0.943	0.942	-	-
System efficiency (DE)	0.914	0.741	0.721	0.828	0.795	0.705	0.788	0.731	0.741
System efficiency (PE)	0.499	0.561	0.637	0.519	0.509	0.501	0.547	0.549	**0.707**
% increase from 1	-	6.076	13.80	2.00	1.00	0.20	4.80	5.00	20.80

Table 8: Comparison efficiency all cases (HHV)

As it can be seen from Table 8, both electric and thermal efficiency are lower than the stated nominal efficiency defined in the inputs for all cases. One of the reasons for this is that the nominal efficiency is based on the gross input, which represents the lower heating value of the fuel. As the higher heating value of the fuel is used in the calculations, the resulting efficiencies become lower. For comparison to studies and data from manufactures based on LHV, the corresponding CHP efficiencies based on LHV are also shown in Table 9. The relation for HHV:LHV for natural gas is 1.108 (Clarke Energy, 2013).

	1	2	3	4	5	6	7	8	9
Thermal efficiency	-	0.577	0.580	0.469	0.436	0.487	0.449	0.579	0.577
Electrical efficiency	-	0.250	0.253	0.264	0.264	0.269	0.267	0.244	0.250
CHP efficiency	-	0.827	**0.832**	0.733	0.701	0.758	0.716	0.824	0.827

Table 9: CHP efficiencies based on LHV

The maximum possible efficiency based on LHV is from the design specifications 0.93, and it is therefore seen that neither of the cases achieves optimal efficiency of the CHP. The nominal efficiencies are based on full output of the CHP, which due to variations in building demand is not possible for the analyzed cases. As the generator cannot operate continuously at full load operation because of varying buildings demand and times when the demand is remarkably lower than the full load output of the generator, the efficiency becomes lower. This leads to frequent part load operation and on-off cycling when there is low or no demand. To enable the generator to operate more frequent at full load operation, either a smaller device should be implemented in the building in cooperation with an auxiliary boiler to only let the generator cover the base-load, and let the boiler cover the rest. Since the CHP model in EnergyPlus is not normalized, the model could not be implemented with different capacities. For further studies this should be reviewed to see the effect of constant full load operation of the CHP. The CHP efficiency would have increased if the thermal demand of the building were higher and full load operation were possible more frequently.

The system efficiency is the relation between the thermal and electrical demand of the building and the energy delivered to the building, either in terms of delivered energy or primary energy. This shows how well the heat output is utilized in the building. These efficiencies considers the power draw of the ancillary components that are required to couple the thermal output of the CHP-device with the building's HVAC and DHW system, such as the storage tank. The system efficiency should be based on primary energy instead of delivered energy as it then accounts for the losses and transformation of electricity in the public grid, and therefore give a better picture of the benefit of CHP. The system efficiency based on delivered energy is higher in the case of gas boiler due to the electricity delivered is assumed to be delivered and distributed in the building without losses. The system efficiency based on PE is better for all CHP cases compared to the gas boiler. For case 2, it has increased with 6.076 %.

Implementing load management further improves the efficiency as seen in case 3. The main reason for this is that the amount of exported electricity has increased, which is beneficial, as well as the amount of imports is reduced as the generator is able to cover a larger part of the demand. The system efficiency has increased with 13.8% compared to case 1.

For case 4, when the power output of the CHP is limited to the electrical demand when operated in follow thermal mode, the system efficiency based on primary energy will decrease as there will be no exports. The reason for this is that exports are considered beneficial and will substitute for some of the imported energy. However, for places with no grid connection and difficulties of enabling exports, such operation will be good as it never produces more electricity than what is demanded by the building. Implementing this restriction makes the device to better match the buildings electricity demand, but not the thermal demand of the building (see section 8.3.1). It is seen that the gas boiler efficiency has increased in this mode compared to the reference case. This is probably due to increased condensation. Because of this, the system efficiency based on delivered energy becomes better than for case 2. The efficiency based on primary energy, however, becomes poorer. Compared to the reference case, it has only improved with 2%. The CHP efficiency is also poorer when electrical surplus restriction is implemented. This is mainly because the generator has to operate more frequent at lower part load ratio, since the electricity demand limits the thermal production when the electricity demand is substantially lower than the thermal demand of the building (remarkably lower than the heat to power ratio of 2.444).

Operating the generator in a follow electric mode gives poorer efficiency for the CHP than in follow thermal mode as is seen for case 5, 6 and 7. However, as the auxiliary boiler coupled to the loop achieves a high efficiency due to condensation, the system efficiency is not too much affected by the reduced CHP efficiency. As can be seen, case 6 achieves the poorest system efficiency both based on delivered energy and primary energy. This is due to the large amount of vented heat from the tank which is lost. This is not that present in case 5 and 7 as thermal surplus restriction is implemented. However, the CHP efficiency is poorer in both case 5 and 7 compared to case 6. This is probably because the generator has to operate at lower part load ratio due to the restriction. The system efficiency based on primary energy has improved with 1%, 0.2% and 4.8% for case 5, 6 and 7, respectively.

For case 8, it can be seen that the thermal efficiency is slightly better than for case 2, but the electrical efficiency is lower which makes the CHP efficiency and the system efficiency lower. The increased thermal efficiency is due to that the generator can operate at higher partial loadings when it operates. However, since it operates fewer hours (see section 8.6); less electricity is produced, which makes it necessary to import more electricity from the grid. This reduces the system efficiency as imports from the grid are not considered beneficial. Also, the system efficiency become poorer as the tank losses has increased as will be seen in Table 10. However, as the losses are small, this increase will only reduce the system efficiency based on primary energy with 1.2% compared to case 2, resulting in an increase of 5% compared to the reference case.

In case 9, the amount of delivered energy of fuel will be the same as for case 2 since the upgraded biogas is assumed to have the same heating value as natural gas. The CHP efficiencies and system efficiency based on delivered energy will therefore be the same. However, as biogas has a lower primary energy factor than natural gas, this result in a significantly higher system efficiency based on primary energy. Using upgraded biogas as fuel is therefore beneficial for the CHP system also on an efficiency point of view. The upgrading process should, however, be taken into account for further investigation on this subject. Compared to the reference case, this case achieves the highest increase in system efficiency based on primary energy and has increased with 20.8%.

Since the system efficiency considers the whole system, the system losses as well as the heat production for each of the cases is of interest. In Table 10 the heat balance for each of the system cases can be seen. Since the heat efficiency is not 1, some skin losses will come from the generator. These losses are included in the thermal efficiency of the generator. The amount of these skin losses depend on the cooling water temperature and resulting engine temperature of the generator.

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**	**Case 9**
CHP skin losses (kWh/m^2a)	-	11.44	11.68	10.99	14.40	17.91	14.24	11.46	11.44
Produced heat CHP (kWh/m^2a)	-	80.40	85.82	27.1	28.34	50.99	30.36	81.59	80.40
Produced heat GB (kWh/m^2a)	90.21	0	0	53.72	52.59	38.117	54.02	0	0
Surplus heat vented from tank (kWh/m^2a)	0	0	0	0	-0.57	-7.63	-0.40	0	0
Tank losses (kWh/m^2a)	-1.76	-1.62	-1.61	1.540	-1.84	-2.07	-1.83	-2.36	-1.62
Total heat transferred (kWh/m^2a)	88.44	78.79	84.20	79.28	78.51	79.40	82.14	79.23	78.79

Table 10: Comparison heat balance, balance of plant

It is seen that the reference case (1) has higher amount of produced heat than the CHP cases. This is because the space heating demand of the building is slightly reduced in the case of implementing CHP as the CHP skin losses contribute to increased internal heat gains of the building when the generator is placed inside the heated area of the building. The heat losses from the tank are low, while the skin losses of the generator represent a larger part. The low tank losses are due to a good insulated tank and that the off-cycle flue gas coefficient of the tank is assumed to be 0. As the pipes are assumed adiabatic, the tank loss is the only loss that will affect the system efficiency based on delivered energy compared to the CHP efficiency.

The CHP cases with implemented load management have higher rate of transferred heat because of the reduced internal gains from electricity consumption. This is because the electricity loads contribute to a certain amount of internal heat gains, which will be reduced when these loads are reduced. For case 3, the space heating demand has increased with $5kWh/m^2a$ which leads to higher amount of heat generated by the CHP.

The heat balance of case 4 remains similar to case 2 and the only difference is the amount heat produced from the CHP. Due to the electrical surplus limitation, the output of the CHP is remarkably reduced, which makes the usage of the auxiliary gas boiler compulsory. It can be seen that the heat output only represents 33.5% of the heat supply for case 4, while for case 2 it represented 100% of the heat supply.

For case 5, 6 and 7 in follow electrical mode, it is seen that the CHP skin losses has increased as well as the tank losses due to elevated temperatures. For case 7, the amount of heat transferred are higher than for case 5 and 6, and is because of the implemented load management. It is seen that the vented heat losses due to overheating of tank are almost eliminated in case 5 and 7, while for case 6 they represent a significant part of the system losses. It is therefore concluded that the heat vented from the tank is remarkably avoided by implementing the thermal surplus restriction. As expected, the amount of heat vented from the tank was highest during the summer months when the thermal demand of the building is lower. It is also here the thermal surplus restriction has greatest impact as can be seen in Figure 49 and Figure 50 which represents the monthly heat distribution for case 5 and 6, respectively. Similar graphs for the other cases can be found in appendix O.

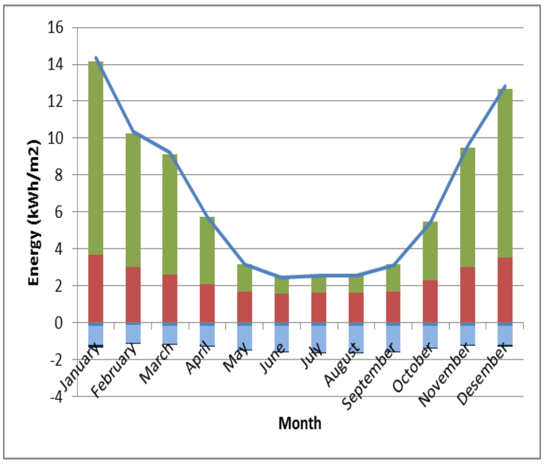

Figure 49: Monthly heat distribution case 5

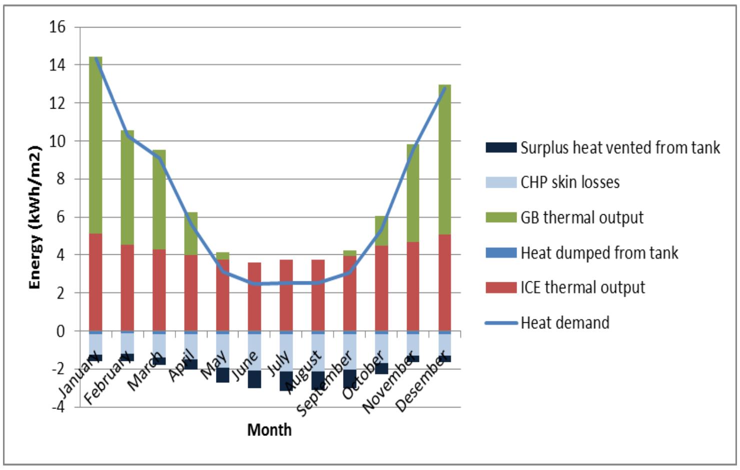

Figure 50: Monthly heat distribution case 6

In case 6, it is seen that the surplus heat produced each month represents the same amount of vented heat from the tank. All heat which is not demanded is therefore wasted to the environment. The CHP device is allowed to operate more time and produce more heat than in case 5, which reduces the dependence on the auxiliary gas boiler. However, this results in higher losses as more heat is vented from the tank. This is especially seen during the summer months. The skin losses of the generator do also become higher as the engine temperature becomes higher when the cooling water temperature increases.

For case 8, it was seen in Table 10 that the tank losses increased with 31.35% compared to case 2 due to the increased thank size. This leads to slightly higher production of the CHP to make up for the elevated losses. As case 9 has the same operating conditions as case 2, the heat balance will be the same. For the building analyzed, it has been seen that the load is sufficiently high to occupy the micro-CHP almost continuously, when operated in thermal load following mode. This makes the throughput of the buffer tank high, which result in lower tank losses as well. Also, since the throughput of the buffer tank is high, it is not strictly necessary with a storage tank in follow thermal mode, but it does, however, allow a degree of flexibility in the operation (SEAI, 2011).

From this, it is seen that the cases which did achieve highest primary energy savings does also achieve best efficiencies based on PE as expected. Case 9 achieves best system efficiency based on PE, followed by case 3 and case 2. Also, as seen for the cases where an auxiliary high efficiency gas boiler is necessary, the gas boiler achieves higher efficiency in operation with the CHP than it did in single operation (case 1). This is due to increased condensation when operating in cooperation with the CHP. To evaluate the CHP efficiency further, it is interesting to look at the variations between seasons. Figure 51 show the monthly overall efficiency for all the cases simulated.

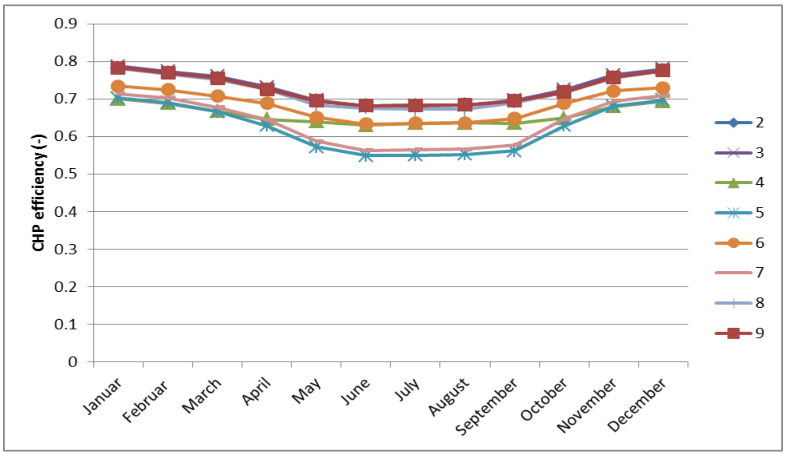

Figure 51: Comparison monthly CHP efficiency case 2-9

For all cases, it is shown that the CHP efficiency is poorer during the warmer months when the thermal demand of the building is low. This affects the resulting yearly efficiency of the device, and makes it lower than it optimally could be if the device could operate at higher output the whole year. This is especially present for case 5 and 7, where the operation is strictly limited due to the thermal demand of the building. It is also seen that the cases in follow thermal mode achieves an allover better efficiency throughout the months than the cases in follow electric mode as it allows the CHP device to operate more time at higher output. The reason to the lower efficiency is the higher frequency of on off operation during the summer months as the thermal demand is not present during the whole day as is the case for the colder months, were space heating is required the whole time.

According to Klobut, Ikäheimo and Ihonen, the percentage of fuel energy input used in producing mechanical work, which results in electrical generation, remains fairly constant until 75% of full load, and thereafter starts decreasing (Klobut, Ikäheimo, & Ihonen). This means that at lower partial loadings more fuel is required per kWh of electricity produced, which leads to decreased efficiency. As the generator produces less electricity during the summer months, the generator operates at a lower partial loading which results in lower efficiency as is seen in Figure 52 and Figure 53, which represents the thermal and electric efficiency, respectively.

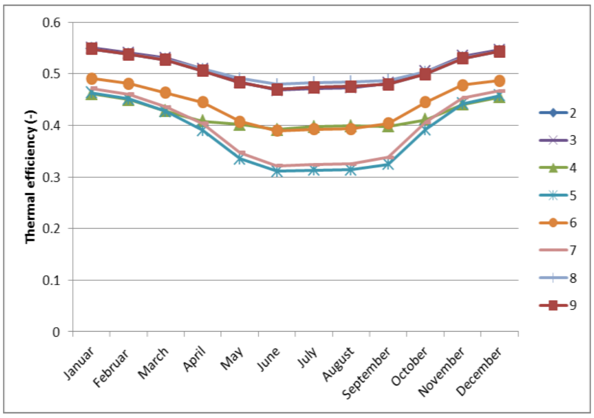

Figure 52: Monthly CHP thermal efficiency case 2-9

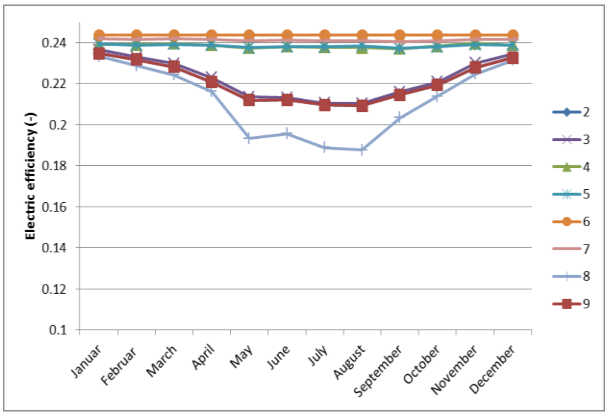

Figure 53: Monthly CHP electric efficiency case 2-9

The cases where the CHP is set to follow the electricity demand of the building achieve poorer thermal efficiency than the cases where the CHP is set to follow the thermal demand of the building. Also in the case where the CHP is set to follow the thermal demand of the building, but has a restriction in the electrical surplus is it noted an allover poorer thermal efficiency for the generator. The reason for this is as it was stated earlier in the thesis, that when the generator operates at higher partial loadings (electricity), the thermal heat recovered becomes poorer.

The cases where the CHP is operated to follow the electrical demand of the building achieve higher efficiency than the cases where the CHP is set to follow the thermal demand of the building. This is because the generator can operate more time at higher partial loading than in the case for the follow thermal operation. It can also be seen that the cases in the follow electrical mode has less variations in electrical efficiency throughout the season than the cases in follow thermal mode. This is due to that the electrical demand remains relatively stable, and there are no large variations between the seasons.

8.6 Operational characteristics

To reduce the need for maintenance of the CHP device, it is desirable to have low on/off cycling, and that the generator operates as continuously as possible. Table 11 shows the operational characteristics for each of the cases simulated in the thesis.

		Time in warm-up mode	**Time in normal mode**	**Time in standby mode**	**Time in cool-down mode**	**Time in off mode**
Case 2	(h/year)	280.21	5244.36	2955.2	280.21	0
	(%)	3.19	59.86	33.73	3.19	0
Case 3	(h/year)	268.166	5366.33	2857.33	268.177	0
	(%)	3.06	61.26	32.61	3.06	0
Case 4	(h/year)	37.35	8526.06	159.25	37.35	0
	(%)	0.43	97.32	1.8	0.43	0
Case 5	(h/year)	58.15	6936.867	1718.75	46.233	0
	(%)	0.667	79.679	19.74	0.531	0
Case 6	(h/year)	0	8760	0	0	0
	(%)	0	100%	0	0	0
Case 7	(h/year)	40.117	7443	1244.65	32.233	0
	(%)	0.46	85.492	14.296	37.0	0
Case 8	(h/year)	298.583	4002.25	4160.6	298.583	0
	(%)	3.4	45.68	47.49	3.4	0
Case 9	(h/year)	280.21	5244.36	2955.2	280.21	0
	(%)	3.19	59.86	33.73	3.19	0

Table 11: Operational characteristics

When the generator operates in normal follow thermal mode in case 2, the generator operates 59.86% of the year in normal operating mode, 33.73% of the time in standby mode and 3.19 % in warm-up and cool-down mode. Due to varying heat conditions and times with no heat demand, the time in warm-up and cool-down mode is higher for this case than for many of the other, which implies that the amount of on/off cycling is more frequent in this case. It is seen that implementing load management (case 3) will slightly increase the generator runtime, and therefore decrease the number of cycles per year. This is good as there will be less on/off operation of the generator. The generator will operate 61.26% in normal operating mode. The increase in operating hours is mainly because of the slightly increased thermal demand of the building.

In case 4, when electrical surplus is not allowed, the operational hours has increased compared to case 2 as the generator supplies less heat, which leads to that the generator can operate longer time before the tank is fully heated and the CHP has to turn off. This does also imply that the number of cycles has decreased, which is beneficial for the maintenance of micro-CHP appliances. However, even though the generator is operating more continuously throughout the year, the generator will operate more often at part load operation, as the electrical demand of the building limits the thermal production. The generator will almost never operate at full load, which decreases the efficiency of the CHP which was seen in section 8.5. The electrical efficiency was increased, but the thermal and overall efficiency did decrease. Therefore this operation mode is not beneficial from an efficiency point of view. This operating mode would have been more suited for buildings with more stable electricity usage throughout the days, and where the relation between electricity and heat demand was similar to the heat to power ratio of the CHP.

For the cases where the generator is set to follow the electrical demand, it can be seen that the operating time has increased significantly and the warm-up and cool-down time has decreased. This implies that there is less on/off cycling of the CHP. For case 6, it can be seen that the CHP operates 100% in normal on-mode. This is because some electrical appliances consume standby power even when not used, which results in some electricity demand present at all hours of the year. However, many existing CHP devices has a restriction in minimum allowed electricity produced for the generator to operate, which is not included in this thesis. This would have restricted the operation of the device, and thus maybe increased the efficiency as low power output operation would have been avoided. According to subtask 5’s report by Klobut, Ikäheimo and Ihonen, minimum operating set point for some IC-engines is 20% of rated power output (Klobut, Ikäheimo, & Ihonen). Implementing this would have limited the use to only operate when the electricity demand was higher than 1.1kW. For further studies the impact of this restriction should evaluated. In case 5 and 7, the operational hours is lower as the generator is forced off when the tank temperature exceeds its upper limit. Case 7 has higher operational hours than case 5 due to that the high peaks are avoided when implementing load management, which allows the generator to operate more time before it is shut down.

As seen for case 8, the plant achieves more on/off cycling by increasing the size. The operational time reduces, and the generator is more time in standby mode. This can be explained by that having a larger tank, more heat can be generated and stored in the tank at each time-step. This reduces the time the generator needs to be on. The generator can produce heat at higher load when it operates, as the storage is capable of storing more heat. However, this result in less electricity production than the case of higher operating hours, which results in poorer all over efficiency as was seen in section 8.5. Compared to literature study, this result was different than expected as it was stated that increasing the tank would lead to less on/off cycling and higher operating hours of the CHP. However, this would probably be the case if the CHP would be differently sized and would operate at constant output when it did operate. For such operation, the impact of having a larger tank size would have been more important, and should be further investigated for future research.

How the operational hours affects the primary energy savings are of interest in the evaluation of the CHP performance, and can be seen in Figure 54.

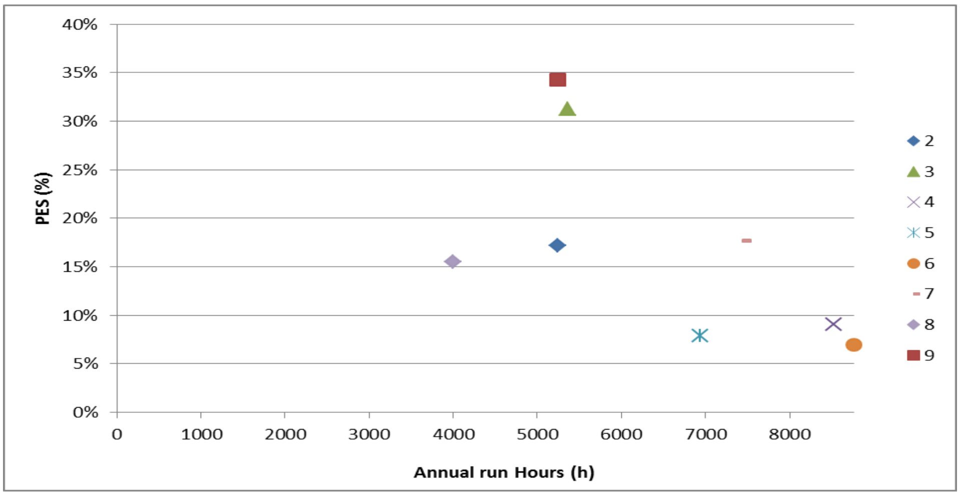

Figure 54: Operational hours versus primary energy savings (PES)

As can be seen, the cases with highest operational hours does not neccessarly achieve the highest primary energy savings. Case 9 achieves highest primary energy savings, but does not have highest operatioanl hours. The resulting primary energy savings depend more on the operating mode chosen rather than the operational hours of the generator. However, comparing cases in same operating mode such as case 2 and 8, it can be seen that higher operating hours results in higher primary energy savings. Similarly for case 4 and 5 (which are similarly operating mode, only one follows the thermal demand and limits the electric output while the other follows the electric demand and limits the thermal output) it can be seen that higher operating hours results in higher primary energy savings.

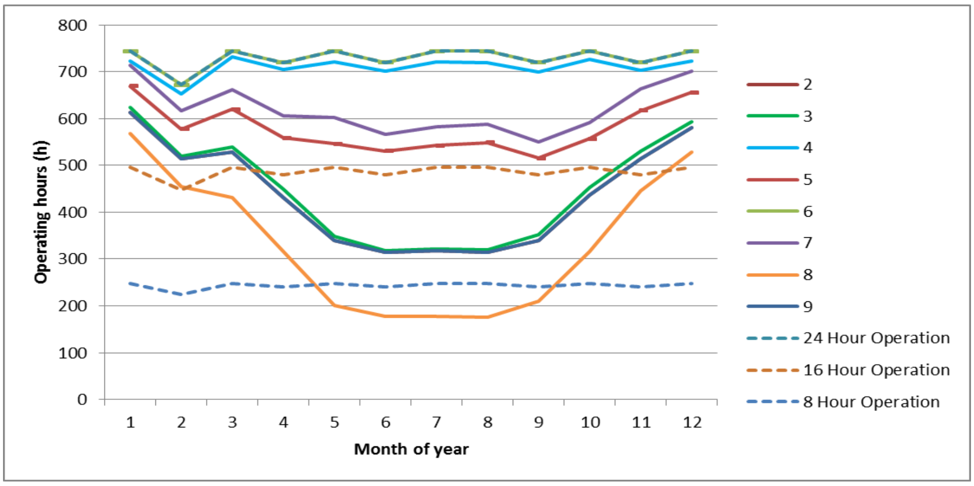

Figure 55: Monthly operational hours all cases

	2	3	4	5	6	7	8	9
Max run hours (h/month)	613.75	623.37	722.4	669.1	744	714.2	567.5	613.75
Min run hours (h/month)	313.87	317.65	652.31	515.53	720	550.92	175.6	313.87
Average run hours (h/month)	436.03	447.19	710.50	578.07	**730**	620.25	**333.52**	436.03

Table 12: Max, min and average run hours

As it can be seen by Figure 55, the cases with follow thermal mode have the largest seasonal variations in operating hours. Case 8 with increased thermal storage has the lowest operating hours, and from May to September, the operation is lower than 8 hours daily. The cases operated in electric demand following mode has higher operating hours than the cases in thermal load following mode and are less affected by seasons. However, implementing thermal surplus restriction to this mode lowers the operating hours during the warm months.

From Table 12, the maximum, minimum and average monthly operation time of each of the cases are seen. The minimum run hours are found in the month June, July and August. The maximum run hours are found in January and December. The lowest average monthly run hours are lowest for case 8 and highest for case 6. As space heating is required and on almost all day during the heating season, a more continuously operation is provided by the CHP device, which results in lower on/off operation. Outside the heating season, however, the CHP device has less continuously operation. This results in more on/off operation off the device as DHW is only demanded at certain points of the day. This reduces the operating hours of the CHP device, which also leads to lower efficiency as on/off operation is not desirable. It can be seen that the cases in follow thermal mode (2, 3, 8 and 9) has largest variations in operation time between summer and winter. This is because the thermal demand of the building varies throughout the seasons, while the electrical demand is more stable. In follow electrical mode, if nothing is specified, the generator will operate continuously throughout the year as there will be some electricity consumption at all hours of the day due to standby power consumption of different electrical equipment. This leads to poorer CHP efficiency, and overheating in the tank as was reviewed in section 8.3.2. With follow electric demand and restrictions in thermal surplus, it can be seen that case 7 has an overall higher amount of operating hours both during summer and winter than case 5. Case 4 with follow thermal operating mode with electric surplus restrictions achieves second highest amount of operating hours throughout the year.

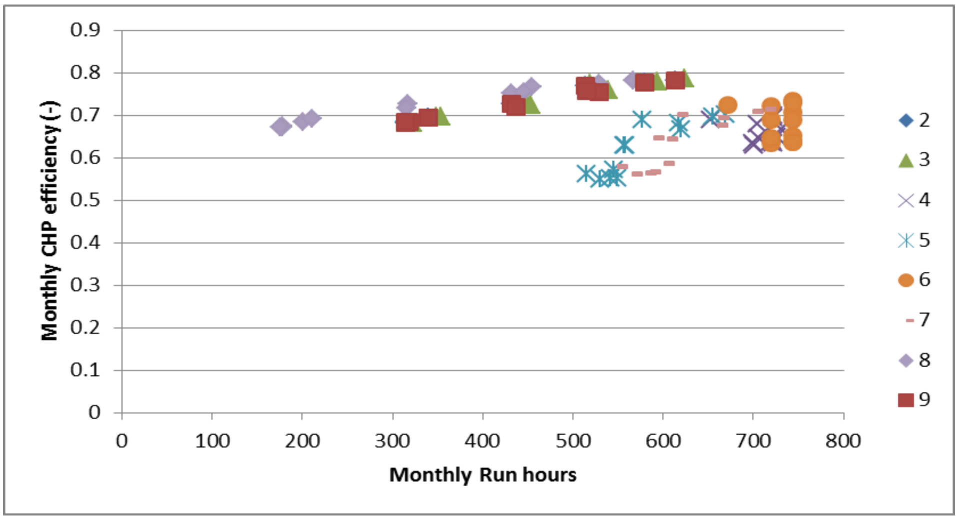

Figure 56: Relation between monthly run hours and efficiency

As it can be seen from Figure 56, the CHP efficiency increases when the monthly run hours increases for most of the cases. Case 4 and 6 does not have the same notable increase depending on operating hours. In case 6 this is because the generator operates continuously the whole year, and the run hours will therefore only depend on the hours of the month. It is seen that the cases in normal follow thermal mode or the cases in follow electrical mode where thermal surplus is restricted has higher dependence on the operating hours of the device than the unrestricted case in follow electrical mode and the restricted case in follow thermal mode (case 6 and 4, respectively).

8.7 Reduced grid interaction

Implementing CHP reduces the dependence on grid electricity as it produces electricity simultaneously as heat. Case 1 depends entirely on electricity imports from the public grid as there is no on-site electricity generation. As the electricity demand remains fairly constant throughout the year with small seasonal variations, the amount of electricity imports during the summer is the same as for the winter. Figure 57-Figure 62 shows the electricity imports and exports during a cold period for case 2-7.

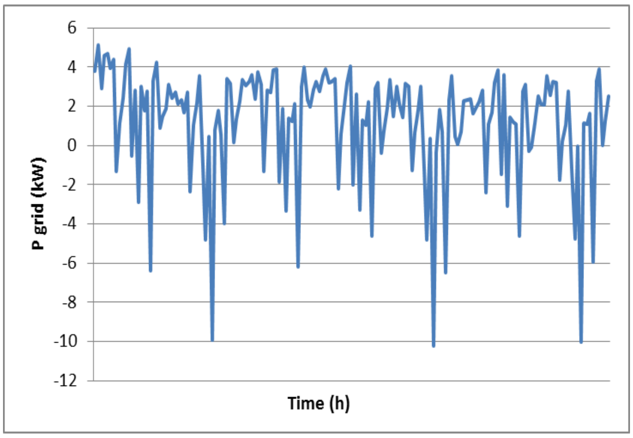

Figure 57: Imports and exports of electricity during a cold period where the temperature reaches its minimum, case 2

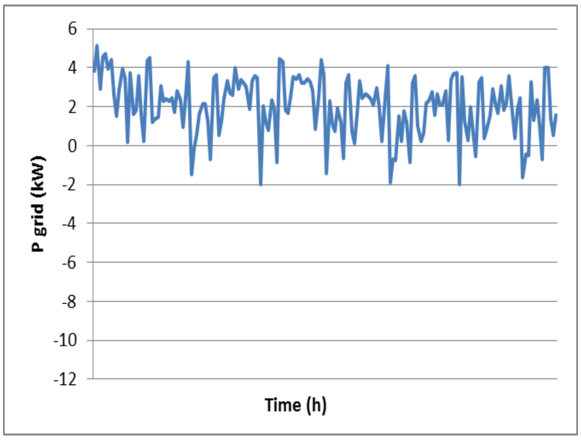

Figure 58: Imports and exports of electricity during a cold period where the temperature reaches its minimum, case 3

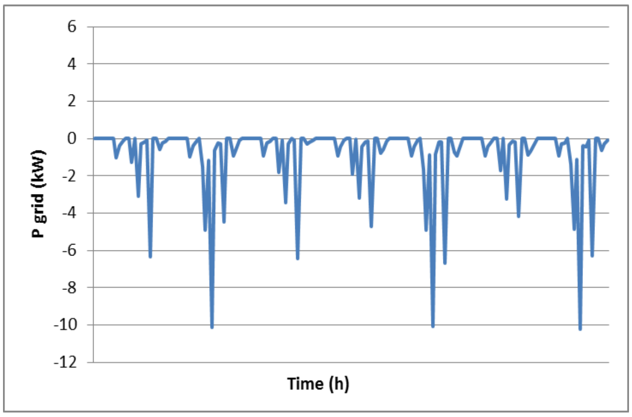

Figure 59: Import/exports during a cold period where the temperature reaches its minimum, case 4

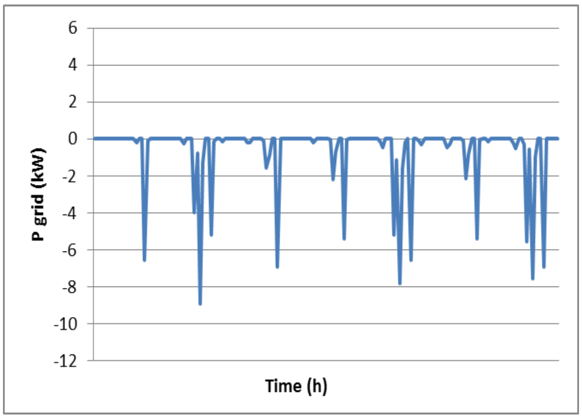

Figure 60: Imports/ exports during a cold period where the temperature reaches its minimum, case 5

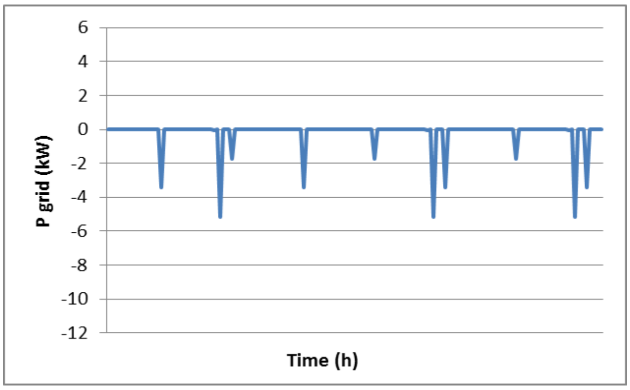

Figure 61: Imports/ exports during a cold period where the temperature reaches its minimum, case 6

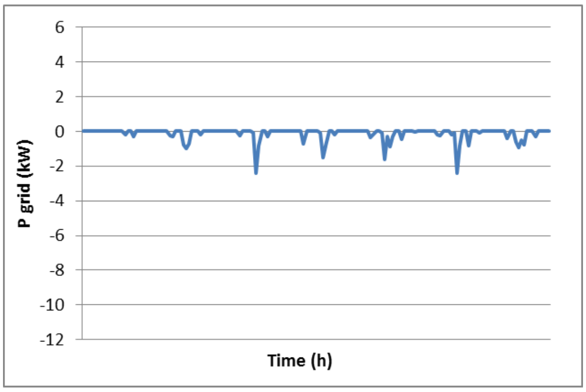

Figure 62: Imports/ exports during a cold period where the temperature reaches its minimum, case 7

As the profile for case 8 and 9 was similar to case 2, these graphs are not included. As can be seen in case 2, a large amount of exports are present, but also significant amount of imports are required as heat and electricity does not peak at the same time. For case 3, when the electricity peaks are shaved by the implemented load management, it is seen that the amount of imports are reduced remarkably. For case 4-7 exports are not present either because the electrical surplus restriction in follow thermal mode, or that the CHP is set to follow the electricity demand of the building.

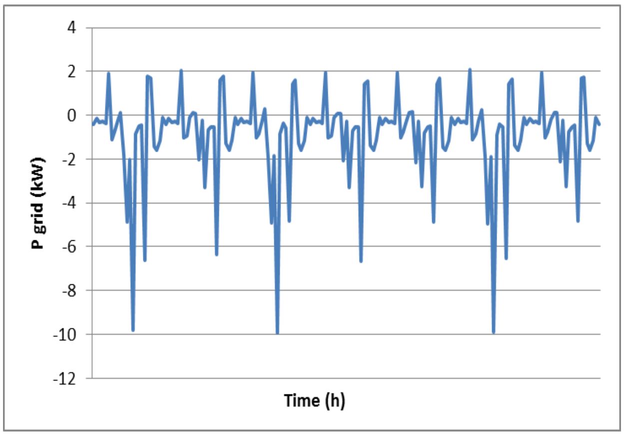

Figure 63: Imports and exports of electricity during a warm period where the temperature reaches its maximum, case 2

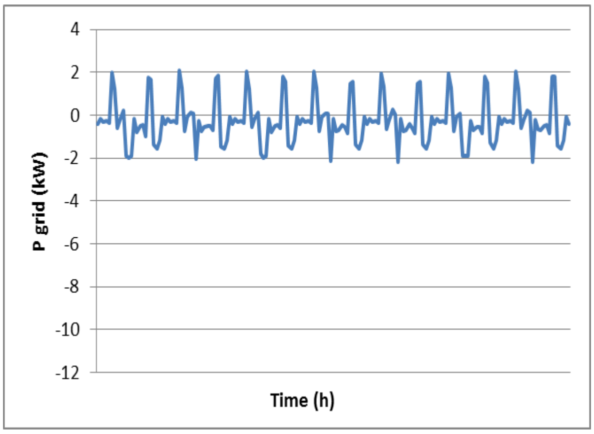

Figure 64: Imports and exports of electricity during a warm period where the temperature reaches its maximum, case 3

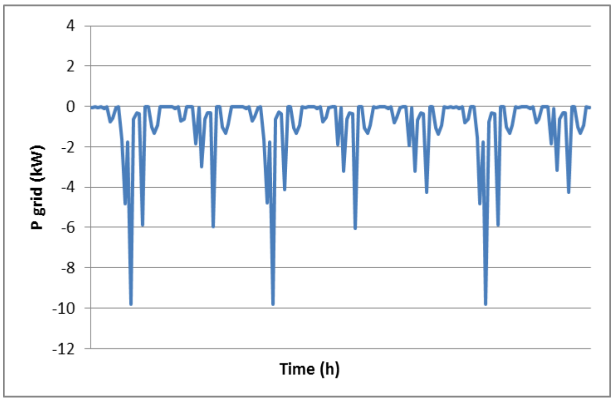

Figure 65: Imports and exports of electricity during a warm period where the temperature reaches its maximum, case 4

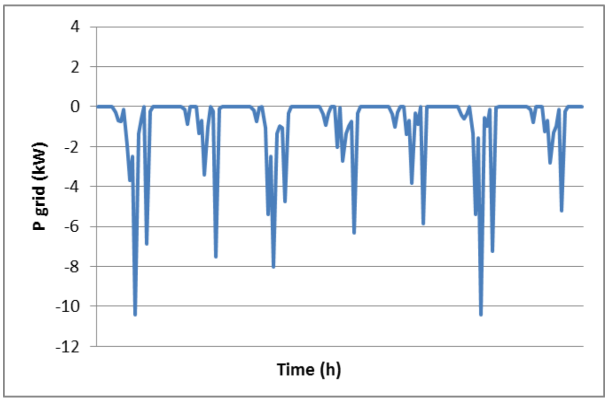

Figure 66: Imports and exports of electricity during a warm period where the temperature reaches its maximum, case 5

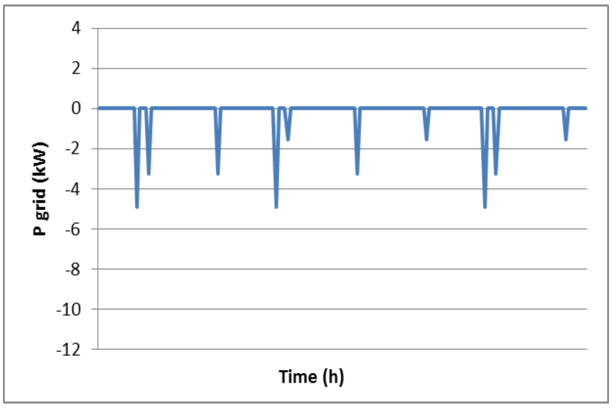

Figure 67: Imports and exports of electricity during a warm period where the temperature reaches its maximum, case 6

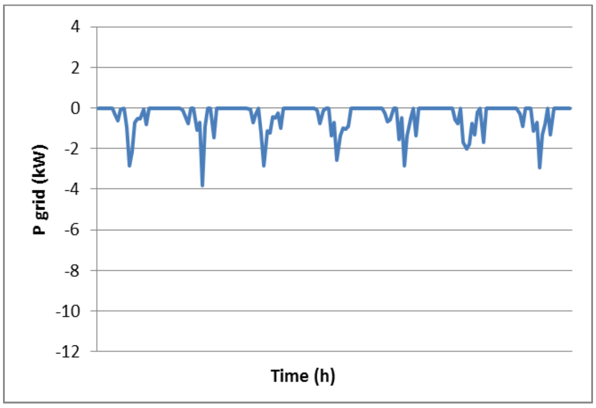

Figure 68: Imports and exports of electricity during a warm period where the temperature reaches its maximum, case 7

Figure 63-Figure 68 show the corresponding import/exports graphs for case 2-7 during a warm period when the temperature reaches its minimum. For case 2 and 3 in follow thermal mode, the amount of exports are less present for this period than it was for the cold period. This is expected as heat and electricity is produced simultaneously and the electricity production follows the heat production. As the amount produced electricity is higher during the cold period, the amount of electricity imports is lower than for the warm period. This shows that the operation of the CHP device in follow thermal mode is more beneficial in periods where the heating demand is high. The amount of imports needed for the two cases has also increased some as the generator produces less electricity due to less heat demand of the building. The cases which are restricted after electricity demand (4-7) has less seasonal variations as the electricity demand remains fairly constant over seasons.

The impact of the electric surplus limitation to the thermal load following operation implemented in case 4 is greater during the heating season and specifically the coldest months when the thermal demand is highest. Without the restrictions, it was produced remarkably excess electricity which was exported to the electricity grid. During the summer months, when there is no demand for space heating, the only thermal demand of the building is for domestic hot water. This resulted in lower exports in case 2, and therefore the impact of the surplus restriction was not that present.

For the electrical following cases (5-7), it is seen that allowing thermal surplus results in lower electricity imports as the generator can cover a larger part of the electricity demand. Also, the implementation of thermal surplus restriction in case 5 and 7 was most notable during the warm period. This is because the thermal demand is lower, which restrict the electricity production. Implementing load management (case 7) resulted in reduced amount of imports even with thermal restriction as the electricity demanded by the building is lower, and the high peaks are not that present.

One of the main purposes with CHP is to enable on-site electricity generation as well as heat. This reduces the dependence on grid electricity. It is therefore interesting to look at how much of the electricity demand the CHP can cover for each seasons, and how much is exported. Table 13 show the average proportion of electricity demand met by CHP and the average daily electricity exports for the heating season, mid-season and the summer. Heating season is defined from January-March and November-December. Mid-season is defined as the months April, May and October, and the summer season is defined as June to September. The definition of the seasons is based on studies from Peacock and Newboroug (Peacock & Newborough, 22. June 2005).

Table 13 shows the average proportion of electricity demand met by the CHP for each season and the average daily electricity exports for all cases simulated. In all cases, except case 6, the CHP device meets the highest proportion of the electricity demand during the heating season, and meets the lowest proportion of electricity demand during the summer. For the cases with present exports, it can also be seen that the average daily amount is highest during heating season and lowest during the summer. This is expected as production follows demand.

	Period of year	**Average proportion of daily electricity requirement met by micro-CHP generation (%)**	**Average daily electrical energy exported (kWh)**
Case 2	Heating season (January-March, November, December)	61.99	52.31
	Mid-Season (April, May, October)	35.67	20.82
	Summer (June-September)	23.52	9.349
Case 3	Heating season (January-March, November, December)	66.72	59.73
	Mid-Season (April, May, October)	39.45	25.61
	Summer (June-September)	26.02	12.099
Case 4	Heating season (January-March, November, December)	80.96	0
	Mid-Season (April, May, October)	73.17	0
	Summer (June-September)	67.65	0
Case 5	Heating season (January-March, November, December)	82.58	0
	Mid-Season (April, May, October)	72.136	0
	Summer (June-September)	68.83	0
Case 6	Heating season (January-March, November, December)	97.855	0
	Mid-Season (April, May, October)	97.97	0
	Summer (June-September)	97.86	0
Case 7	Heating season (January-March, November, December)	92.018	0
	Mid-Season (April, May, October)	80.98	0
	Summer (June-September)	77.423	0
Case 8	Heating season (January-March, November, December)	60.34	51.809
	Mid-Season (April, May, October)	30.82	21.02
	Summer (June-September)	18.42	9.583
Case 9	Heating season (January-March, November, December)	61.99	52.31
	Mid-Season (April, May, October)	35.67	20.82
	Summer (June-September)	23.52	9.349

Table 13: Average proportion of electricity demand met by CHP and average daily electricity exports

The proportion of daily electricity requirement met by micro-CHP generation is increasing when implementing the load management in case 3 compared to case 2. This is mainly because the high electrical peaks are avoided, which make it possible for the generator to cover more of the buildings electricity demand when the unit is on. As the electricity demand is reduced, so is the amount of required imports. This leads to a larger amount of exports, as the building demands less electricity. However, the average amount of electricity covered by the CHP has not increased as much as the imports have been reduced. The main reason for this is that the load management shaves the electricity peaks, but the amount of electricity produced by the CHP remains the same. Therefore the main benefit is the avoided electricity imports rather than the increased amount of building demand covered by the CHP.

Since the main benefit off using load management as an operational strategy is the reduced grid interaction as the electricity peaks are shaved, an comparison in daily production from the CHP versus imports and exports between case 2 and 3 is off interest. In Figure 69 and Figure 70 this is seen for a cold day.

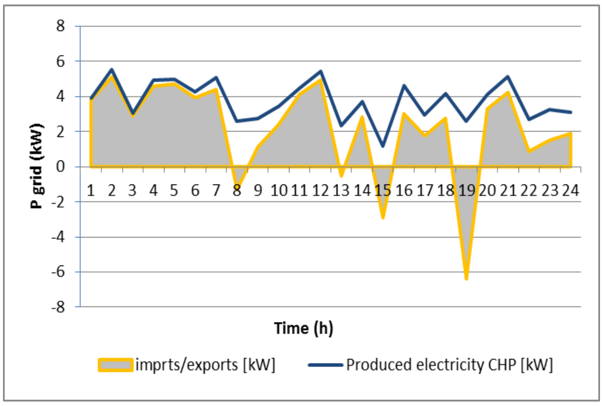

Figure 69: Own generation and exported-imported electricity balance cold day case 2

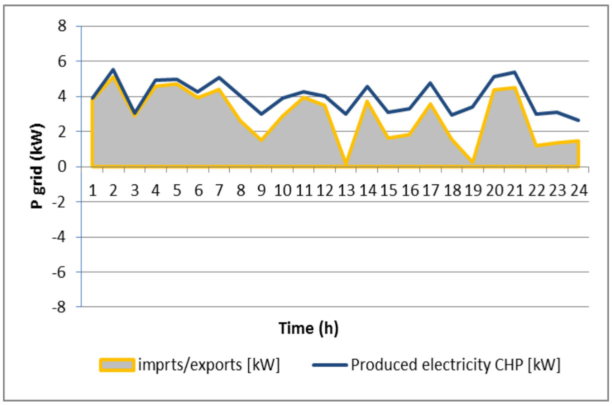

Figure 70: Own generation and exported-imported electricity balance cold day case 3

The negative values represent the imports, while the positive values represent the exports for the import/export curve. The difference between the produced electricity and the import/exports curve represents the electricity demand of the building. The demand of the building is the interval between the produced electricity and the import/export graph. As seen, by implementing load management the amount of imports required during the cold winter day is eliminated. The micro-CHP is capable of covering the entire demand, and only exports which are considered beneficial are present.

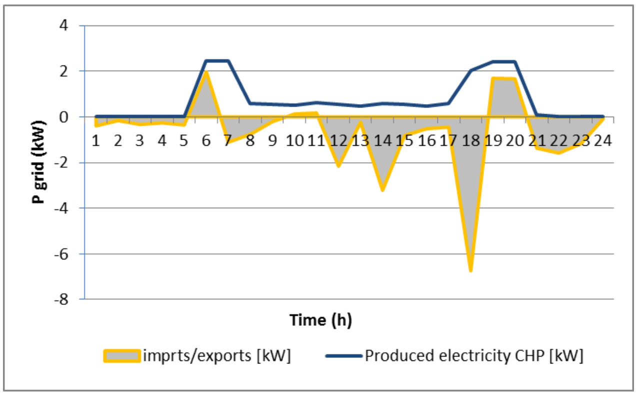

Figure 71: Own generation and exported-imported electricity balance warm day case 2

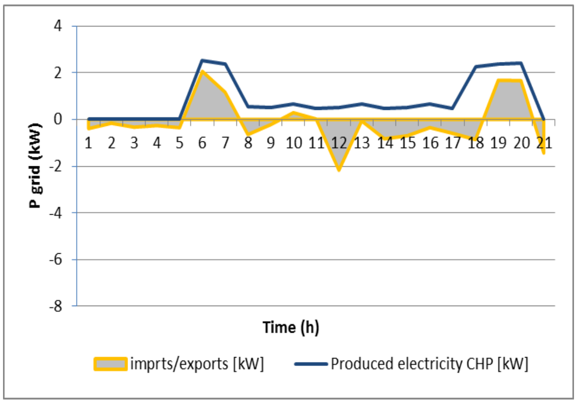

Figure 72: Own generation and exported-imported electricity balance warm day case 3

As can be seen from Figure 71 and Figure 72, the effect of load management pay a significant role in the amount of grid imports required also during the warm season. However, as the electricity produced most of the time is relatively small since the heat demand is low, the micro-CHP will not be able to cover as much of the demand as it was during the heating season, even with load management. To be able to cover the entire demand during these periods, the demand does either have to be further restricted after the domestic hot water usage or an electrical storage has to be implemented to store the surplus electricity for times with electricity deficit.

For case 4, on the other hand, the impact of the seasonal variations does not pay too much of an impact as can be seen in Figure 73 and Figure 74.

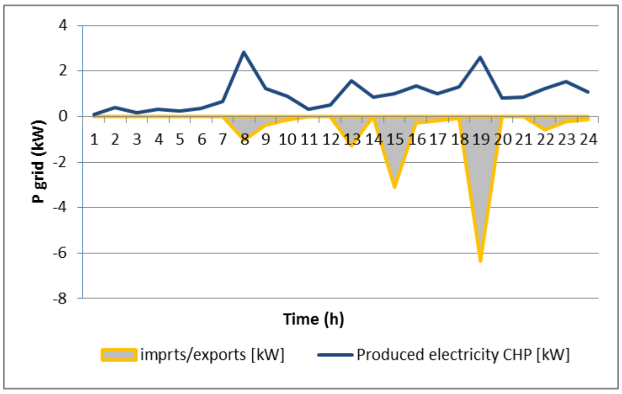

Figure 73: Own generation and exported-imported electricity balance cold day case 4

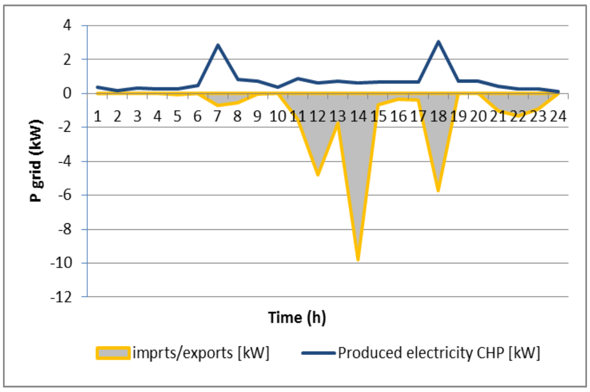

Figure 74: Own generation and exported-imported electricity balance warm day case 4

As electricity exports are not allowed, the produced electricity is significantly lower than it was for case 2 and 3. The times where electricity imports are required represents the times where the thermal demand restricts the electricity output as it is set to follow the thermal demand. Comparing to case 2 as was seen in Figure 69 and Figure 71, for the cold and warm period respectively, it can be seen that the produced electricity has been reduces significantly by implementing the restriction, especially for the cold day.

The seasonal and hourly variations in building demand and operating mode of CHP affect how the generator operates and its capability to cover the electricity demand. Figure 75 represents the yearly proportion of demand covered by CHP versus utility grid for the simulated cases. The corresponding values can be seen in Table 14.

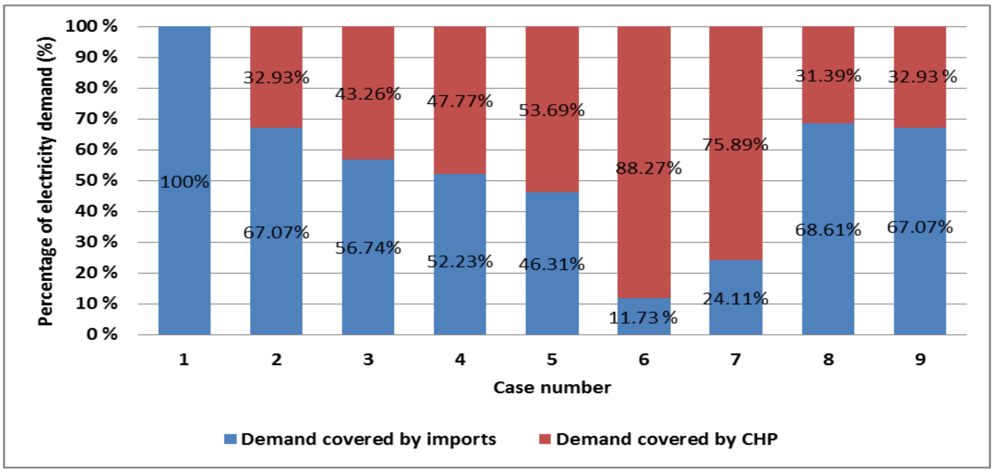

Figure 75: Proportion of demand covered by CHP versus utility grid, all cases

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**	**Case 9**
El produced CHP [kWh/m^{2}a]	-	34.86	37.28	15.26	17.14	28.19	18.09	34.31	34.86
Imports [kWh/m^{2}a]	31.93	21.42	11.44	16.68	14.80	3.75	5.75	21.91	21.42
Exports [kWh/m^{2}a]	-	24.34	28.56	0	0	0	0	24.28	24.35
Demand [kWh/m^{2}a]	31.93	31.94	20.15	31.94	31.96	31.94	23.84	31.94	31.94
% of demand covered by imports	100	67.07	43.26	47.77	46.31	**11.73**	24.11	68.61	67.07
% of el produced exported	-	69.83	**76.61**	0	0	0	0	70.77	69.83

Table 14: Electricity distribution case 1-9

By operating the CHP in follow electrical mode, less imports are required from the public grid as the generator is capable to cover a larger part of the electricity demand of the building. The greatest reduction in grid imports is seen in case 6, where the amount is reduced to 11.73%. The generator is here able to cover almost the entire electricity demand of the building. However, as reviewed in section 8.3.2, system losses became greater as heat were vented from tank due to overheating at times when the thermal demand of the building was significantly lower than the heat supplied from the generator. The greatest amount of exported electricity is seen in case 3, when load management is implemented. The amount of exports does in this case represent 76.61% of the produced electricity. The reason to this high amount of exports is due to mismatch between demand and supply as the generator is set to follow the thermal demand of the building. As electricity and heat peaks at different hours of the day, substantially more electricity is produced at times when the thermal demand is high and the electrical demand is low. The amount of imports required to cover the demand is in case 3 is 56.74% compared to 67.07% in case 2. To improve the systems capability to cover a larger amount of the electricity demand in follow thermal mode, electrical storage could be implemented to store the surplus electricity for times with electricity deficit. For better matching between supply and demand, the electricity and heat peaks in the building should happen at the same time. However, this is not realistic as electricity and heat often not peaks at the same time. But restrictions can be done in the electricity demand. A well-functioning load management can result in better operational conditions for the CHP generator and make it a better match for the building.

Limiting the electrical surplus in follow thermal mode (case 4) enables the generator to cover a larger amount of the electricity demand. The amount of grid imports required has decreased from 67.07% to 47.77 %. This means that the generator better matches the building’s electricity demand. Compared to the reference case with the condensing gas boiler and grid electricity, however, this reduction is still significant.

Both case 5 and 7 meets a higher proportion of the electricity demand compared to the cases in follow thermal mode. By implementing load management, a higher proportion of the electricity demand is met as the electricity demand of the building is lowered and high peaks are avoided. For case 6, the thermal demand of the building has not an impact on the electricity produced and did therefore represent the greatest reduction in grid imports.

Increasing the thermal storage, however does not lead to improved grid interaction compared to case 2, and the amount of imports has increased with ~1%.

8.8 CO_2- emissions

One of the promoting arguments in using CHP is the allover resulting CO_2 savings compared to the conventional gas boiler. However, these savings depend on the emission factor for each of the energy sources used. Table 15 show the CO_2 production coefficient used in the calculations.

	CO_2 production coefficients K (kg/MWh)		
	NS-EN 15603:2008	SAP 2012	Net-ZEB definition (yearly average 2014-2029)
Natural gas	277	-	-
Biogas	-	98	-
Electricity	617	-	269.7

Table 15: CO_2- production coefficients (NS-EN 15603:2008, 2008) (Dokka, 2011) (Pout & BRE, 2011)

As can be seen, the CO_2 production coefficient for electricity using the net-ZEB definition is substantially lower than today's UCPTE electricity mix. This will affect the environmental benefits of implementing CHP. In the results, the value of HHV is used for the delivered energy to calculate the CO_2- emissions related to this energy.

The emissions coefficient for the electricity using NET-ZEB definition is calculated based on equation 29 taken from the "Proposal for CO_2-factor for electricity and outline of a full ZEB-definition" (Dokka, 2011):

$$K_{el}(t) = \begin{cases} 361 - 8.3 \cdot [t_{yr} - 2010], & t_{yr}\ between\ 2010\ and\ 2055 \\ 0 & ,\ t_{yr}\ after\ 2055 \end{cases} \tag{29}$$

Where,

$K_{el}(t)$	is the CO_2 factor for electricity for year t, in g/kWh;
t_{yr}	is the actual year;

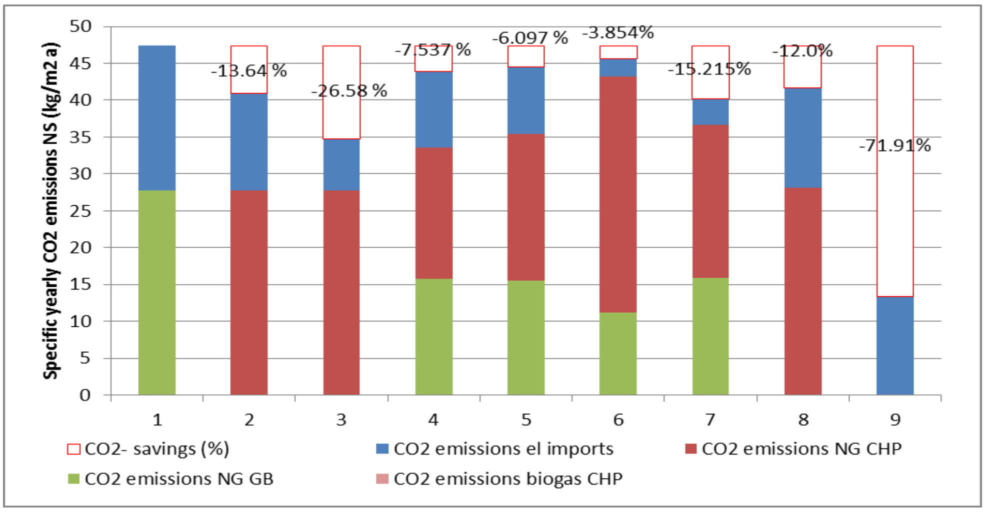

Figure 76: CO_2 emissions UCPTE electricity mix

On an environmental perspective the cases in follow thermal mode achieves the highest amount of CO_2-savings compared to the reference case (1) as can be seen in Figure 76. Case 2 represents 13.64% CO_2-savings compared to the reference case. To achieve low CO_2 emissions, it is preferable to have a system with steady production and few operational cycles. As can be seen, using the emission factor for the current UCPTE electricity mix, CO_2 savings are achieved. By implementing load management as was done in case 3, higher CO_2 savings are achieved, and the amount has increased to 26.58 %. This indicates that buildings with more stable electricity demand is beneficial for the CHP operation, and where the relation between the thermal demand and electrical demand is higher. By limiting the electrical surplus as was done in case 4, on the other hand the CO_2 savings were reduced to 7.537%. Likewise, it is seen that for the electrical following modes, the CO_2 savings are in general lower except for case 7 where load management is implemented. However, the savings are still lower than for case 3 with load management in follow thermal mode, and has savings of 15.2% compared to the reference case 1. Implementing increased thermal storage did not result in greater CO_2 savings and the savings are 1.61% lower than for case 2.

The greatest CO_2 savings are achieved in case 9, when upgraded biogas is used as fuel. This is as expected, as biogas is considered a CO_2 neutral fuel. Using the substitution principle for exported electricity as presented in section 4.4, the CO_2 emissions from biogas fuel are completely limited. This result in 71.91% CO_2 savings compared to the reference case. In reality these savings would be lower as it would require a higher amount of regular biogas to achieve the upgraded biogas. However, the results represent its potential. However, it has to be notified that the CO_2 production factor for biogas is taken for SAP report for proposed carbon emission factors and primary energy factor, while the factor for natural gas is taken from NS-EN 15603:2008. The CO_2 production factor for natural gas in SAP's report is 202 kg/MWh, while in NS-EN 15603:2008, an average value for gas is stated to be 227 kg/MWh. Using the corresponding factor for natural gas from SAP's report would have made the total CO_2 savings for CHP with biogas slightly smaller. However, as the factor from NS-EN 15603:2008 is used for the rest of the results, it will be kept the same for clarity sake. Biogas does in either of the two cases achieve significantly CO_2 savings compared to the conventional case with natural gas.

As the CHP is operated during the whole year, the seasonal variations in emissions savings are of interest. Figure 77 show the daily CO_2 savings for case 2, 3 and 4 compared to the reference case 1.

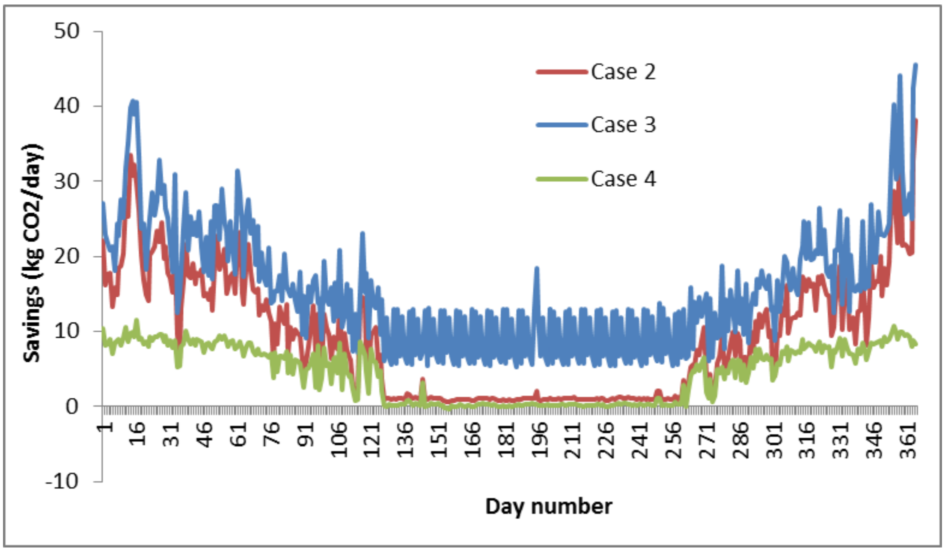

Figure 77: Yearly distribution of CO_2-savings for case 2, 3 and 4-UCPTE mix

As can be seen, the CO_2 savings are greatest during the heating season when the thermal demand of the building is higher. This is mainly because the generator produces more electricity and thus, the amount of imports needed to cover the electricity demand is reduced during these months. It can be seen that the overall savings are highest in case 3. The difference is most notable during the summer, as the savings for both case 2 and 4 are small here. Case 4 achieves the lowest CO_2 emissions of the three cases, and has smaller variations between summer and winter. This is mainly because the electricity demand restricts the thermal and electrical output of the CHP, which results in no electricity exports to be substituted from the amount produced. During the summer it can be seen that for case 2 and 4, the CHP does barely result in CO_2 savings as the efficiency of the CHP is poorer when the load is smaller.

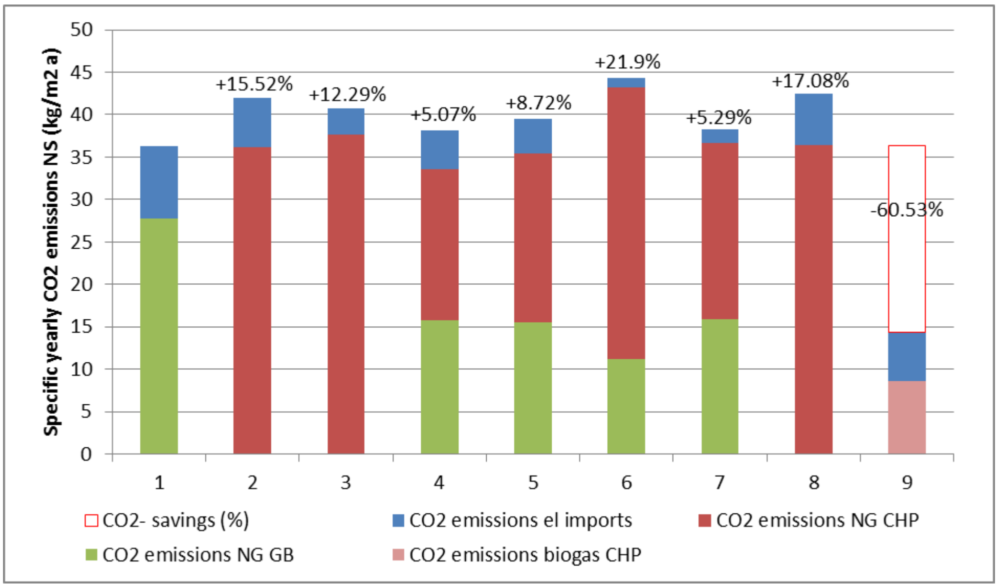

Figure 78: CO_2 emissions NET-ZEB definition of electricity mix

In a NET-ZEB perspective, however, it can be seen in Figure 78 that the resulting CO_2-emissions for the CHP cases become poorer. Calculating based on NET-ZEB emission factor for the yearly average from now until 2029, an addition of 15.52% in CO_2 emissions is seen in case 2. Case 3 represents a better environmental fit on a future perspective than case 2, but does however not achieve savings compared to the reference case. An increase in CO_2 emissions of 12.29% is seen. Case 4 represents the best fit for the CHP regarding CO_2 emissions on a future perspective when using natural gas as fuel source. Only a small increase of 5.07% is seen compared to the reference case. Case 6 is seen as the less beneficial CHP case on a future perspective, increasing the CO_2 emissions with 21.9%. The only case who achieves savings on a future perspective is case 9, where renewable upgraded biogas is used as a fuel. As this fuel is carbon neutral, it will contribute to low emissions, and large CO_2-savings are seen also in a NET-ZEB context.

It is therefore to conclude that using NET-ZEB definition will not be beneficial for the CHP system in the system cases where natural gas is used as fuel. It is seen that the cases with unlimited thermal or electrical surplus has the highest emissions. For the cases in follow thermal operation mode with unlimited electricity surplus this is explained by the huge amount of exported electricity. When the emission factor for grid electricity is low, exports will no longer be as beneficial for the CHP. A remarkable addition in CO_2 emissions is seen, which makes the CHP case not to be a sustainable option compared to the gas boiler on a future environmental perspective. The CO_2 factor for electricity is expected to decrease over the upcoming years as electricity production is becoming greener (Dokka, 2011). This questions the benefits on a future basis of implementing residential CHP on a CO_2 perspective. Therefore, the CHP system should represent a net benefit in CO_2 emissions also on a future perspective in order to be a sustainable option. The use of renewable fuel should be further investigated, and pilot project should be developed to enable an efficient operation in practice also on these fuels. If this is obtained, huge environmental benefits will result as was seen in case 9.

These results indicates that in areas where electricity is derived from high carbon fossil fuels, such as coal or peat, the uptake of micro-CHP on site can give significant CO_2 reductions. However, in areas where electricity is derived from more renewable sources, such as in Norway, where 99% of the electricity generation comes from hydropower, CHP fueled on natural gas will not be beneficial in an environmental perspective. This corresponds well to what former studies from SEAI have concluded as well (SEAI, 2011). Fueled on renewable fuels, however, the CHP represent a reduction also on a future perspective and is a more viable option. Aspects like security of supply, economic cost and efficient upgrading processes of biogas have an impact on the sustainability and degree of implementation on a future perspective.

9. Discussion and comparison to former studies

From the results, it has been seen that a heat-driven operation of the CHP is optimal for dwellings with low heat to electricity ratio, as surplus heat is avoided. As well, electricity exports are seen as beneficial in a net-ZEB context as they contribute to avoided electricity production from larger power plants with higher primary energy consumption and CO_2-emissions. For such operation, the most common operation is grid-parallel operation as a connection to the public grid is essential to avoid electricity loss. For the heat-lead operation, a connection to the public grid is needed if battery storage is not implemented. This leads to a need for a well-functioning integration and that the electricity fed into the grid is able to be used and will result beneficial for the consumers both on an environmental and economic perspective. According to a study funded by the UK government and conducted in co-operation with electricity distribution companies, existing distribution networks could accommodate up to a 50% penetration of all households with micro-CHP before there would be any notable impact on the electricity network (Energy saving trust, 2005). However, to make it possible for the ICE-generator to work nearly as a micro power station providing the grid with electricity, it is necessary with monetary compensation for the electricity fed into the grid. This can be done by feed-in tariffs, net-metering or time-of use metering (Alanne, Micro-Cogeneration-I : Introduction).

When implementing follow electrical operation scheme for the CHP, elevated tank temperatures was seen, especially during the summer months, if thermal surplus restriction was not implemented. This can be explained by the CHP device simultaneously production of heat and electricity. As the electricity demand will remain more-over constant throughout the year, while the thermal demand is significantly lower during the summer, excess heat production will result. This heat is stored in the tank until the temperature exceeds its upper limit and venting is needed. This amount of heat will get lost if seasonal storage is not implemented, which is not desirable for the system. As seasonal thermal storage was not an option in this thesis, implementation of a control sensor on the supply temperature from the tank, and thus restricting the thermal surplus was done. This restricted the operation of the CHP to only operate until the tank was heated to its upper limit that was set to be 75°C. Temperatures were decreased to remain within a stable limit, and vented heat lost to the environment was avoided. This operation of the device is so-far not well tested and most of the in-market CHP products are constructed to follow the thermal demand of the building. Further research should be done to achieve a better operation in follow electric mode where the usage of seasonal storage for instance may be an important solution for improving the operation.

As elevated temperatures was seen for the CHP cases in follow electrical mode, it is desired that an emergency cooling unit should be installed in the return flow of the micro-CHP. This should be done in order to limit the return flow temperature at times when the thermal demand is low. This can be done by for instance installing heating plates to lead off the heat. These should be used as good as possible to not waste the heat, for instance in a drying room (Simader, Krawinkler, & Trnka, March 2006). Houses with swimming pool can use them as both emergency cooling unit and storage of excess heat by the use of heat exchangers.

When thermal surplus restriction was implemented on the follow electric mode it was seen that the yearly operation time decreased. Comparing to former studies done by A.D. Peacock and M. Newborough, this effect is common (Peacock & Newborough, 22. June 2005). In the study by Peacock and Newborough, the yearly operation time decreased with 12 %, while in this thesis, the thermal restriction reduced the operation time with 20.32%. The thermal surplus was also mostly seen during the warm season, which is also the case for the simulated cases in this report.

From an efficiency point of view, the highest CHP efficiency achieved was 75.15% in case 3. This was the case where the demand of the building did have higher heat to electricity ratio due to the implemented load management. This shows that for the ICE-device, buildings with higher heat to electricity ratios are desirable. According to Arsalis, Nielsen and Kær (Arsalis, Nielsen, & Kær, 2011) combustion-based systems, such as the internal combustion engine technology, are not suitable for micro-CHP applications mainly due to their high thermal-to-electric ratio, and also due to their low efficiencies at part-load operation. Fuel cell-based stationary power generation technology is capable of achieving high efficiencies, with lower emissions as compared to combustion-based systems. Compared to studies by Amir A. Aliabadi, Murray J. Thomson and James S. Wallace, a CHP efficiency based on HHV of 75.15% looks normal in the case of internal combustion engines (Amir, Murray, & James, 22/01- 2010).

To achieve higher efficiencies for CHP, it is possible to use condensing CHP devices. Senertec Dahs has devices with a condenser coupled to it. These devices can, according to Dach-Senertec webpages, achieve efficiencies up to 92% (based on HHV) and 102% (based on LHV) if driven at full load operation. Without the condenser, the efficiency is 79% (based on HHV) and 88% (based on LHV). The condenser makes it possible to provide an additional 2.5 kW of heat by utilizing the latent heat (SenerTec UK, 2014).

The choice of operating mode and strategy to be applied to the CHP system depends on the building, the region where it is implemented, the electricity prices, the availability of storage and the characteristics of the CHP device used. For buildings with high thermal demand compared to electrical demand, combustion based micro-CHP systems achieves good operational characteristics. As it was seen in this thesis, all cases achieved higher efficiency during the heating season, when more heat was demanded by the building. However, as the thermal demand of the building is expected to decrease over the upcoming years due to better insulated building envelope, the combustion based CHP devices should be able to achieve higher power to heat ratio. This is especially important in electrical following operation to avoid excess heat production, and thus waste the heat.

Another challenge for power control is that for the usual present micro-CHP technologies it is only available on/off operation and it may be required to have long start-up and shutdown periods. Also, at start-up phase, a substantial fuel demand is needed and the existing micro-CHP devices have low part-load efficiency. Therefore, it has also been seen from previous studies that houses with a steady demand close to specific power output is preferable for micro-CHP appliances (Alanne, Micro-Cogeneration-I: Introduction). This corresponds well to the findings of this master. As was seen from the results, the implementation of load management resulted beneficial for the operation of the CHP. The electricity demand was shaved, which made the operation of the CHP in both heat-led and electricity-led mode better. For further increased performance, an operation where the generator could operate near its full load power output would have been beneficial, as it was seen that when the generator operated at higher loadings, the performance of the system improved.

In order to achieve an optimal operation of the CHP, a grid-connected system should be established. An infrastructure where electricity feed-in to the public grid is important for an optimal operation of the CHP in dwellings with low electrical demand and high thermal demand. To avoid restriction in thermal output of the generator due to low electricity demand, either exports or battery storage should be available to ensure a stable operation of the CHP. On-site electricity production fed in to the public grid results in avoided electricity production from larger power, which results beneficial in a net-ZEB context.

10. Conclusions

In this thesis, the performance of different operational strategies applied to a micro-CHP system supplying a multi-family building built after the Norwegian building norm, TEK10, has been investigated. To evaluate the performance of a micro-CHP device, a detailed model of the system was needed in order to predict the electrical and thermal performance with sufficient temporal resolution and accuracy. All strategies have been compared to a high-efficient condensing gas boiler, which represents the best system available in the market. A high-efficient condensing gas boiler was chosen in order to evaluate the possibilities for increased market penetration for CHP technology.

Two operating mode have been reviewed. First, the CHP-device was set to meet the entire thermal demand and part of the electricity demand. Then the CHP was restricted to follow the thermal demand but only until the electrical demand limit was reached. The result of this was that the CHP-device only covered parts of the thermal and electrical demand. Afterwards, the CHP-device was set to cover the entire electrical demand of the building, and the corresponding part of the thermal demand possible under this operation which was implemented both with and without thermal surplus restrictions. In the case were thermal surplus was allowed, the CHP-device was able to cover almost the entire electrical demand of the building. However, this impacted the system efficiency as system losses increased due to wasted vented heat from the tank. With thermal surplus restriction, wasted heat was avoided, but resulted in lower operation time of the CHP-device and less of the electricity demand covered by the CHP. To enable the generator to cover a larger part of the electricity demand, even in the restricted mode, load management was implemented. This lead to higher system efficiency, primary energy savings, more reduced grid interaction and higher CO_2-savings than the restricted case without load management. The cases in follow thermal mode had significant amount of electricity exports, especially in the heating season due to high thermal demand of the building. Implementing restriction in electricity surplus impacted the efficiency of the CHP as the generator had to operate more time at part load ratio. This implies that grid connection is essential for achieving good operation of CHP in thermal following mode.

For primary energy, it was found that case 9 with upgraded biogas as fuel in follow thermal operation mode gave highest primary energy savings. The savings obtained was 34.3%. A part from the usage of renewable fuel it was seen that implementation of load management had positive effect on the operation as it shaved the electricity peaks. This resulted in higher primary energy savings compared to the other cases due to less electricity imports and increased exports which is seen beneficial in a net-ZEB context. Implementation in thermal following mode resulted in primary energy savings of 31.29% compared to the reference case. Implementation in electrical following mode, however, resulted in lower savings and represented only 17.69% compared to the reference case. In general, it was seen that the cases which followed the electrical demand of the building achieved less primary energy savings than the cases which followed the thermal demand of the building. The lowest primary energy savings was achieved in case 6, with savings of only 6.98% compared to the reference case.

Regarding energy efficiency, it was seen that case 9 achieved the best system efficiency based on primary energy with a value of 70.7% based on HHV. This case represented a 20.8% increase in system efficiency compared to the reference case. In general, it was seen that the cases in follow thermal mode achieved better system efficiencies than the cases in follow electrical mode. The implementation of load management also had a positive effect on the system efficiency, and case 3 represented the second best efficiency, with an increase of 13.8% compared to the reference case. This case also had the best CHP efficiency, with a value of 75.1% on a HHV basis. The poorest CHP efficiency was seen in case 5, with a value of 63.3% on a HHV basis. The electrical efficiencies were best for the cases in follow electrical mode, while the thermal efficiencies were best for the cases in follow thermal mode. However, the reduction in efficiency was most pronounced for the thermal efficiency, and therefore had most impact on the resulting fuel efficiency.

Regarding reduced grid interaction, it was seen that case 6 resulted in the highest reduction in imports from the public electricity grid. Imports were reduced to 11.73%, making the CHP able to cover 88.27% of the building's electricity demand. However, this impacted the system efficiency as significant amount of heat was wasted during the summer months due to overproduction of heat. Implementing restriction in thermal surplus lead to higher dependency on grid electricity as was seen in case 5. 45.31% of the annual electricity demand was in this case imported from the grid. Implementing load management to this mode resulted in the highest reduction in grid dependency without affecting the temperature and thus avoiding wasted heat. Grid imports represented in this case 24.11% of the yearly demand, which is a significant reduction compared to the reference case. As expected, the highest amount of exports was seen in the follow thermal mode, where case 3 represented the largest part due to the implemented load management. The exports represented 76.61% of the produced CHP electricity.

Regarding the operational characteristics, it was seen that follow electrical mode did achieve more continuously operation compared to the follow thermal operation. This was mainly due to that the electricity demand was more constant throughout the year. The CHP operation was therefore less affected by temporal variations and transient heat loads. However, for the cases with thermal surplus restriction in follow electrical mode, the operational hours was reduced as this restricted the operation. The operational hours was in this case, as well as for the follow thermal mode cases, lower during the summer than the winter due to the reduction in building heat demand.

Regarding CO_2-emissions, it was seen that the use of upgraded biogas resulted in the highest CO_2-savings when using both CO_2-factor for the UCPTE electricity mix and the Net-ZEB definition. By using the UCPTE electricity mix, 70.9% CO_2-savings was achieved for case 9 compared to the reference case, while using the NET-ZEB definition, 60.53% CO_2 savings was achieved. This indicates that the usage of renewable fuel with same characteristics as natural gas in CHP represents significant environmental benefits. However, the use of natural gas resulted in less savings. When using the UCPTE electricity mix, savings were achieved in all cases, while when using the NET-ZEB definition, neither of the cases gave reduced CO_2 emissions compared to the reference case. For the UCPTE electricity mix, highest CO_2 savings was achieved in case 3, representing a 26.58% reduction in emissions compared to the reference case. The lowest CO_2-savings was seen in case 6, representing only a 3.85% reduction. The net-ZEB definition represents a cleaner electricity production, while the UCPTE electricity mix represents a mix highly dependent on fossil resources. It can therefore be concluded that micro-CHP gives significant CO_2-reductions in areas where electricity is derived from high carbon fossil fuels. However, in areas where electricity is derived from more renewable sources, such as in Norway, where 99% of the electricity generation comes from hydropower, CHP fueled on natural gas will not be beneficial in an environmental perspective. The usage of renewable fuels is therefore essential in such areas to make micro-CHP be a competitor to the conventional gas boiler.

11. Recommendations for further work

Simulations in this thesis were performed on a well-insulated multifamily building constructed after TEK10 (Kommunal- og regionaldepartamentet, 2010). For further studies, the use of micro-CHP to supply a building construction after passive house requirements should also be evaluated. It has been shown in previous studies that poorly insulated dwellings with high thermal heating demand achieves higher efficiency in the CHP system than well insulated envelopes with lower thermal heating demand (Kelly N. , Clarke, Ferguson, & Burt, 2008).

It would also be interesting to evaluate the effect of using a smaller generator, which is set to meet part of the thermal demand and part of the electrical demand at its full load operation. In this way, the CHP should be sized to only cover the base load of the building, and thus the generator would be less affected by temporal variations in demand and thus enable a more continuous operation at higher efficiency. According to Annex 42 final report, the CHP achieves optimal operation of the CHP device when it is implemented to cover 80-90% of the thermal energy demand of the building (Beausoleil-Morison, April 2008). With this operation, the CHP covers the base load, while the auxiliary boiler covers the peaks.

In the future the goal is to achieve zero energy / plus energy house / autonomous houses which are meeting the electrical demand by local generation. Micro-CHP is here a relevant option if the optimal operation is implemented. However, the challenges are that the thermal demand of residential buildings is decreasing significantly due to forthcoming low energy and passive construction standards. The electrical demand on the other hand may decrease, remain the same or even increase in the future. As the current micro-CHP technologies have relatively low electricity/heat ratio, a high electrical demand and a low thermal demand of a building may make it challenging for the CHP integration. This was seen from the simulation result in this thesis. When load management was implemented, the electricity demand was reduced, which made the heat to electricity demand relation greater, and the operation of the CHP was improved. An optimal operation of the CHP devices is therefore necessary in order to increase the efficiency and the viability of micro-CHP for market penetration.

Due to this development it is interesting to view different developments of integration of the CHP system. Devices with a higher electricity/heat ratio would make micro-CHP more competitive in the future as they could better match the demand of the building. More research should be done in this area, and pilot projects should be developed to better understand the operation of the CHP. This is because the existing simulation models only represent an approximation to the real life operation, but cannot predict exact answers. However, it gives an important view on which operational strategies that have the potential to improve the operation, and which strategies which will not. This eases the amount of necessary real life developments of demo-projects.

For further studies and research, focus on cooling applications based on micro CHP and absorption systems would also be interesting to investigate as this subject so far is not well understood. Further interesting aspects of development to review closer in upcoming studies are polygeneration and hybrid systems. Polygeneration is the simultaneously production of electricity, heat and cooling energy at various enthalpy levels, and fuel synthesis (e.g. hydrogen). In polygeneration, the fuel synthesis is the main product, and the electricity, heat and cooling are considered as by-products. In this way, fuel production is done as well as the by-products is well used to achieve high efficiency and avoid energy waste. However, this option is more common for large-scale plants rather than small-and micro-scale plants (ICPS, 2014).

In hybrid systems, the micro-CHP device is combined with other on-site production units such as solar, micro-wind and heat pump. For hybrid system to work properly a set of control configurations has to be implemented. Which device to cover what has to be reviewed in order to implement an optimal operation between the devices, and thus further increase the efficiency. Micro-CHP can thus be an option for use in isolated regions as it produces both heat and electricity. This would especially be relevant for buildings with no grid connection. The usage of an independent CHP system coupled with a battery system and a storage tank could ensure both heat and power supply to the dwelling. The usage of renewable fuel would further make this system more environmentally beneficial as was concluded from the results conducted in this thesis.

For future studies, optimal sizing of the micro-CHP for maximum economy would also be interesting to review. Further system in cooperation with auxiliary components such as adsorption heat pump to increase system efficiency and the total thermal output of the CHP should be analyzed in more detailed. This requires a proper analysis of the economic efficiency and viability of CHP, which is a central concept when evaluating the possibility of increased CHP implementation. The economical efficiency can be evaluated through familiar methods used in investment mathematics. Some of these methods are the annuity method, the net present value method and the internal rate of return method. In the annuity method, the annual capital cost will be calculated from the investments determined on the basis of an interest rate fixed with the owner and the corresponding period of use using the subsequent annuity. In this method, the annual cost of heat is added up, and the generated electricity is subtracted to find the annual cost of heat production (Simader, Krawinkler, & Trnka, March 2006). The net present value method calculates the present value of the investment. Using the net present value over the years of useful life gives both the payback period and the profit at the end of the period. This shows if the implementation will give a net benefit or a net deficit over its useful lifetime (Simader, Krawinkler, & Trnka, March 2006). In the last method, internal rate of return method, the actual percentage rate of return on the capital investment is calculated.

The possibilities for grid exports should also be analyzed in more detail in future studies. As this requires an appropriate infrastructure, and depends on different factors such as electricity prices, power capability of grid etc., the profitability of exports needs to be examined. If exports do not present a profit for the consumer, such operation will not be attractive as the consumers will always chose a technology over another based on economical savings as well as environmental savings. As long as other technologies are cheaper, and represent the same security of supply, it will be difficult for CHP to penetrate the market. When connecting a CHP device to the public grid, the economic cost is a major factor of interest which is not included in this thesis. According to Klobut, Ikäheimo and Ihonen, the connection cost may be up to 200-400€, and yearly counting cost is about 60€ (Klobut, Ikäheimo, & Ihonen). For a grid connection, a special meter has to be installed in order to measure the electricity injected to the grid by the micro-CHP device. Until now, this meter is the only available product in the market for an advanced grid connection and management (Klobut, Ikäheimo, & Ihonen).

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Appendix A: Storage tank parameters

Reference storage tank:

Storage tank parameters	**Value**	**Units**
Number of nodes	10	-
Tank volume	0.5	m^3
Tank height	1.6625	m
Tank shape	Vertical cylinder	-
Boiling point of tank fluid	98	°C
Heater 1 priority control	MasterSlave	
Heater 1 setpoint temperature	60	°C
Heater 1 deadband temperature difference	10	°C
Heater 1 capacity	2000	W
Heater 1 height	1.33	m
Heater 2 setpoint temperature	50	°C
Heater 2 deadband temperature difference	5	°C
Heater thermal efficiency	0.8	-
Fuel type	Natural gas	-
Off Cycle parasitic fuel consumption rate	0	W
Off Cycle parasitic heat fraction to tank	0.8	-
Off cycle parasitic height	0.5	m
Ambient temperature Indicator	22	°C
Uniform skin loss coefficient to ambient	0.546	W/m^2K
Skin loss fraction to zone	1	-
Off cycle flue loss coefficient to ambient temperature	0	W/K
Use side effectiveness	1	-
Use side inlet height	0.0	m
Use side outlet height	1.6625	m
Source side effectiveness	1	-
Source side inlet height	1.6625	m
Source side outlet height	0.0	m
Inlet mode	Seeking	-
Use side design flow rate	Autosize	m^3/s
Source side design flow rate	Autosize	m^3/s
Indirect water heater recovery time	0.75	hr
Additional destratification conductivity	0.1	W/m^2K

Appendix B: Specifications gas boiler

Model parameter	**Value**	**Units**
Fuel type	Natural gas	-
Nominal capacity	25 000	W
Efficiency curve temperature evaluation variable	Leaving boiler	-
Nominal thermal efficiency	0.89	-
Design boiler water outlet temperature (Tw)	70	°C
Max design boiler water flow rate	0.0021	m3/s
Minimum part load ratio (PLR)	0.10	-
Maximum part load ratio (PLR)	1.00	-
Optimum part load ratio (PLR)	1.00	-
Temperature upper limit water outlet	80	°C
Boiler flow mode	Not modulated	-
Parasitic electric load	0	W

Condensing boiler efficiency curve parameters:

A0	1.124970374	-
A1	1.014963852	-
A2	-0.02599835	-
A3	0.0	-
A4	-1.4046E-6	-
A5	-0.00153624	-
Minimum value of PLR	0.1	-
Maximum value of PLR	1.0	-
Minimum value of Tw	30.0	-
Maximum value of Tw	85.0	-

*Note: The efficiency curve did not work as expected throughout the simulation, but was kept as the example file with a condensing gas boiler in energy plus used the stated efficiency curve. Results were also simulated without the efficiency curve implemented, and the results were almost similar.

Appendix C: Specifications micro ICE- generator

Model parameter		**Value**	**Units**
Operating bounds	P_{max}	5500	W
	P_{min}	0	W
Maximum cooling water temperature	$T_{cw,out,max}$	80	°C
Maximum rate of change in fuel flow	$(\frac{d\dot{m}_{fuel}}{dt})_{max}$	∞	kg/s^2
Maximum net electrical power rate of change	$(\frac{dP_{net}}{dt})_{max}$	∞	W/s
Thermal mode characteristics	$[MC]_{eng}$	63605.6	W/K
	$[MC]_{HX}$	1000.7	W/K
	UA_{HX}	741	W/K
	UA_{loss}	13.7	W/K
Standby mode power use	$P_{net,standby}$	0	W
Warm-up characteristics	$t_{warm\text{-}up}$	60	s
Cool-down characteristics	$P_{net,\ cool\text{-}down}$	0	W
	$t_{cool\text{-}down}$	60	s
Electrical efficiency coefficients	a0	0.27	-
	a1-a26	0	-
Thermal efficiency coefficients	b0	0.66	-
	b1-b26	0	-

$[MC]_{eng}$ is the thermal capacitance of the engine control volume

$[MC]_{HX}$ is the thermal capacitance of the cooling water control volume

UA_{HX} is the overall thermal conductance between the thermal mass and the cooling water control volumes.

UA_{loss} is the effective thermal conductance between the engine control volume and the surroundings

Appendix D: Building parameters

Building parameters:	**Value**	**Units**
Total floor area	450	m^2
Area roof	150	m^2
Area glazed	60.3	m^2
Area door	2.00	m^2
Total air volume	1350	m^3
U-values		
Opaque	0.160	$W/(m^2K)$
Glazed	1.016	$W/(m^2K)$
Door	1.181	$W/(m^2K)$
Floor	0.145	$W/(m^2K)$
Roof	0.113	$W/(m^2K)$
Thermal bridges	0.06	$W/(m^2K)$
Infiltration rate	1.0	1/hr
SFP factor ventilation	2.5	
Heat recovery effectiveness	-	
Specific air amount in ventilation	1.2	$m^3/h \cdot m^2$
Ventilation fan pressure rise	100	Pa
Ventilation fan total efficiency	0.9	-

*Note: The infiltration rate should be 1.2

Appendix E: Pumps

Supply pump parameter (pump in loop between CHP or gas boiler and storage tank):

Model parameter:	**Value**	**Units**
Rated Flow Rate	Autosized by software	m^3/s
Rated pump head	2000	Pa
Rated power consumption	Autosized by software	W
Motor Efficiency	0.87	-
Pump control type	Intermittent	-

Circulation pump parameters (pump in loop between storage tank and building loads):

Model parameter:	**Value**	**Units**
Rated Flow Rate	Autosized by software	m^3/s
Rated pump head	1	Pa
Rated power consumption	Autosized by software	W
Motor Efficiency	1	-
Pump control type	Intermittent	-

Appendix F: ICE model engineering description

The micro CHP model used in EnergyPlus is an empirical model, but is dynamic in respect to the thermal heat recovery as the performance is a function of the engine temperature. The model is also dynamically in respect to possible warm up and cool down periods. The relevant model equations are the following and are taken from the EnergyPlus engineering references (US Department of Energy, 2013):

$$\eta_e = f(\dot{m}_{cw}, T_{cw,o}, P_{net,ss})$$
$$\eta_{th} = f(\dot{m}_{cw}, T_{cw,o}, P_{net,ss})$$
$$q_{gross} = P_{net,ss}/n_e$$
$$q_{gen,ss} = n_q q_{gross}$$

$$N_{fuel} = q_{gross}/LHV_{fuel}$$

$$\dot{m}^{t\to\Delta t}_{fuel} = \begin{cases} \dot{m}^{t\to\Delta t}_{fuel,demand} & if\ \frac{d\dot{m}_{fuel}}{dt} \le \left(\frac{d\dot{m}_{fuel}}{dt}\right)_{max} \\ \dot{m}^{t}_{fuel} \pm \left(\frac{d\dot{m}_{fuel}}{dt}\right)_{max} & if\ \frac{d\dot{m}_{fuel}}{dt} > \left(\frac{d\dot{m}_{fuel}}{dt}\right)_{max} \end{cases}$$

$$\dot{m}_{air} = f(P_{net,ss})$$

$$P^{t\to\Delta t}_{net} = \begin{cases} P^{t\to\Delta t}_{net,ss} & if\ \frac{dP_{net}}{dt} \le \left(\frac{dP_{net}}{dt}\right)_{max} \\ P^{t}_{net} \pm \left(\frac{dP_{net}}{dt}\right)_{max} & if\ \frac{dP_{net}}{dt} > \left(\frac{dP_{net}}{dt}\right)_{max} \end{cases}$$

$$[MC]_{eng}\frac{dT_{eng}}{dt} = UA_{HX}\left(T_{cw,o} - T_{eng}\right) + UA_{loss}\left(T_{room} - T_{eng}\right) + q_{gen,ss}$$

$$[MC]_{cw}\frac{dT_{cw,o}}{dt} = [\dot{m}C_P]_{cw}\left(T_{cw,i} - T_{cw,o}\right) + UA_{HX}\left(T_{eng} - T_{cw,o}\right)$$

Where,

η_e	is the steady-state, part load, electrical conversion efficiency of the engine [-]
η_{th}	is the steady state , part load, thermal conversion efficiency of the engine [-]
$\dot{m}_{cw}$	is the mass flow rate of the plant fluid through the heat recovery section [kg/s]
$T_{cw,i}$	is the cooling water inlet temperature through the heat recovery section [°C]
$T_{cw,o}$	is the cooling water outlet temperature through the heat recovery section [°C]
$P_{net,ss}$	is the steady-state electrical output of the system [W]
q_{gross}	is the gross heat input into the engine [W]
$q_{gen,ss}$	is the steady- state rate of heat generation within the engine [W]
LHV_{fuel}	is the lower heating value of the fuel used [J/kg or J/kmol]
N_{fuel}	is the molar fuel flow rate [kmol/s]
$\dot{m}_{fuel}$	is the mass fuel flow rate [kg/s]
$\dot{m}_{air}$	is the mass flow rate of air through the engine [kg/s]

$[\boldsymbol{MC}]_{\boldsymbol{eng}}$	is the thermal capacitance of the engine control volume [W/K]
$[\boldsymbol{MC}]_{\boldsymbol{cw}}$	is the thermal capacitance of the encapsulated cooling water and heat exchanger shell in immediate thermal contact [J/K]
$\boldsymbol{T}_{\boldsymbol{room}}$	is the temperature of the surrounding environment [°C]
$\boldsymbol{T}_{\boldsymbol{eng}}$	is the temperature of the engine control volume [°C]
$[\dot{\boldsymbol{m}}\boldsymbol{C}_{\boldsymbol{P}}]_{\boldsymbol{cw}}$	is the thermal capacitance flow rate associated with the cooling water [W/K]
$\boldsymbol{UA}_{\boldsymbol{HX}}$	is the effective thermal conductance between the engine control volume and the cooling water control volume [W/K]
$\boldsymbol{UA}_{\boldsymbol{loss}}$	is the effective thermal conductance between the engine control volume and the surrounding environment[W/K]

These equations are the basis of the model and EnergyPlus solves these equations dynamically. Further description of the dynamic model can be found in EnergyPlus Engineering reference (US Department of Energy, 2013) and Annex 42 (Beausoleil-Morrison, Ferguson, Griffith, Kelly, Maréchal, & Weber, 2007). The CHP model has a number of different operating modes. The operating mode for a given system time step is determined from the mode during the previous time step, user inputs, and high-level controls from elsewhere in EnergyPlus. The operating mode is reported after each time step. The different operation modes are given as follow:

Operating mode	**Main Criteria**	**Notes**
Off	Availability schedule value=0	No consumption of power or fuel.
Stand By	Availability schedule value ≠ 0	Consumes stand by power but no fuel
Warm Up	Load (thermal or electric) >0.0 Availability schedule ≠0 Time Delay < elapsed time since entering warm up mode. Engine temp < nominal engine temp	Two alternative sub –modes: Stirling engines use warm up by nominal engine temperature while internal combustion engines uses time delay. Fuel is consumed but no power is produced.
Normal Operation	Load (thermal or electric) >0.0 Availability schedule ≠0 Time Delay > elapsed time since entering warm up mode. Engine temp ≥ nominal engine Temp	Fuel is consumed and power is produced.
Cool Down	Load (thermal or electric) =0.0 Availability schedule ≠0	The alternative sub- modes where the engine can be forced to go through a complete cool down cycle before allowed to go back into warm up or normal mode. No fuel is consumed and no power is consumed.

Appendix G: Water heater model engineering description

The stratified water heater object in EnergyPlus is based on the following equations taken from the engineering reference (US Department of Energy, 2013), and the nodes are coupled by vertical conduction effects, internode fluid flow ant temperature inversion mixing. The model uses the Forward-Euler numerical method to simultaneously solve the differential equations governing the energy balances on the nodes.

Energy Balance

The stratified model solves the following fundamental differential equation governing the energy balance on a mass of water. Since the model is stratified it must solve the energy balance on n number of nodes simultaneously. Node 1 is at the top of the water tank and node *n* is at the bottom of the water tank.

$$m_n c_p \frac{dT_n}{dt} = q_{net,n}$$

Where

m_n	is mass of water for node *n*
c_p	is specific heat of water
T_n	is temperature of water for node *n*
t	is time
$q_{net,n}$	is net heat transfer for node *n*

The net heat transfer rate q_{net} is the sum of gains and losses due to multiple heat transfer pathways.

$$q_{net,n} = q_{heater,n} + q_{oncycpara,n} + q_{offcycpara,n} + q_{oncycloss,n} + q_{offcycloss,n} + q_{cond,n} + q_{use,n} + q_{source,n} + q_{flow,n} + q_{invmix,n}$$

where

$q_{heater,n}$	is heat added by heater 1 or heater 2
$q_{oncycpara,n}$	is heat added due to on-cycle parasitic loads (zero when off)
$q_{offcycpara,n}$	is heat added due to off-cycle parasitic loads (zero when on)
$q_{oncycloss,n}$	is heat transfer to/from the ambient environment (zero when off)
$q_{offcycloss,n}$	is heat transfer to/from the ambient environment (zero when on)
$q_{cond,n}$	is heat transfer due to conduction between the node above and below
$q_{use,n}$	is heat transfer to/from use side plant connections
$q_{source,n}$	is heat transfer to/from the source side plant connections
$q_{flow,n}$	is heat transfer due to fluid flow from the node above and below
$q_{invmix,n}$	is heat transfer due to inversion mixing from the node above and below

$q_{oncycloss,n}$ and $q_{offcycloss,n}$ are defined as:

$$q_{oncycloss,n} = UA_{oncyc,n}(T_{amb} - T_n)$$

$$q_{offcycloss,n} = UA_{offcyc,n}(T_{amb} - T_n)$$

Where

$UA_{oncyc,n}$	is on-cycle loss coefficient to ambient environment (zero when off)
$UA_{offcyc,n}$	is off-cycle loss coefficient to ambient environment (zero when on)
T_{amb}	is temperature of ambient environment

$q_{cond,n}$ is defined as:

$$q_{cond,n} = \frac{kA_{n+1}}{L_{n+1}}(T_{n+1} - T_n) + \frac{kA_{n-1}}{L_{n-1}}(T_{n-1} - T_n)$$

Where

k	is fluid thermal conductivity of water, 0.6 W/mK
A_{n+1}	is shared surface area between node n and n+1
L_{n+1}	is distance between center of mass of node n and n+1
T_{n+1}	is temperature of node n+1
A_{n-1}	is shared surface area between node n and n-1
L_{n-1}	is distance between center of mass of node n and n-1
T_{n-1}	is temperature of node n-1

$q_{use,n}$ and $q_{source,n}$ are defined as:

$$q_{use,n} = \varepsilon_{use}\dot{m}_{use}c_p(T_{use} - T_n)$$

$$q_{source,n} = \varepsilon_{source}\dot{m}_{source}c_p(T_{source} - T_n)$$

Where

ε_{use}	is heat exchanger effectiveness for the use side plant connections
$\dot{m}_{use}$	is mass flow rate for the use side plant connections
T_{use}	is inlet fluid temperature for the use side plant connections
ε_{source}	is heat exchanger effectiveness for the source side plant connections
$\dot{m}_{source}$	is mass flow rate for the source side plant connections
T_{source}	is inlet fluid temperature for the source side plant connections

$q_{flow,n}$ is defined as:

$$q_{flow,n} = \dot{m}_{n+1}c_p(T_{n+1} - T_n) + \dot{m}_{n-1}c_p(T_{n-1} - T_n)$$

Where

$\dot{m}_{n+1}$	is mass flow rate from node *n+1*
$\dot{m}_{n-1}$	is mass flow rate from node *n-1*

$q_{invmix,n}$ is defined as:

$$q_{invmix,n} = \dot{m}_{invmix,n+1} c_p (T_{n+1} - T_n) + \dot{m}_{invmix,n-1} c_p (T_{n-1} - T_n)$$

$\dot{m}_{invmix,n+1}$	is mass flow rate from node *n+1* due to temperature inversion mixing
$\dot{m}_{invmix,n-1}$	is mass flow rate from node *n-1* due to temperature inversion mixing

Inversion mixing occurs when the node below is warmer than the node above. The difference in temperature drives a difference in density that causes the nodes to mix. Usually inversion mixing occurs very rapidly.

The use and source fluid steam outlet temperatures calculation procedure depends on the values of the effectiveness. If the effectiveness is 1.0, then complete mixing of the fluid steam and the tank water is assumed. This is the case for the water heater used in this master. In this case the outlet temperatures for the use and the source streams will be simply the tank water temperatures at point of the outlet nodes.

The system of simultaneous differential equations is solved using the Forward-Euler numerical method. The system time step is divided into one-second substep.

In the system model, the design volume water flow rates are autosized as this is convenient when the thermal tank is connected to plant loops. When the water thermal tank is connected to the supply side of plant loop and flow rates are autosized, the flow rate is the sum of the flow requests of all the various components on the demand side of that plant loop. When the water thermal tank is connected on the demand side of a plant loop (e.g. as for indirect heating with a boiler) and flow rates are autosized, the design flow rates are calculated with the following equation:

$$\dot{V} = -\left(\frac{V}{t_{Recover} * 3600 * \varepsilon}\right) * Ln\left[\!\left[\frac{(T_{PlantDesign} - T_{Setpoint})}{(T_{PlantDesign} - T_{start})}\right]\!\right]$$

Where

V	is volume of tank
$t_{Recover}$	is user parameter for the time it takes for the tank to recover from assumed starting temperature to an assumed setpoint temperature. For water heaters, the starting temperature is 14.4° C and the final assumed setpoint temperature is 57.2°C. In the cases simulated the setpoint is 60°C.
ε	is ε_{use} or ε_{source}
$T_{PlantDesign}$	is the exit temperature specified in the Plant Sizing object.
$T_{Setpoint}$	is the final tank temperature of 57.2°C or 60°C as defined in our case.
T_{start}	is the initial tank temperature of 14.4° C.

Domestic hot water:
Water use connections:
If coupled to a plant loop, T_{hot} is taken from the plant loop inlet node.

Appendix H: Schedules hot water, people and activity level

Domestic hot water:

Time of day:	Fraction (0-1):
00:00-06:00	0.0
06:00-08:00	0.5
08:00-18:00	0.1
18:00-21:00	0.6
21:00-24:00	0.0

People:

For weekdays:

Time of day:	Fraction (0-1):
00:00-07:00	1.0
07:00-09:00	0.5
09:00-14:00	0.0
14:00-16:00	0.5
16:00-18:00	0.75
18:00-24:00	1.0

For Saturday:

Time of day:	Fraction (0-1):
00:00-11:00	1.0
11:00-16:00	0.5
16:00-19:00	1.0
19:00-24:00	1.0

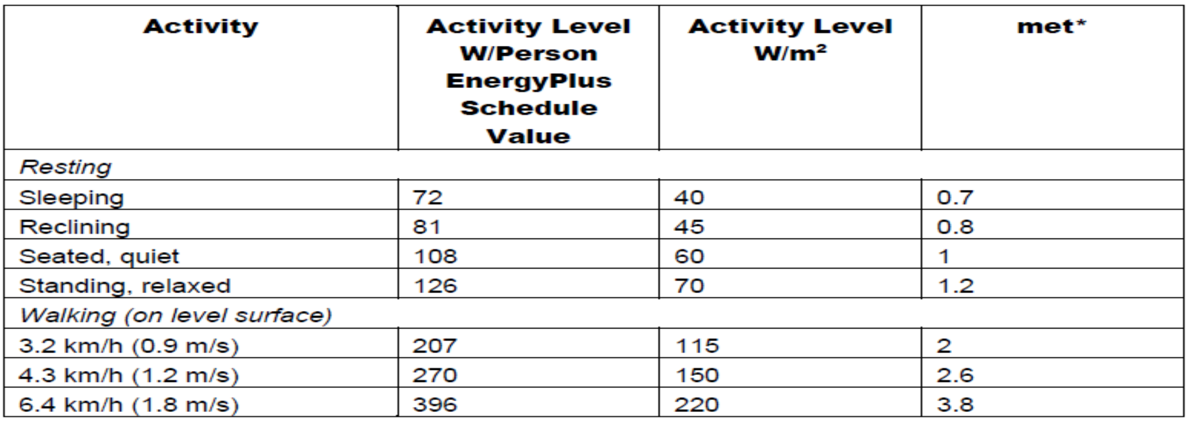
For Sunday:

Time of day:	Fraction (0-1):
00:00-11:00	1.0
11:00-06:00	0.5
16:00-19:00	1.0
19:00-24:00	1.0

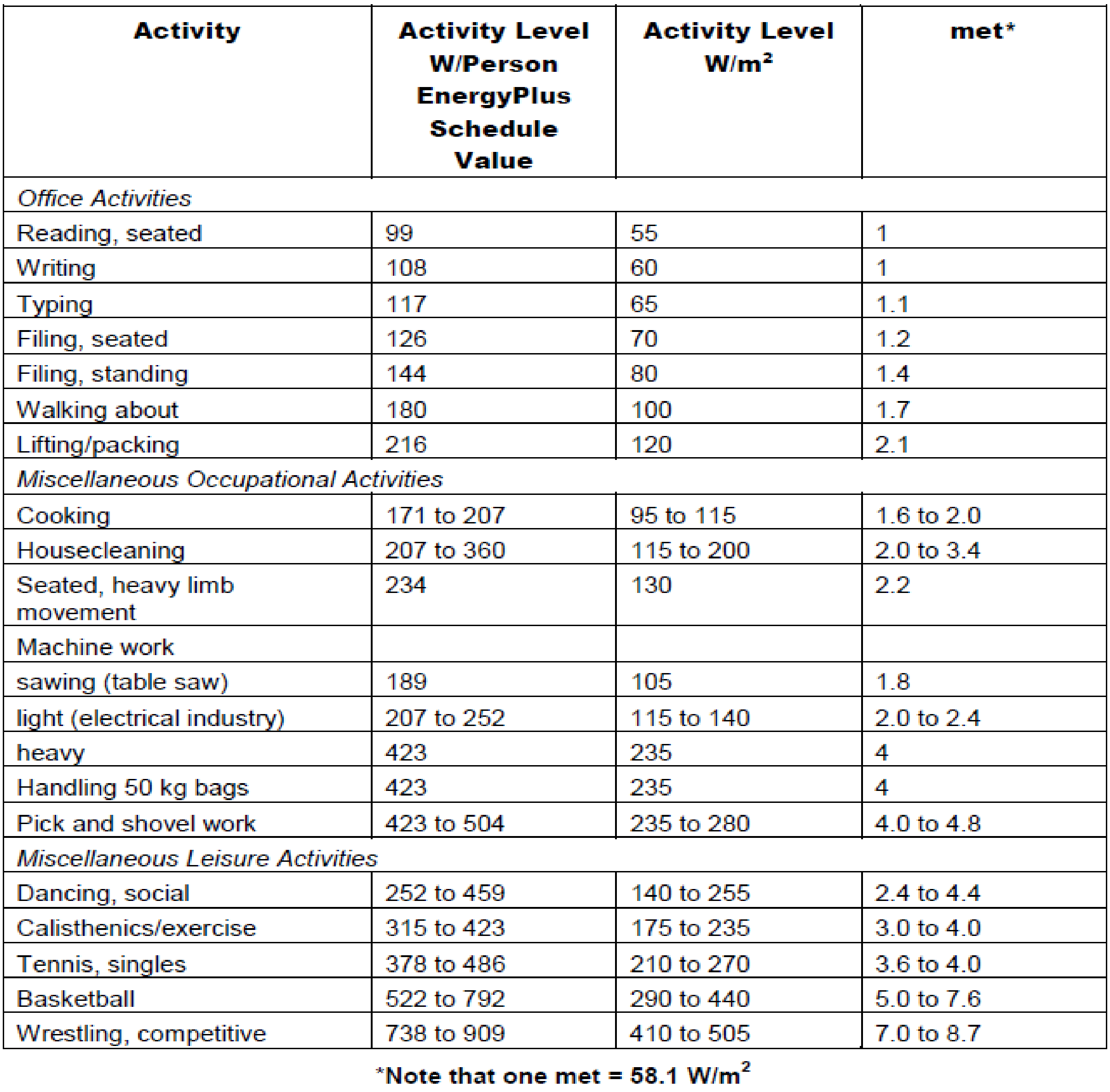
Activity level:

Time of day:	Any number
00:00-07:00	70
07:00-17:00	70
17:00-20:00	95
20:00-24:00	70

The activity levels are estimated values for average activity level in normal family apartments where the values are based on values for each activity which can be seen in the following tables:



Activity	Activity Level W/Person EnergyPlus Schedule Value	Activity Level W/m^2	met*
Resting			
Sleeping	72	40	0.7
Reclining	81	45	0.8
Seated, quiet	108	60	1
Standing, relaxed	126	70	1.2
Walking (on level surface)			
3.2 km/h (0.9 m/s)	207	115	2
4.3 km/h (1.2 m/s)	270	150	2.6
6.4 km/h (1.8 m/s)	396	220	3.8



Activity	Activity Level W/Person EnergyPlus Schedule Value	Activity Level W/m^2	met*
Office Activities			
Reading, seated	99	55	1
Writing	108	60	1
Typing	117	65	1.1
Filing, seated	126	70	1.2
Filing, standing	144	80	1.4
Walking about	180	100	1.7
Lifting/packing	216	120	2.1
Miscellaneous Occupational Activities			
Cooking	171 to 207	95 to 115	1.6 to 2.0
Housecleaning	207 to 360	115 to 200	2.0 to 3.4
Seated, heavy limb movement	234	130	2.2
Machine work			
sawing (table saw)	189	105	1.8
light (electrical industry)	207 to 252	115 to 140	2.0 to 2.4
heavy	423	235	4
Handling 50 kg bags	423	235	4
Pick and shovel work	423 to 504	235 to 280	4.0 to 4.8
Miscellaneous Leisure Activities			
Dancing, social	252 to 459	140 to 255	2.4 to 4.4
Calisthenics/exercise	315 to 423	175 to 235	3.0 to 4.0
Tennis, singles	378 to 486	210 to 270	3.6 to 4.0
Basketball	522 to 792	290 to 440	5.0 to 7.6
Wrestling, competitive	738 to 909	410 to 505	7.0 to 8.7

***Note that one met = 58.1 W/m^2**

Appendix I: Activity schedule lighting

Light activity (0-1)				
Time	**Winter (des- feb)**	**Spring (mar-may)**	**Summer (jun-aug)**	**Autumn (sep-nov)**
00:00	0.001	0.007	0.000	0.014
01:00	0.000	0.000	0.000	0.000
02:00	0.000	0.000	0.000	0.000
03:00	0.000	0.000	0.000	0.000
04:00	0.000	0.000	0.000	0.000
05:00	0.012	0.000	0.025	0.009
06:00	0.435	0.094	0.215	0.172
07:00	0.581	0.524	0.208	0.607
08:00	0.684	0.431	0.388	0.526
09:00	0.779	0.157	0.438	0.341
10:00	0.102	0.072	0.150	0.131
11:00	0.255	0.272	0.168	0.052
12:00	0.502	0.393	0.328	0.370
13:00	0.553	0.468	0.392	0.260
14:00	0.737	0.331	0.418	0.576
15:00	0.757	0.192	0.464	0.759
16:00	0.797	0.268	0.584	0.891
17:00	0.868	0.357	0.478	0.675
18:00	0.936	0.335	0.739	0.742
19:00	0.290	0.104	0.209	0.403
20:00	0.220	0.118	0.063	0.167
21:00	0.726	0.188	0.306	0.765
22:00	0.786	0.202	0.589	0.696
23:00	0.456	0.444	0.432	0.652

Appendix J: Activity schedule electrical appliances

Activity level								
Time	**FREEZER (0-1)**	**FRIDGE (0-1)**	**PC (0-1)**	**TV1 (0-1)**	**HOB (0-1)**	**MICROWAVE (0-1)**	**DISH_WASHER (0-1)**	**WASHING_MACHINE standby (0-1)**
00:00	0.00000	0.00000	0.03401	0.02344	0.00045	0.00160	0.00000	0.00049
01:00	0.33772	0.30000	0.03401	0.02344	0.00045	0.00160	0.00000	0.00049
02:00	0.00000	0.18333	0.03401	0.02344	0.00045	0.00160	0.00000	0.00049
03:00	0.33772	0.11667	0.03401	0.02344	0.00045	0.00160	0.00000	0.00049
04:00	0.10746	0.30000	0.03401	0.02344	0.00045	0.00160	0.00000	0.00049
05:00	0.23026	0.30000	0.03401	0.02344	0.00045	0.00160	0.00000	0.00049
06:00	0.33772	0.00000	0.03401	0.02344	0.00045	0.00160	0.00000	0.00049
07:00	0.33772	0.30000	0.03401	0.02344	0.00045	0.00160	0.78333	0.00049
08:00	0.00000	0.30000	0.03401	0.02344	0.00045	0.00160	0.21667	0.00049
09:00	0.27632	0.30000	0.03401	0.02344	0.00045	0.00160	0.00000	0.00049
10:00	0.06140	0.30000	0.03401	0.02344	0.00045	0.00160	0.00000	0.00049
11:00	0.33772	0.00000	0.03401	0.02344	0.00045	0.00160	0.00000	0.00049
12:00	0.33772	0.30000	0.03401	0.83724	0.26700	0.00160	0.00000	0.00049
13:00	0.15351	0.30000	0.03401	0.23503	0.00045	0.00160	0.00000	0.00049
14:00	0.18421	0.25000	0.03401	0.02344	0.00045	0.00160	0.83333	0.00049
15:00	0.33772	0.05000	0.03401	0.02344	0.00045	0.00160	0.16667	0.00049
16:00	0.33772	0.30000	0.03401	0.25130	0.00045	0.00160	0.00000	0.00049
17:00	0.00000	0.30000	0.16281	1.00000	0.00045	0.00160	0.00000	0.00049
18:00	0.33772	0.30000	1.00000	0.39779	0.26700	0.46440	0.98333	0.00049
19:00	0.03070	0.00000	0.51701	0.43034	0.00045	0.00160	0.01667	0.00049
20:00	0.30702	0.00000	0.51701	0.51172	0.00045	0.00160	0.00000	0.00049
21:00	0.33772	0.26667	1.00000	1.00000	0.00045	0.00160	0.00000	0.00049
22:00	0.33772	0.03333	1.00000	0.90234	0.00045	0.00160	0.00000	0.00049
23:00	0.00000	0.30000	0.87120	0.60938	0.00045	0.00160	0.00000	0.00049

Activity level				
Time	**WASHER_DRYER used (0-1)**	**WASHING_MACHINE Used (0-1)**	**MICROWAVE unused (0-1)**	**WASHER_DRYER unused (0-1)**
00:00	0.00040	0.00049	0.00160	0.00040
01:00	0.00040	0.00049	0.00160	0.00040
02:00	0.00040	0.00049	0.00160	0.00040
03:00	0.00040	0.00049	0.00160	0.00040
04:00	0.00040	0.00049	0.00160	0.00040
05:00	0.00040	0.00049	0.00160	0.00040
06:00	0.00040	0.00049	0.00160	0.00040
07:00	0.00040	0.00049	0.00160	0.00040
08:00	0.00040	0.00049	0.00160	0.00040
09:00	0.00040	0.00049	0.00160	0.00040
10:00	0.00040	0.00049	0.00160	0.00040
11:00	0.26454	0.00049	0.00160	0.00040
12:00	0.05564	0.37308	0.00160	0.00040
13:00	0.20076	0.04411	0.00160	0.00040
14:00	0.85006	0.03393	0.00160	0.00040
15:00	0.00040	0.00049	0.00160	0.00040
16:00	0.00040	0.00049	0.00160	0.00040
17:00	0.00040	0.00049	0.00160	0.00040
18:00	0.00040	0.00049	0.00160	0.00040
19:00	0.00040	0.00049	0.00160	0.00040
20:00	0.00040	0.00049	0.00160	0.00040
21:00	0.00040	0.00049	0.00160	0.00040
22:00	0.00040	0.00049	0.00160	0.00040
23:00	0.00040	0.00049	0.00160	0.00040

Weekly use schedules:

Day	TV	Dish washer	Microwave	Washing machine	Washer dryer	Freezer	Fridge	PC	Hob
Mon	TV1	DISH_WASHER	MICROWAVE	WASHING _MACHINE standby	WASHER_DRYER unused	FREEZER	FRIDGE	PC	HOB
Tue	TV1	DISH_WASHER	MICROWAVE unused	WASHING_MACHINE used	WASHER DRYER used	FREEZER	FRIDGE	PC	HOB
Wed	TV1	DISH_WASHER	MICROWAVE	WASHING _MACHINE standby	WASHER_DRYER unused	FREEZER	FRIDGE	PC	HOB
Thu	TV1	DISH_WASHER	MICROWAVE unused	WASHING _MACHINE standby	WASHER_DRYER unused	FREEZER	FRIDGE	PC	HOB
Fri	TV1	DISH_WASHER	MICROWAVE	WASHING_MACHINE used	WASHER DRYER used	FREEZER	FRIDGE	PC	HOB
Sat	TV1	DISH_WASHER	MICROWAVE unused	WASHING _MACHINE standby	WASHER_DRYER unused	FREEZER	FRIDGE	PC	HOB
Sun	TV1	DISH_WASHER	MICROWAVE	WASHING_MACHINE used	WASHER DRYER used	FREEZER	FRIDGE	PC	HOB

Appendix K: Demand management

Demand Manager Assignment List

Model parameter	Value	Units
Meter name	Electricity:Facility	-
Demand limit	4000	W
Demand limit safety fraction	0.8	-
Demand window length	15	min
Demand manager priority	Sequential	-
Demand manager 1 object type	DemandManager:ElectricalEquipment	-
Demand manager 1 Name	TV Demand Manager	-
Demand manager 2 object type	DemandManager:ElectricalEquipment	-
Demand manager 2 Name)	Dish washer Demand Manager	-
Demand manager 3 object type	DemandManager:ElectricalEquipment	-
Demand manager 3 Name	Microwave Demand Manager	-
Demand manager 4 object type	DemandManager:ElectricalEquipment	-
Demand manager 4 Name	Washing machine Demand Manager	-
Demand manager 5 object type	DemandManager:ElectricalEquipment	-
Demand manager 5 Name	PC Demand Manager	-
Demand manager 6 object type	DemandManager:ElectricalEquipment	-
Demand manager 6 Name	Washer dryer Demand Manager	-
Demand manager 7 object type	DemandManager:Lights	-
Demand manager 7 Name	Lights Demand Manager	-

Demand Manager:Electrical equipment

TV Demand Manager

Model parameter	Value	Units
Availability schedule name	TV	-
Limit control	Fixed	-
Minimun Limit Duration	60	min
Maximum Limit Fraction	0	-
Selection control	All	-
Electric equipment name	TV	-

Dish washer Demand Manager

Model parameter	Value	Units
Availability schedule name	Dish washer	-
Limit control	Fixed	-
Minimun Limit Duration	60	min
Maximum Limit Fraction	0	-
Selection control	All	-
Electric equipment name	Dish washer	-

Microwave Demand Manager

Model parameter	**Value**	**Units**
Availability schedule name	Microwave	-
Limit control	Fixed	-
Minimun Limit Duration	60	min
Maximum Limit Fraction	0	-
Selection control	All	-
Electric equipment name	Microwave	-

Washing machine Demand Manager

Model parameter	**Value**	**Units**
Availability schedule name	Washing machine	-
Limit control	Fixed	-
Minimun Limit Duration	60	min
Maximum Limit Fraction	0	-
Selection control	All	-
Electric equipment name	Washing machine	-

PC Demand Manager

Model parameter	**Value**	**Units**
Availability schedule name	PC	-
Limit control	Fixed	-
Minimun Limit Duration	60	min
Maximum Limit Fraction	0	-
Selection control	All	-
Electric equipment name	PC	-

Washer dryer Demand Manager

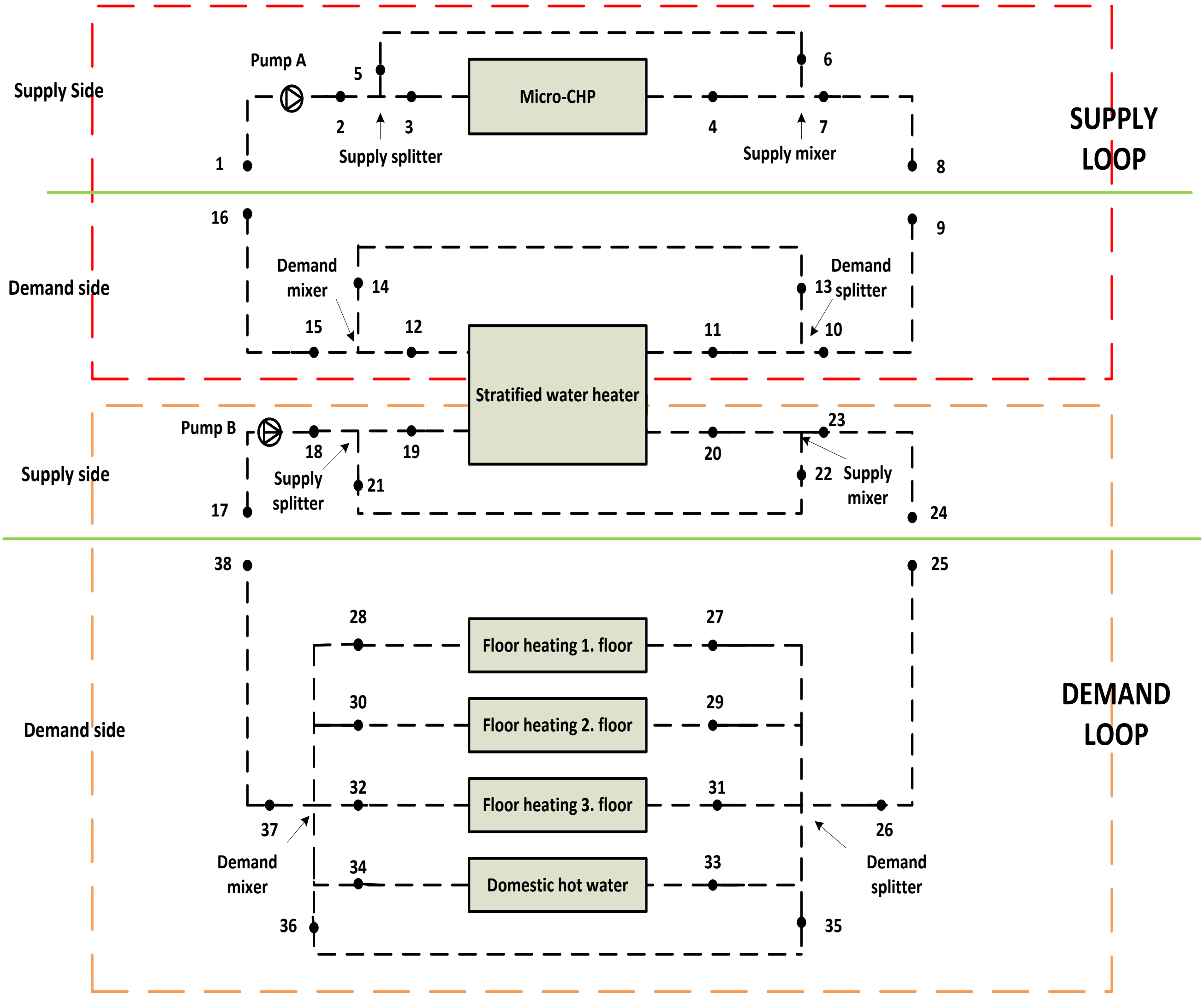
Model parameter	**Value**	**Units**
Availability schedule name	Washer dryer	-
Limit control	Fixed	-
Minimun Limit Duration	60	min
Maximum Limit Fraction	0	-
Selection control	All	-
Electric equipment name	Washer dryer	-

Demand Manager:Lights

Lights Demand Manager

Model parameter	**Value**	**Units**
Availability schedule name	Lighting	-
Limit control	Fixed	-
Minimun Limit Duration	60	min
Maximum Limit Fraction	0.85	-
Selection control	All	-
Electric equipment name	Lighting	-

Appendix L: EnergyPlus model sketch of system with CHP only



Pump A:	CHP pump
Pump B:	Circulation pump

Node number: **Node name:**

Supply loop:

Supply side:

1	CHP Pump Inlet node
2	CHP pump Outlet node
3	CHP inlet node
4	CHP outlet node
5	CHP Supply Bypass Inlet node
6	CHP Supply Bypass Outlet node
7	CHP Outlet pipe inlet node

8	CHP Outlet pipe outlet node

Demand side:

9	CHP Demand Inlet pipe inlet node
10	CHP Demand Inlet pipe outlet node
11	SHW Source side inlet node
12	SHW Source side outlet node
13	CHP Demand Bypass pipe Inlet node
14	CHP Demand Bypass pipe outlet node
15	CHP Demand Outlet pipe inlet node
16	CHP Demand Outlet pipe outlet node

Demand loop:

Supply side:

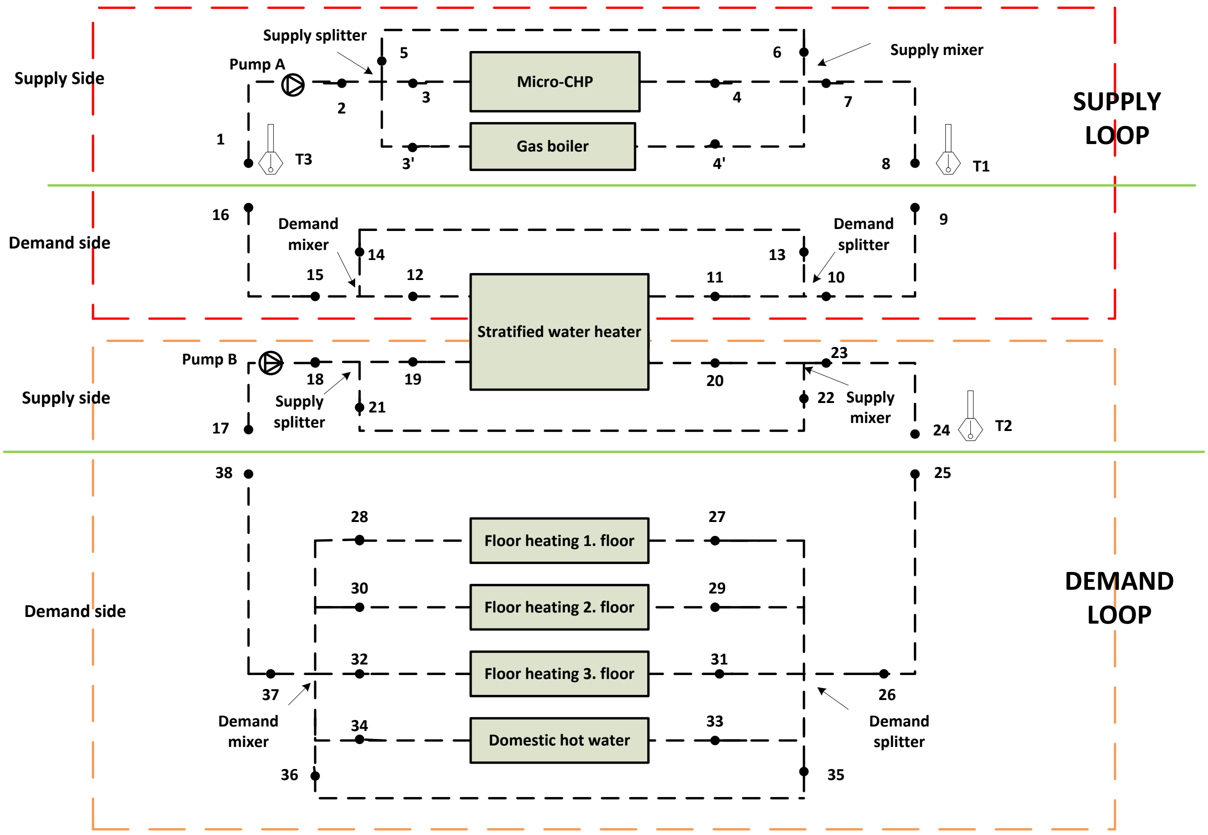
17	CircPump Inlet node
18	CircPump Outlet node
19	SHW use side inlet node
20	SHW use side outlet node
21	Supply Bypass inlet node
22	Supply Bypass outlet node
23	SHW Outlet pipe inlet node
24	SHW Outlet pipe outlet node

Demand side:

25	Water demand Inlet pipe inlet node
26	Water demand Inlet pipe outlet node
27	Water floor heating 1 inlet node
28	Water floor heating 1 outlet node
29	Water floor heating 2 inlet node
30	Water floor heating 2 outlet node
31	Water floor heating 3 inlet node
32	Water floor heating 3 outlet node
33	Tap water inlet node
34	Tap water outlet node
35	Demand bypass inlet node
36	Demand bypass outlet node
37	Water Demand Outlet pipe inlet node
38	Water Demand Outlet pipe outlet node

As it can be seen, the points of the splitter and mixers are pointed at in the figure.

Appendix M: EnergyPlus model sketch of system with CHP and gas boiler



Pump A:	CHP pump
Pump B:	Circulation pump

Node number:	**Node name:**

Supply loop:

Supply side:

1	CHP Pump Inlet node
2	CHP pump Outlet node
3	CHP inlet node
4	CHP outlet node
3’	Gas boiler inlet node
4’	Gas boiler outlet node
5	CHP Supply Bypass Inlet node
6	CHP Supply Bypass Outlet node
7	CHP Outlet pipe inlet node
8	CHP Outlet pipe outlet node

Demand side:

9	CHP Demand Inlet pipe inlet node
10	CHP Demand Inlet pipe outlet node
11	SHW Source side inlet node

12	SHW Source side outlet node
13	CHP Demand Bypass pipe Inlet node
14	CHP Demand Bypass pipe outlet node
15	CHP Demand Outlet pipe inlet node
16	CHP Demand Outlet pipe outlet node

Demand loop:

Supply side:

17	CircPump Inlet node
18	CircPump Outlet node
19	SHW use side inlet node
20	SHW use side outlet node
21	Supply Bypass inlet node
22	Supply Bypass outlet node
23	SHW Outlet pipe inlet node
24	SHW Outlet pipe outlet node

Demand side:

25	Water demand Inlet pipe inlet node
26	Water demand Inlet pipe outlet node
27	Water floor heating 1 inlet node
28	Water floor heating 1 outlet node
29	Water floor heating 2 inlet node
30	Water floor heating 2 outlet node
31	Water floor heating 3 inlet node
32	Water floor heating 3 outlet node
33	Tap water inlet node
34	Tap water outlet node
35	Demand bypass inlet node
36	Demand bypass outlet node
37	Water Demand Outlet pipe inlet node
38	Water Demand Outlet pipe outlet node

As it can be seen, the points of the splitter and mixers are pointed at in the figure.

Node temperature sensors:

T1	Supply water storage tank set temperature sensor (70 °C)
T2	Supply water building loads set temperature sensor (55 °C)
T3	Cooling water temperature sensor (max allowable 80 °C)

Appendix N: EnergyPlus plant loop description

The plant temperature of the supply equipment entering the loop must equal the temperature entering the demand equipment. So the temperature entering the storage tank has to equal the temperature at the outlet of the gas boiler or the micro-CHP since no losses will appear through the pipes as they are made adiabatic. The plant outputs must match the system inputs and vice versa. The setpointManager:schedule controls the temperatures to be at the desired temperature (US Department of Energy, 2013). There are two types of loops within the HVAC simulation in EnergyPlus; an air loop and a plant loop. The air loop uses air as the transport medium while plant loops use a liquid fluid of the user's choice, typically water. The system used in this master does only have plant loops, except for the design ventilation implemented. The two plant loops are named supply loop and demand loop and represent the loop between the supply device and the storage tank and the storage tank and the demand loads. The plant loops are for organizational clarity and simulation logistics divided into "half loops". These half loops represent the supply and demand side of the main loop. The plant supply loop side contains the supply equipment such as gas boiler and micro-CHP, while the demand side contains the storage tank in the case of the loop named supply loop. In the case of the demand loop, the supply side will be the storage tank while the demand side will be the heating system of the building (floor heating and domestic tap water).

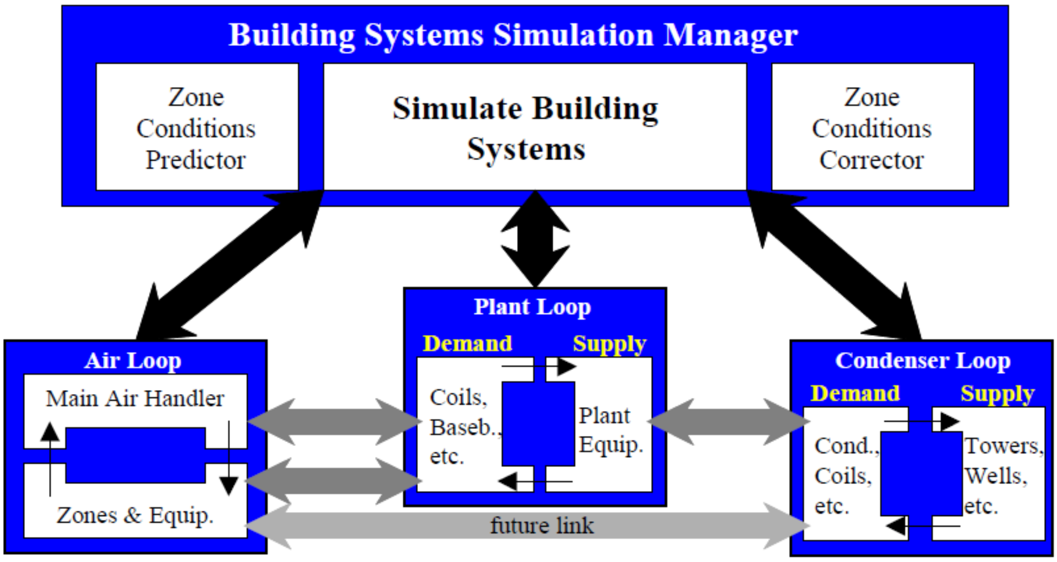


Figure 1: Connections between the main HVAC Simulation Loops and Half Loops (US Department of Energy, 2013).

The plant equipment on the half loop is described by a set of branches. Branches can be set in series and in parallel. The branches represent the pipes, supply equipment, heating equipment, storage tank and pumps. The system will be coupled together through the branch list, which defines which branches are on the demand and supply side of each plant loop. Through the concept of splitter and mixer, the heat is supplied to the acquired equipment. Each half loop may only have one splitter and one mixer. And within any single branch, there may only be components in series and not in parallel. All equipment that is coupled in parallel has to be divided through the splitter and mixer. Since the plant supply and demand are divided into two separate half loops, chillers or boiler may be in parallel to each other in the supply side and coils may be in parallel to each other on the demand side. Also, there are some restrictions when placing pumps within a particular half-loop to avoid the need for overly complex solver routines. In general, all pumps placed between A and B in figure 2 are defined as loop pumps, and all pumps placed between Ci and Di are defined as branch pumps. The pump placed on the inlet to the storage tank seen in appendix L, is therefore defined as a loop pump as it is the first component on the first branch (inlet branch to the storage tank). This makes the pump placed on the inlet to the micro-CHP or gas boiler also defined as a loop pump.

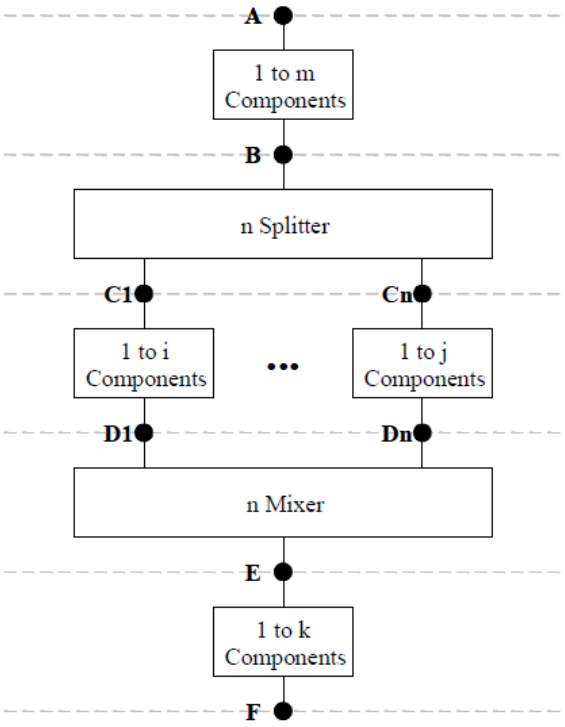
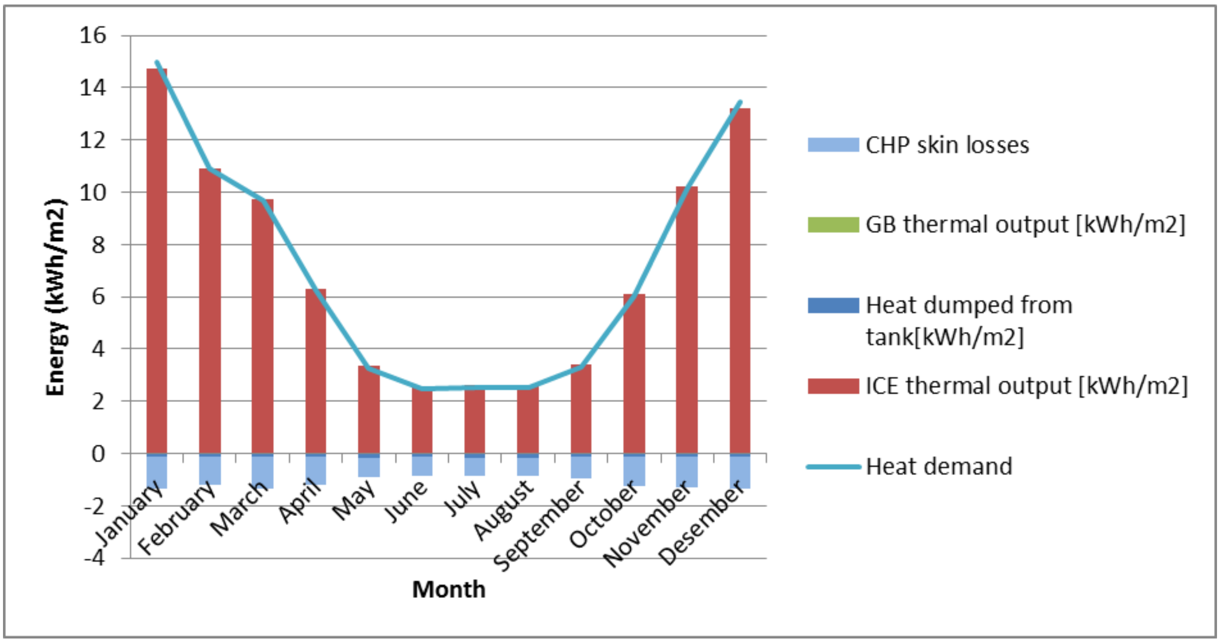


Figure 2: EnergyPlus Branch layout for individual plant half-loops (US Department of Energy, 2013).

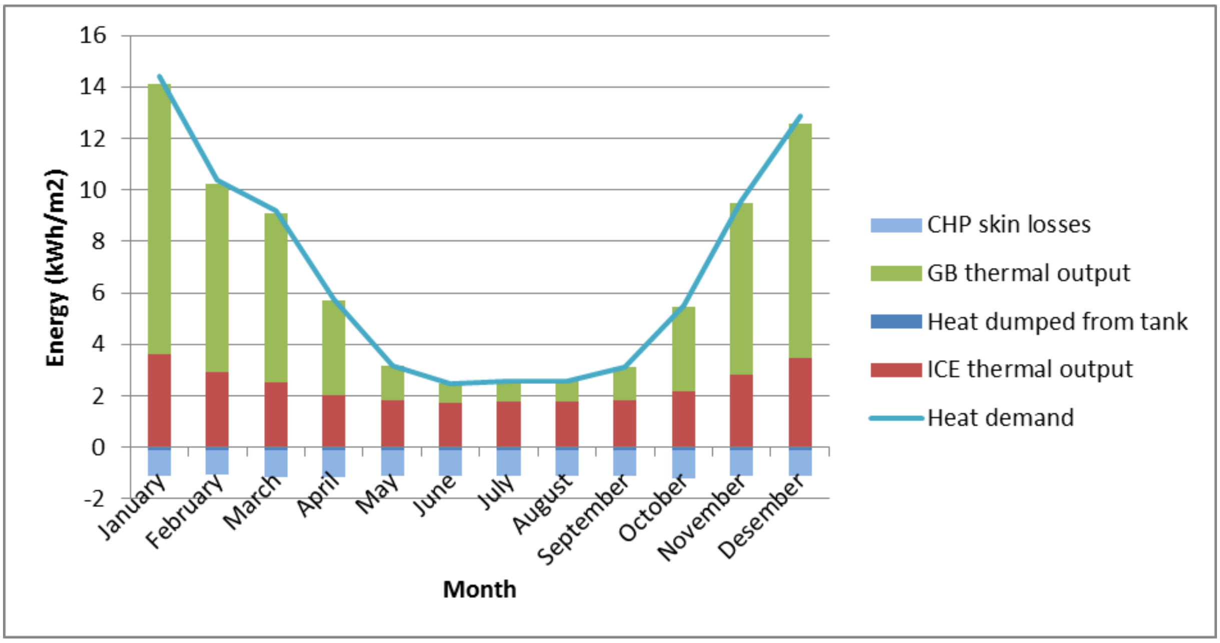
Each branch has one or more components linked together in series. In the model made in this master, each branch do only have one component, as the supply and demand equipment is coupled together through splitter and mixer and will be in parallel. The branch has system nodes that store properties at a location on the loop, like temperature, enthalpy, flow rate etc., at the beginning and the end of the branch. Components on the branch take the conditions of the node at their inlet and use that information as well as overall control information to simulate the component and write the outlet data to the node following the component. This information is then used either by next component on the branch or establishes the outlet conditions for the branch. Therefore data at the inlet and outlet of each branch are calculated and can be computed by the simulation. However, as mentioned earlier, due to the concept of the splitter and mixer, the temperatures on the branches placed between the splitter and mixer will be the same as EnergyPlus does not do a hydraulic calculation. Even though the plant model in EnergyPlus is flexible, the topology of the plant system will be different from the topology of the actual plant system in a building. This is because EnergyPlus focuses on modeling building energy performance over long periods of time and is not intended as a completely flexible system that directly models any actual plant system with its full complexity and exact layout. But the modeling models a sufficient similar approach to the real system and will therefore give a realistic picture of the expected energy use using the specified system plant (US Department of Energy, 2013).

Appendix O: Monthly heat output and losses versus demand building

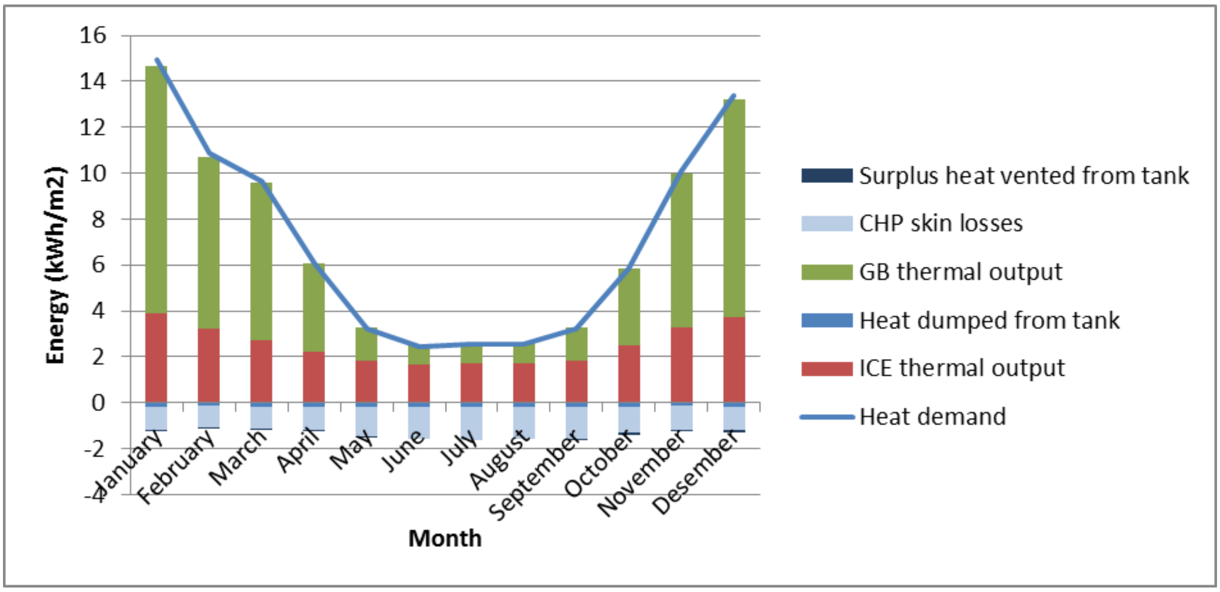
Case 2,3, 8 and 9:



Case 4:



Case 7:


16
14
12
10
8
6
4
2
0
-2
-4
Energy (kWh/m2)
January
February
March
April
May
June
July
August
September
October
November
Desember
Month
Surplus heat vented from tank
CHP skin losses
GB thermal output
Heat dumped from tank
ICE thermal output
Heat demand

Appendix P: Scientific paper

The paper is added as an independent document on next page.

OPTIMAL OPERATING STRATEGIES OF THE MICRO-CHP FOR IMPROVED INTERACTION BETWEEN THE ELECTRICAL AND THERMAL DEMAND AND SUPPLY

Kristin Folstad
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ABSTRACT

This paper evaluates the performance of a Senertec internal combustion engine, which is one of today's market leading micro-CHP devices, compared to a conventional high-efficient gas boiler. Due to its characteristic behavior, the best performance is achieved when operating in thermal following mode with grid connection to enable electricity exports. Operating in electric demand following mode lead to higher operation time, but due to poorer heat recovery at times with low electrical demand, the performance of the system became poorer. The use of renewable fuels in CHP has the potential in achieving remarkable savings in both primary energy and CO2-emissions, but is today not well developed and needs further investigation to enable proper performance and security of supply.

INTRODUCTION

The final energy consumption in buildings in EU27, Switzerland and Norway has come mainly from oil, gas and electricity during the last two decades (BPIE, 2011). This final energy consumption will likely continue, and therefore it is important to look at the potential of a more efficient use of these sources. Combined heat and power (CHP) is seen as an emerging technology in using these energy sources more efficiently as it produces electricity and heat from the same fuel source. It has the potential to reduce primary energy consumption and associated greenhouse gas emissions. CHP is considered as a potential energy supply solution within a net-ZEB concept due to these potential effects (Alanne & Saari, 2003). CHP can run on renewable fuels, but fossil fuels are most commonly used. However, even though the devices are usually fuelled with natural gas, it is considered a low-carbon technology due to that it contributes in a more efficient use of the limited fossil resources (Day, Ogumka, Jones, & Dunsdonm, 2009).

CHP has the potential to cover both the thermal and electrical demand of a building, but problems around its dynamics hamper its market penetration. CHP systems have large thermal outputs, while the thermal demand of buildings decreases through better insulated building envelopes. The benefits of using a CHP device compared to the problems around its dynamics need to be analyzed in order to evaluate the potential of integration for use in buildings.

In this paper, the CHP integration in a residential multi-family building (MFB) will be compared to a conventional gas boiler and different optimization strategies will be simulated and evaluated. The building complies with the Norwegian building norm, TEK10. The scope for this paper is to define an optimal control system for satisfying different energy demand variations in a multi-family dwelling. The energetic and CO2 benefits for the implementation of a micro-CHP system depend heavily on the "non-CHP" reference situation. As the reference case in this study is a condensing gas boiler which has high efficiency; the benefit of using CHP will depend on the system configuration of the CHP. It is important that the CHP device operates as efficient as possible, and that the power and heat output is produced in a rate that achieves high net benefit on a future basis regarding primary energy, energy efficiency, reduced grid interaction and CO2 emission.

The tool used for analyzing the CHP system performance is the building simulation tool EnergyPlus. EnergyPlus is chosen as it is a well-developed simulation tool, and has an already existing CHP model integrated. The CHP model used is based on the international Energy Agency's Energy Conservation in Buildings and Community Systems (IEA ECBCS) Annex 42 for a Senertech internal combustion engine production unit.

MICRO-CHP TECHNOLOGY

Internal combustion engines (ICE) are the most established micro-CHP appliance. The typical characteristics for an ICE-based micro-CHP are its low cost, high efficiency, wide power range and ability to run on different fuels (Klobut, Ikäheimo, & Ihonen). It is based on the automotive engine, and possible fuels are diesel, biodiesel, gasoline, natural gas, biogas and landfill gas. The possibility of using renewable fuels makes it an interesting choice for energy supply, even though natural gas and diesel oil are the most common fuels.

The typical benefits of ICE devices are that they have high electrical efficiency, large power range and have the possibility of using a varying range of fuels. The drawbacks are that they need service regularly, are noisy, which is not desirable for building application, and their emissions strongly depend on the fuel used (Alanne & Saari, 2003). These units are best applicable for buildings with smooth electricity and heat consumption profiles. Micro-CHP appliances consume more fuel than condensing boilers, so the benefit of using CHP comes from the electricity generated. ICE units operate most effectively when they run for extended periods of time with very few start-up cycles. This is because most of the wear on the engine occurs during start-up (SEAI, 2011).

Integration of micro- CHP systems into operating buildings may be challenging. This is because the loads are small and the load diversity is limited. The CHP device produces heat and electricity simultaneously, and in residential buildings there will be time where it requires one but not the other. Therefore it is difficult to define the best strategy for how it is best to use the micro-CHP for optimal efficiency and to cover the energy demand at the best rate possible. Factors like optimal sizing and control of the CHP system, how to meet peak loads (both electrical and thermal), need for and sizing of thermal storage, standardized technique for grid connection, ability to export electricity, emergency power operation (grid outage), safety, standards and code issues are important to look at when defining the system specifications and operating mode (Bell, et al., November 4, 2005).

PERFORMANCE ASSESSMENT METHODOLGY

The performance assessment will be analyzed in terms of primary energy, energy efficiency, grid interaction and CO_2 emissions.

Primary energy

Primary energy represents the energy use associated with the embodied energy in natural resources such as crude oil, coal, natural gas, sunlight etc. It represents the delivered energy before any anthropogenic conversion or transformation. Primary energy rating makes possible to sum different types of energies (e.g. thermal and electrical) as they integrate the losses of the whole chain, which includes the losses outside the building system boundary (prEN 15203/15315, 2006).

The primary energy consumption to generate electricity and heat will be considered for both micro-CHP and reference system. The primary energy demand is defined by equation 1:

$$PE = \sum\left(DE_i\, f_{prim,del,i}\right) - \sum\left(XE_i\, f_{prim,exp,i}\right) \tag{1}$$

where

PE	is yearly primary energy demand, in kWh;
DE	is yearly delivered energy for energy source i, in kWh;
XE_i	is the yearly exported energy for energy source i;
$f_{prim,del,i}$	is primary energy factor for energy source i, in kWh/kWh;
$f_{prim,del,i}$	is the primary energy factor for the exported energy source i;

(NS-EN 15603:2008, 2008).

For comparison between the micro-CHP system and the conventional reference system, the primary energy savings (PES) will be evaluated. This is given by equation 2:

$$PES = \frac{PE_{TOT,GB} - PE_{TOT,CHP}}{PE_{TOT,GB}} \cdot 100\ \% \tag{2}$$

Where

$PE_{TOT,GB,}$	is primary energy of fuel and electricity consumed by the conventional system, in kWh ;
$PE_{TOT,CHP}$	is the primary energy of fuel and electricity consumed by the CHP system, in kWh.

Energy efficiency

The overall energy efficiency depends on several factors; the prime mover, the size of the plant, the temperature at which the recovered heat can be utilized and conditioning and operating regime of the cogeneration unit. It is a measure of how efficient the energy is produced, distributed, stored, converted and used (Dorer & Weber, 2007).

Both CHP and system performance are evaluated based on equations 3-8. Efficiencies regarding the specific efficiencies of the CHP unit and the reference case of a condensing gas boiler are based on equations from EN 15316-4-4:2007 (NS-EN 15316-4-4:2007, July 2007), while system efficiencies are based on proceedings conceded by Annex 42 (Dorer & Weber, 2007).

CHP efficiency:

$$\eta_{CHP} = \frac{CHP\ System\ output}{CHP\ System\ input} = \frac{OE_{th,CHP} + OE_{El,CHP}}{DE_{Fuel}} \tag{3}$$

CHP thermal efficiency:

$$\eta_{th} = \frac{CHP\ thermal\ output}{CHP\ System\ input} = \frac{OE_{th,CHP}}{DE_{Fuel}} \tag{4}$$

CHP electrical efficiency:

$$\eta_{el} = \frac{CHP\ electrical\ output}{CHP\ System\ input} = \frac{OE_{El,CHP}}{DE_{Fuel}} \tag{5}$$

Boiler efficiency:

$$\eta_{boiler} = \frac{Boiler\ energy\ output}{Boiler\ energy\ Input} = \frac{OE_{th,boiler}}{DE_{Fuel}} \tag{6}$$

System efficiency based on delivered energies:

$$\eta_{DE} = \frac{NE_{SH}+NE_{DHW}+NE_{El}}{\sum DE_i} \tag{7}$$

System efficiency based on primary energies:

$$\eta_{PE} = \frac{NE_{SH}+NE_{DHW}+NE_{El}}{\sum PE_i} \tag{8}$$

Where

$OE_{th,CHP}$	is the thermal output of the CHP device;
$OE_{El,CHP}$	is the electrical output of the CHP device;
$OE_{th,boiler}$	is the thermal output of the boiler;
DE_{Fuel}	is the gross input to the generator;
DE_i	is the delivered energy of source *i*;
PE_i	is the primary energy of source *i*;

Reduced grid interaction

This assessment is based on an analysis of the building related to the reduced grid interaction. In this context, reduced grid interaction means reduced grid import as exported electricity is assumed beneficial for CHP. This is only an assumption, and in reality a grid structure has to be organized to make electricity export feasible economically as well as environmentally.

The exported and delivered electricity from/to grid can be explained by equation 9 and 10, respectively:

$$XE_{El-NetGrid} = \begin{cases} XE_{ElGrid} - DE_{ElGrid} & if\ XE_{ElGrid} > DE_{ElGrid} \\ 0 & if\ XE_{ElGrid} \leq DE_{ElGrid} \end{cases} \tag{9}$$

And

$$DE_{El-NetGrid} = \begin{cases} DE_{ElGrid} - XE_{ElGrid} & if\ DE_{ElGrid} > XE_{ElGrid} \\ 0 & if\ DE_{ElGrid} \leq XE_{ElGrid} \end{cases} \tag{10}$$

Where,

$XE_{El\text{-}NetGrid}$	is the net amount of electricity exported to the grid;
$DE_{El\text{-}NetGrid}$	is the net amount of electricity delivered from the grid;

CO_2-emissions

The CO_2 emissions are calculated by the equation 11 taken from (NS-EN 15316-4-4:2007, July 2007) :

$$m_{CO2} = \sum(DE_i \cdot K_{del,i}) - \sum(XE_i K_{exp,i}) \tag{11}$$

where,

m_{co2}	is the yearly CO_2 emissions, in kilograms;
DE_i	is the yearly delivered energy for the energy source *i*, in kWh;
XE_i	is the yearly exported energy for the energy source *i*, in kWh;
$K_{del,i}$	is the CO_2 factor for the delivered energy source *i*, in kg/kWh.
$K_{exp,i}$	is the CO_2 factor for the exported energy source *i*, in kg/kWh.

In order to compare the CO_2 equivalent emissions by the CHP system and the reference system, equation 12 is used.

$$\Delta mCO_2 = \frac{mCO_2^{GB} - mCO_2^{CHP}}{mCO_2^{GB}} \cdot 100\ \% \tag{12}$$

Where,

ΔmCO_2	is the CO_2-savings using the CHP system, in %;
mCO_2^{GB}	is the CO_2-emissions for the reference system, in kg/kWh;
mCO_2^{CHP}	is the CO_2-emissions for the CHP system, in kg/kWh;

SIMULATION MODEL

The main objective with CHP modeling is to predict the thermal and electrical outputs of a cogeneration device as precise as possible.

The internal combustion engine used in this study is a Senertech ICE, which is based on an Otto cycle (Thomas, 2008). This unit is chosen because there existed already calibrated data for this engine in the simulation tool used, EnergyPlus. As this engine is one of the market-leading micro-CHP appliances, an evaluation of its optimal performance is of interest. In the simulations, the ICE cogeneration model will consist of two sub-models.

1. An engine/generator unit model that predicts the heat production and the electrical generation in response to changing building energy demand.
2. A thermal storage model that predicts the energy and mass flows in all other portions of the ICE cogeneration systems.

A thermal storage is includes as this ensures a more stable and secure operation of the CHP. The CHP model used is based on the generic ICE/Stirling engine model developed by Annex 42, and represents any combustion-based cogeneration device (Ian, Ferguson, Griffith, Kelly, & Weber, 2007). The model has a nominal electric efficiency of 0.27 and nominal thermal efficiency of 0.66. The heat to power ratio of the engine is 2.44. These efficiencies are based on lower heating value (LHV) of the fuel.

The generator has an upper capacity of 5.5kW electric output.

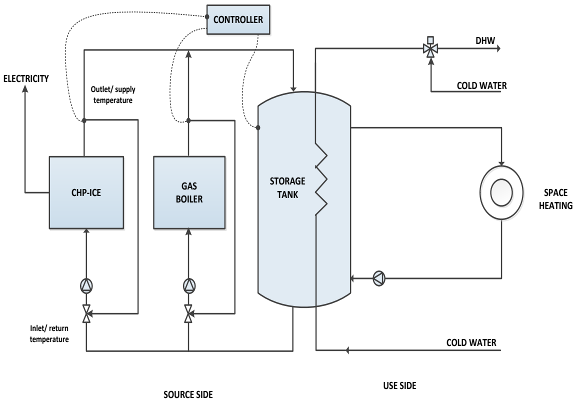

Figure 1 Configuration CHP system

The CHP system configuration is shown in figure 1. The auxiliary gas boiler is coupled in parallel to supply peak demands at times when the CHP device is not able to cover the entire demand. Heat is supplied to the tank with a supply temperature of 70°C. Domestic hot water is set to have a supply temperature of 55°C to avoid legionella. Temperature sensors are placed inside the tank to ensure acceptable tank temperatures. At the top of the tank, the set temperature is set to be 60°C. To avoid overheating of the storage, a maximum temperature limit is set for the storage tank. This is the temperature where the tank water becomes dangerously hot and is vented through boiling or an automatic safety. Any extra heat added to the tank after this maximum temperature is immediately vented. This temperature is set to 98°C. To control the cooling water mass flow rate to the CHP unit, an internal control is chosen. This indicates that the flow of cooling water is controlled inside the CHP device, similarly to an automobile's thermostat (EnergyPlus- US Department of Energy, 2013). The maximum cooling water temperature is set to be 80 °C.

The CHP model is integrated in a multi-family building constructed after the Norwegian building norm, TEK 10, having a total floor area of 450 m^2. The building model is made with low-radiant floor heating, a simple balanced constant air ventilation and domestic hot water profiles are made based on standard usage from NS 3031 (NS 3031:2007+A1:2011, 2007/2011). Electricity demand profiles are made based on data from CREST domestic electricity demand model, which can be downloaded from Loughborough University's homepage (Richardson & Thomson, 2010). The thermal and electrical energy demand for a typical cold and warm day can be seen in Figure 1 and 2.

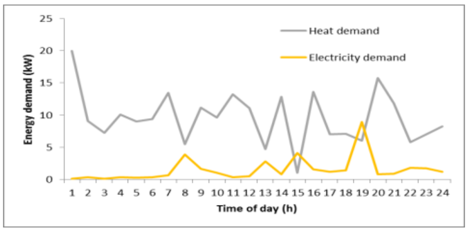

Figure 2 Power and heat demand cold day

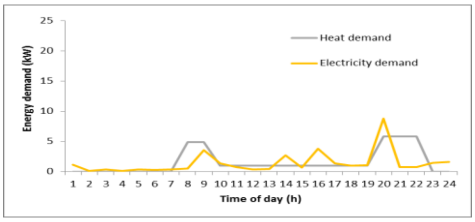

Figure 3 Power and heat demand warm day

OPTIMIZATION STRATEGIES

Load management

Load management or demand management is a procedure to adjust the electrical demands rather than the output of the plant. This can be done by for example forced switch-off of large power consumers such as sauna stoves and ovens or by limited simultaneous use of electrical appliances (Alanne, Micro-Cogeneration-I: Introduction). Today, demand management usually concerns the demand for electricity, but in the future demand management for other utilities such as natural gas or water might be possible. The main principle with the demand management controls is to shut off or reduce the power to non-essential loads. This, in order to reduce the overall building demand which will be beneficial for the CHP device as it can cover a larger part of the building's demand, and thus reduce the amount of imports from the electricity grid. Typical controls are:

- Shut off or dim electric lights, equipment, or HVAC systems
- Reset the thermostatic set points on HVAC systems (if electrical)
- Reduce the load of a set of similar components by rotating one or more components "off" for a short time interval
- Turn on generators to meet some or all the building's demand
 (EnergyPlus- US Department of Energy, 2013)

The first approach in the load management will be to reduce the electricity demand below the standard values for yearly electricity in NS 3031:2007+A1:2011 (NS 3031:2007+A1:2011, 2007/2011). This value is in total 28.9kWh/m^2. The building has pretty low energy demand for lighting, while the energy demand for electrical appliances are relatively high. Therefore, the majority of the demand management should be done here.

Power control

In order to achieve an optimal match between demand and supply it is possible to implement several operation modes. The control of the micro-CHP device defines the basis on which the prime mover is activated, deactivated or turned down. The device can be set to operate in a heat following mode, electrical follow mode, a time-led mode or a hybrid approach may be adopted (Peacock & Newborough, 22. June 2005).

For the heat following operation mode, start and stop control decisions will be based on temperature differences between the indoor and outdoor temperature. The micro-CHP device will operate to cover the whole thermal demand of the building, and electricity will be produced thereafter. This can, however result in more frequent on-off operation of the device, at least in periods when the thermal demand of the building is not stable. The benefit is that the whole thermal demand will be covered by the CHP device, and a supplementary boiler is not necessary as long as the thermal output of the generator is large enough to cover the peaks. The electrical excess produced by the CHP in the case of thermal load following mode is stored in batteries or fed into the grid. It is assumed that the exports from the CHP incur negligible distribution losses before it reaches its point of use. Electrical shortage is covered by grid electricity or by discharging the battery storage. Only grid electricity has been implemented as an option in this study.

For electricity following mode, the cogeneration device is operated to cover the electrical demand of the building as far as possible. This will reduce the amount of imports significantly, but thermal surplus may be generated at times when it is not needed. Also, when the electricity demand is low, the CHP device will often not be able to cover the thermal demand of the building. This make it necessary to have a large enough storage tank to store the surplus heat, and a supplementary boiler to cover the thermal demand at times when the CHP-device is unable to cover the demand.

On an electricity supply basis, the system is set to operate in parallel with other systems. Then the CHP system will supply the consumer until it reaches it maximum electrical output. The part not covered by this output is imported from the electricity grid. For parallel power applications, the micro-CHP and utility grid can operate simultaneously, and power can be supplied into the utility grid (Klobut, Ikäheimo, & Ihonen). The thermal output of the system will be used whenever possible, and rejected to the atmosphere otherwise. For the use of biomass as fuel, this rejected heat can also be used to dry the fuel (Klobut, Ikäheimo, & Ihonen).

For the follow electrical mode two different control options will be investigated for the ICE:

1. Unrestricted thermal surplus, ICE. The operation of the micro-CHP system depends on the electricity demand of the building, and heat is produced thereafter independent on the thermal demand of the building. In this option thermal surplus is allowed, and will get stored in the storage tank as far as possible and wasted when the tank exceeds its upper limit.
2. Restricted thermal surplus, ICE. The CHP system is set to follow the electricity demand as in (1), but only if $(NE_{SH}+NE_{DHW})>OE_{th,CHP}$, or if $(NE_{SH}+NE_{DHW})< OE_{th,CHP}$ and $T_{store}<T_{max}$. Applying this control ensures that the thermal output of the micro-CHP system will better match the thermal demand of the building, and thermal surplus is avoided. However, this may result in more start/stop events of the device (Peacock & Newborough, 22. June 2005).

T_{max}	is the maximum temperature setting of the thermal storage, which is set to 75°C;
NE_{SH}	is the demand for space heating, in kWh;
NE_{DHW}	is the demand for domestic hot water, in kWh;
$OE_{th,CHP}$	is the thermal output of the CHP, in kWh;

Thermal storage

One common form for short-term storage is the usage of buffer tanks in the system configurations. A stratified storage tank is used in this study. Stratification in a storage tank depends mainly on the volume of the tank, the size, location and design of the inlets and outlets, and the flow rates of entering and leaving streams. Stratified tanks are useful for maximizing the thermal energy efficiency of non-continuous and semi-continuous processes. Liquid at two or more dissimilar temperatures is stored within the same tank to provide a buffer for variations in heating and cooling loads. Control of the thermocline between the hot and cold fluid regions is needed to minimize thermocline growth and maximize operation of the storage tank (Walmsley, Atkins, & Riley). Two storage tank sizes is analyzed: 500 l and 1000 l. Buffer storage integrated in a building's heating system helps reducing the peak demand and energy consumption, especially when energy costs during peak periods are much higher than those in off-peaks periods (Nelson, Balakrishnan, & Murthy, 24 September 1998). Thermal storage tank is used to provide greater operational flexibility during transient load demands.

Use of renewable fuel

To lower the CO_2 emissions, the use of biogas as a fuel instead of natural gas has been viewed as an option. Biogas is considered as a more renewable fuel than natural gas, and since it comes from sources which naturally would have contributed to CO_2 emissions, the contribution of CO_2 emissions will be remarkably smaller. Principally biogas can be produced from household waste and agrifood industry. During the processing of biogas, generally approximately 65% methane (CH_4) and about 30% carbon dioxide (CO_2) is produced (Malik & Mohapatra, 2012). Biogas can also be upgraded to be a substitute for natural gas. Upgraded biogas, also called biomethane, can be interchangeable with natural gas and is also superior to natural gas in several aspects. Biomethane is cleaner burning as it does not contain hydrocarbons heavier than CH_4. Biomethane does also offer the opportunity for a carbon negative fuel, not just carbon neutral, as it is a renewable source of CH_4 and the biogas source can be from waste (Mezei, 2010).

The upgraded biogas can be supplied to the already developed natural gas grids and delivered to households and industry. The expected energy requirement for a single produced cubic meter of natural gas substitute (upgraded biogas) is equal to around 0.3 kWh (Makaruk, Milthner, & Harasek, 2010).

RESULTS AND DISCUSSION

Difference cases with different operational strategies have been made to evaluate the effect of each operation and its impact on the CHP-device. The cases are presented in table 1

Table 1
Cases simulated

Case number	**Description**
1	Reference case: GB, storage tank with reference parameters
2	CHP only with storage with reference parameters and follow thermal mode
3	CHP only with storage, follow thermal mode and load management
4	CHP and GB with storage and follow thermal, limit electrical surplus mode
5	CHP and GB with storage tank size 0.5 m^3 and follow electrical mode with restricted thermal surplus
6	CHP and GB with storage tank size 0.5 m^3 and follow electrical mode with unrestricted thermal surplus
7	CHP and GB with storage tank size 0.5 m^3 , follow electrical mode as in 5 and with load management
8	CHP only follow thermal mode tank size 1.0 m^3
9	CHP only with storage, follow thermal mode and upgraded biogas as fuel

Primary energy

The primary energy factors for natural gas and electricity used in the calculations are from NS-EN 15603:2008 as seen in table 1. The primary energy factor for biogas is taken from SAP's report for proposed carbon emission factor and primary energy factor (Pout & BRE, 2011).

Table 2
Primary energy factors from (NS-EN 15603:2008, 2008), biogas from (Pout & BRE, 2011)

	Primary energy factors f_P	
	Non-renewable	Total
Natural gas	1.36	1.36
Biogas	1.092	1.092
Electricity mix UPCTE	3.14	3.31

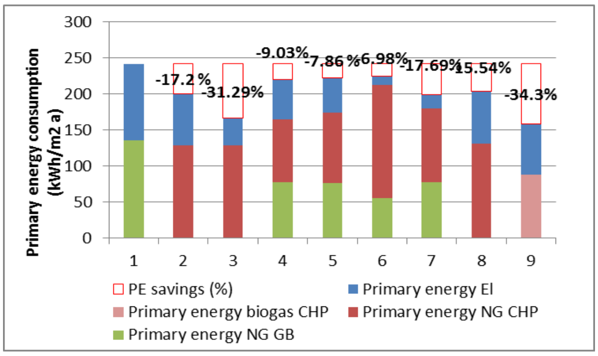

Figure 4 Primary energy savings

As can be seen by figure 4, case 9 achieve the highest primary energy savings with a reduction of 34.3% compared to the reference case. Generally, the cases in follow thermal mode achieve greatest primary energy savings. Applying load management further increases the savings, and the primary energy consumption reduces with 31.29% in the case of thermal following operation mode and 17.69% in electrical following operation mode. Electrical following operation mode without implemented load management achieves low primary energy savings due to the frequent use of the auxiliary gas boiler and less efficient heat production.

Energy efficiency

The efficiencies are based on higher heating value, and are presented in table 3. Case 9 achieves the best system efficiency based on primary energy, representing an increase of 20.8% compared to the conventional gas boiler. This is mainly due to the low primary energy usage as upgraded biogas is used, which is considered a renewable fuel. As can be seen, the cases in thermal following operation mode achieve better system efficiency than the cases in electric load following mode. Also regarding the specific CHP efficiency, these cases achieves best operation. The cases in electric load following mode achieves higher electric efficiency, but since the

Table 3
Comparison efficiency all cases (HHV)

	1	2	3	4	5	6	7	8	9
Thermal efficiency	-	0.521	0.524	0.423	0.394	0.440	0.405	0.523	0.521
Electrical efficiency	-	0.226	0.228	0.238	0.238	0.243	0.241	0.220	0.226
CHP efficiency	-	0.747	**0.751**	0.662	0.633	0.684	0.646	0.744	0.747
Gas boiler efficiency	0.902	-	-	0.941	0.941	0.943	0.942	-	-
System efficiency (DE)	0.914	0.741	0.721	0.828	0.795	0.705	0.788	0.731	0.741
System efficiency (PE)	0.499	0.561	0.637	0.519	0.509	0.501	0.547	0.549	**0.707**
% increase from 1	-	6.076	13.80	2.00	1.00	0.20	4.80	5.00	20.80

thermal recovery efficiency becomes remarkable poorer this reduces significantly the all-over performance of the system. In case 6 with unrestricted thermal surplus, the corresponding losses were significantly higher than the other cases. This is due to unmatch between thermal supply and demand, especially during summer season. For all the CHP cases analysed, the CHP efficiency was lower during the summer months. This indicates that CHP has better operation when the thermal demand of the building is high, and the relation between the thermal and electrical demand of the building becomes closer to the heat to power ratio of the CHP.

Operational characteristics

Figure 5 shows the monthly operational hours for each of the cases simulated.

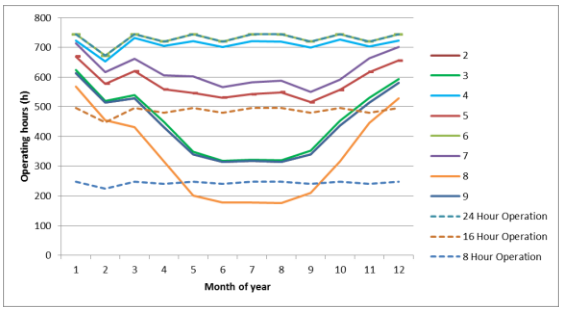

Figure 5 Monthly operational hours

As can be seen, the cases in electric following operation mode achieve higher monthly operating hours than the cases in thermal load following operation mode. This is due to a continuous electricity demand during the seasons as some electrical devices consume standby power even when not in use. As the CHP is set to follow the electrical demand, the CHP can operate continuously, as some electricity demand is present at all hours of the year. With unrestricted thermal surplus, the CHP could therefore operate at full operation the whole year. Restricting the thermal surplus led to lower operation time as the device could not operate if the tank temperature exceeded 75°C. The cases in thermal load following operation mode was more affected by demand variations over seasons as the thermal demand of the building was significantly higher during the cold season than the warm season. This led to higher operating hours during the colder months. Increasing the thermal storage led to lower operating hours as the output of the generator was higher at each time step as more heat could be stored in the tank. As the thermal demand of the building remained the same, the generator had to operate less time as the tank then could supply heat to the building for longer intervals than with a smaller tank size.

Reduced grid interaction

One of the main promoting arguments for the application of micro-CHP in buildings is its reduced grid interaction. The amount of imports reduced is beneficial as this avoids electricity imports from larger power plants with higher emissions, as well as transmission losses are avoided as the electricity is produced on site. Figure 6 shows the proportion of demand covered by the CHP versus utility grid for all cases simulated.

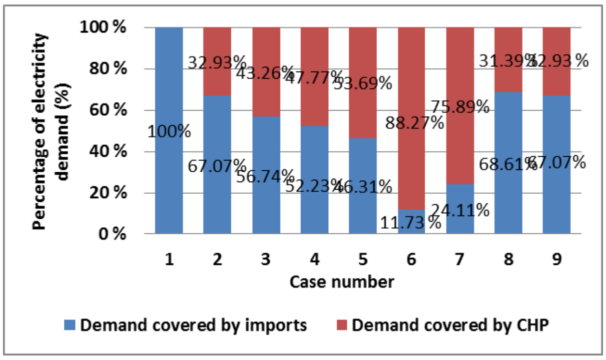

Figure 6 Proportion of demand covered by CHP versus utility grid, all cases

As can be seen, the CHP covers the greatest part of the electricity demand in case 6. This is as expected as the generator is set to follow the electrical demand of the building without thermal surplus restriction. In this case, the CHP covers the demand until it reaches its upper capacity limit. Only the demand exceeding 5.5 kW is imported from the utility grid. However, in this operation mode, significant thermal surplus was present during the summer season, which reduces the efficiency as this amount is wasted. Implementation of seasonal thermal storage would here be an option to increase efficiency as heat waste would be remarkably reduced. However, this option was not included in this study. By implementing thermal surplus restriction, the amount of electricity demand covered by the CHP significantly reduces. In this case, the generator was only able to cover 53.69% of the electricity demand. Implementing load management, however, makes the CHP device more capable to cover the demand, and the CHP covers 75.89%. In thermal load following operating mode, the generator covers less of the electricity demand. However, the amount of exports is significant without implemented electrical surplus restriction. Case 3 in follow thermal operation mode with implemented load management represents the highest amount of exports, representing 76.61% of the produced CHP electricity.

CO_2-emissions

Another promoting argument for using CHP is the allover resulting CO_2 savings compared to the conventional gas boiler. However, these savings depend on the emission factor for each of the energy sources used. Table 4 show the CO_2 production coefficient used in the calculations.

Table 4

CO_2-production coefficients (NS-EN 15603:2008, 2008) *(Dokka, 2011) (Pout & BRE, 2011)*

	CO_2 production coefficients K (kg/MWh)		
	NS-EN 15603	SAP 2012	Net-ZEB (yearly average 2014-2029)
Natural gas	277	-	-
Biogas	-	98	-
Electricity	617	-	269.7

As can be seen, the CO_2 production coefficient for electricity using the net-ZEB definition is substantially lower than today's UCPTE electricity mix. This will affect the environmental benefits of implementing CHP. In the results, the value of HHV is used for the delivered energy to calculate the CO_2-emissions related to this energy.

The emissions coefficient for the electricity using net-ZEB definition is calculated based on the following formula taken from the "Proposal for CO_2-factor for electricity and outline of a full ZEB-definition" (Dokka, 2011):

$$K_{el}(t) = \begin{cases} 361 - 8.3 \cdot [t_{yr} - 2010], & t_{yr}\ between\ 2010\ and\ 2055 \\ 0 & ,\ t_{yr}\ after\ 2055 \end{cases}$$

Where,

$K_{el}(t)$	is the CO_2 factor for electricity for year t, in g/kWh;
t_{yr}	is the actual year;

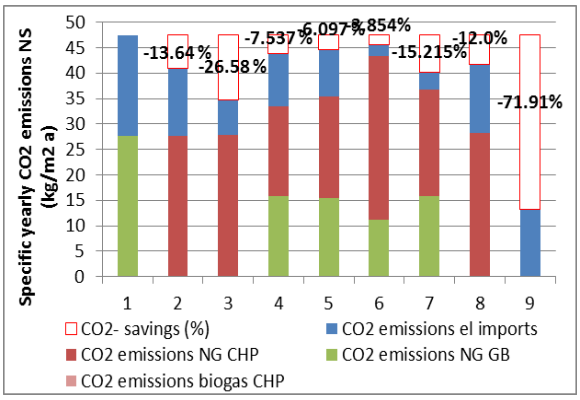

Figure 7 CO-emissions UCPTE electricity mix

On an environmental perspective the cases in follow thermal mode achieves the highest amount of CO_2-savings compared to the reference case (1) as can be seen in figure 6. The use of upgraded biogas as fuel (case 9) results in the greatest CO_2 savings. This is as expected, as biogas is considered a CO_2 neutral fuel. As exported electricity is substituted from the total emissions from the CHP, the resulting CO_2 emissions from biogas fuel are completely limited. Using natural gas as fuel, however, results in significant lower CO_2-savings, where the highest savings are achieved in case 3. This indicates that buildings with more stable electricity demand is beneficial for the CHP operation, and where the relation between the thermal demand and electrical demand is higher.

Using the Net-ZEB CO_2 emission factor for electricity mix, CO_2 savings were only seen in case 9 when upgraded biogas was used as fuel. The other cases resulted in an increase in emissions compared to the reference case. This questions the benefits on a future basis of implementing residential CHP on a CO_2 perspective as the CO_2 factor for electricity is expected to decrease over the upcoming years as electricity production is becoming greener (Dokka, 2011). Therefore, the CHP system should represent a net benefit in CO_2 emissions also on a future perspective in order to be a sustainable option. The use of renewable fuel should be further investigated, and pilot project should be developed to enable an efficient operation in practice also on these fuels. If this is obtained, huge environmental benefits will result

CONCLUSION

The study investigated the performance of different operational strategies applied to a micro-CHP system supplying a multi-family building built after the Norwegian building norm TEK10. To evaluate the performance of a micro-CHP device, a detailed model of the system was needed in order to predict the electrical and thermal performance with sufficient temporal resolution and accuracy. All strategies have been compared to a high-efficient condensing gas boiler, which represents the best system available in the market. A high-efficient condensing gas boiler was chosen in order to evaluate the possibilities for increased market penetration for CHP technology.

For primary energy and CO_2 emissions, it was found that case 9 represented the highest savings, which shows that the usage of renewable fuels in CHP is beneficial on an environmental perspective compared to natural gas. However, this depends on the security of supply and the possibility to transfer upgraded biogas in the already existing natural gas networks. By using natural gas as fuel, the implementation of load management in thermal load following operation achieved highest primary energy savings as well as CO_2-savings, and represented 31.29% and 26.58%, respectively. It was in general seen that the thermal load following operation scheme resulted beneficial over the electric load following scheme in all the performance assessments reviewed except for reduced grid interaction. Case 6 resulted in the highest reduction in imports, where imports were reduced to 11.73% of the total electricity demand. However, this impacted the system efficiency as significant amount of heat was wasted during the summer months due to overproduction of heat. Such operation would strictly depend on seasonal storage to be beneficial. Case 3 represented the highest CHP efficiency with a value of 75.1% (HHV), and case 9 represented the highest system efficiency with a value of 70.7% (HHV). From this it can be concluded that further investigations and development of pilot projects should be done to determine a proper operation of CHP in thermal load following mode using renewable fuels.

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