NTNU
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Temporal Carbon Intensity of Current and Future Energy Carriers at NTNU Gløshaugen

Emil Dæhlin

Master of Energy and Environmental Engineering
Submission date: June 2018
Supervisor: Helge Brattebø, EPT
Co-supervisor: Christian Solli, NTNU Property Division

Norwegian University of Science and Technology
Department of Energy and Process Engineering

Norwegian University
of Science and Technology

Department of Energy
and Process Engineering

EPT-M-2018-25

MASTER THESIS

for

student Emil Dæhlin

Spring 2018

Temporal carbon intensity of current and future energy carriers at NTNU Gløshaugen

Tidsavhengige karbon-intensiteter til nåværende og fremtidige energibærere på NTNU Gløshaugen

Background and objective

FME ZEN – The Research Centre on Zero Emission Neighbourhoods in Smart Cities is aiming to develop solutions for buildings, neighbourhoods and city areas which will contribute to the realization of a carbon-neutral society. The built environment is responsible for a large share of the Norwegian energy use and greenhouse gas (GHG) emissions. Hence, the development of smart cities with Zero Emission Neighbourhoods can be of utmost importance to reach the Norwegian Government's goal to reduce greenhouse gas emissions to 40% by 2030 compared to 1990.

A large share of the emissions from the built environment can be attributed to emissions from energy use. The magnitude of these emissions is highly dependent on which energy carriers are used to what extent, and the primary energy input into the energy carriers. In Norway, a relatively large share of the heating demand has historically been covered by cheap and renewable electricity from the grid. The power system is however expected to undergo a major transformation the next years, especially characterized by an increasing deployment of new renewable energy and increasing interconnection with the European power system. The implications of this and how it can motivate the deployment of local new renewable energy production should be investigated in this master thesis.

The co-location of NTNU around Elgeseter/Gløshaugen include new construction of 92 000 m2 and rehabilitation of 45 000 m2 university buildings. The Norwegian Parliament has suggested to set an ambition goal of an energy positive campus, producing more energy than it uses during its lifetime. The GHG-emissions that can be saved by this, is highly dependent on the GHG-emission intensities of the different energy carriers and to which extent they are covering the electricity and heating demand of the buildings. This suggests that an in-depth analysis of the energy system in a GHG emission context can give important insights to decision making processes for a construction project with ambitious environmental goals.

The goal of this master thesis is to develop / establish CO_2-intensities for the energy carriers relevant for NTNU Gløshaugen. The CO_2-intensities should be established with different assumptions and scenarios and display how the CO_2-intensity varies over time. The results will be an important contribution to future assessments on the lifecycle GHG-emissions of the campus and may give valuable input in a decision-making context for deciding the environmental ambition level of the new campus.

The following tasks are to be considered:

The main objective of this work is to establish CO_2-intensities for different energy carriers that are relevant for covering the energy demand at the new NTNU campus. This objective should be attained by carrying out the following tasks:

1. Carry out a literature study with a scope of relevance to this project.
2. Describe the energy system and technologies for the relevant energy carriers at NTNU Gløshaugen ini the period from 2018 to 2050.
3. Perform an in-depth analysis of the emission-intensities (g CO_2-eq/kWh) for each of the energy carriers and with associated technologies throughout the period, given different assumptions and scenarios, including high resolution on influential temporal and local factors.
4. Estimate the dimension of the different energy solutions to cover the energy demand from 2018 to 2050. Based on this, estimate the emissions from energy use in the analysis period including the potential for avoided emissions by substitution of grid energy by local renewable energy.
5. Discuss strengths and weaknesses of the work and suggest future research needs relevant to the study performed.

-- ” --

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.

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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, 9. February 2018

Professor Helge Brattebø
Academic Supervisor

Research Advisor: Environmental advisor Christian Solli, NTNU Property division.

Summary

In recent years, an increasing attention has been given to the temporal variations in indirect greenhouse gas emissions connected to energy use in buildings. The traditional approach in Life Cycle Assessments has been to use annual average emission intensities. In this study, carbon emission intensities [g CO2-eq/kWh] have been developed for energy carriers relevant for a university campus in Norway. This includes an hourly carbon emission intensity for purchased electricity based on historical production and physical flow between regions. The carbon emission intensities of heat from a district heating grid and a local heating grid based on heat pumps are assessed based on monthly production data and relevant plans for future development. The emission intensities are further combined with the simulated energy use of the university campus future building stock to estimate the energy-related greenhouse gas emissions from the building stock in the period 2018 to 2050.

The use of high temporal resolution on emission intensities was found to give lower emissions from the building stock than with average annual emission intensities. The absolute value of the emission intensity of district heat, together with how it varies throughout the year, is highly dependent on allocation choices in modelling the heat supply system. It is shown how different assumptions give different results for the carbon emission intensities and overall emissions towards 2050. This will again have implications for strategies regarding the deployment of new renewable energy solutions at the university campus in the years to come.

Sammendrag

I senere år har det blitt viet økende fokus til tidsavhengige karbon-intensiteter knyttet til indirekte CO2-utslipp fra energibruk i bygninger. Den tradisjonelle fremgangsmåten i livssyklusanalyse har vært å bruke årlige gjennomsnittlige utslippsintensiteter. I denne studien har det blitt utviklet karbon-intensiteter [g CO2-ekvivalenter/kWh] for energibærere relevante for NTNU Gløshaugen. Dette inkluderer karbon-intensiteter med timesoppløsning for kjøpt elektrisitet basert på historisk kraftproduksjon og fysisk flyt mellom prisregioner. Karbon-intensiteten til fjernvarme og lokal varme fra varmepumper har blitt utviklet med månedlig tidsoppløsning, basert på produksjonsdata og planer for utvikling av energisystemene. Utslippsintensitetene er videre kombinert med den simulerte energibruken til den fremtidige bygningsmassen på NTNU Gløshaugen for perioden 2018 til 2050.

Karbon-intensiteter med høy tidsoppløsning viste seg å gi lavere totale utslipp fra bygningsmassen enn årlig gjennomsnittlige utslippsintensiteter. Størrelsesordenen til utslippsintensiteten til fjernvarme, samt hvordan den varierer gjennom året, avhenger av valg knyttet til allokering av utslipp. Ulike antakelser viste seg å gi ulike resultater, som igjen vil ha ulik innflytelse for valg knyttet til fremtidig utvikling av lokale fornybare løsninger på campus.

Preface

This study is a Master Thesis for The Industrial Ecology Programme at NTNU. The structure of the thesis is unconventional in the sense that the study is intended to be published in the journal *Energy*. The research paper *Temporal Carbon Intensities of Current and Future Energy Carriers at NTNU Gløshaugen*, should therefore be considered as the main part of this Master Thesis. The supplementary materials will present the background for the methodology and results.

The study will emphasize some parts of the assignment text more than others. These choices were taken in agreement with the supervisors.

The study was intended to include an in-depth analysis of the future emission intensity of electricity. This was intended to be based on the results of a simulation of the European power grid done by an external researcher. Due to continuous postponing of the simulation results, it was decided to instead analyse the electricity grid based on historical data. This approach will display the methodological concepts applicable also to simulations of the future electricity grid. Because the analysis is based on historical data, the study shows a clear weakness in identifying the emission intensities *throughout the period*, as stated in the assignment text.

Another aspect which will be emphasized less than first intended, is the estimation of future emissions from energy use in the analysis period. This is due to several reasons. Firstly, the large uncertainty which the above-mentioned approach will lead to makes the calculation of the total results merely a demonstration of the approach. Secondly, the delivered energy obtained from the building stock model is a demonstration of the model, rather than an accurate estimation of the expected future delivered energy to Gløshaugen. Thirdly, the future energy system of Gløshaugen is still not conceptualized, and a range of opportunities are possible to supply the energy demand to the buildings the next 32 years. The three above-mentioned aspects argue for a larger emphasis on the current energy system and expected changes in the next few years. The study should therefore be interpreted as a demonstration of the concepts and methods, rather than accurate results for GHG emissions towards 2050.

This Master Thesis is the final chapter of my five years as a student at NTNU. It has been some very good years. For the contribution and help with finishing this thesis, I would like to thank a handful of people. Thanks to Aleksandra Woszczek, Jan Sandstad Næss, Magnus Inderberg Vestrum, Nina Holck Sandberg and Carine Lausselet for inspiration, help and discussions. A special thank you goes to my two supervisors Christian Solli and Helge Brattebø for guidance and for pushing me in the right direction. I would also like to thank my good friends here in Trondheim, and lastly my girlfriend Sofie.

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Temporal Carbon Intensity of Current and Future Energy Carriers at NTNU Gløshaugen

Highlights

- Carbon emission intensities [g CO2-eq/kWh] have been established for electricity, district heating and heat pumps supplying a university campus in Norway with energy.
- The carbon intensities were developed with high temporal resolution and with high focus on local factors.
- The use of a high temporal resolution for carbon emission intensities leads to lower emissions than annual average emission intensities in this case study.
- Different allocation choices will have different implications for local renewable energy deployment policy.

Abstract

In recent years, an increasing attention has been given to the temporal variations in indirect greenhouse gas emissions connected to energy use in buildings. The traditional approach in Life Cycle Assessments has been to use annual average emission intensities. In this study, carbon emission intensities [g CO2-eq/kWh] have been developed for energy carriers relevant for a university campus in Norway. This includes an hourly carbon emission intensity for purchased electricity based on historical production and physical flow between regions. The carbon emission intensities of heat from a district heating grid and a local heating grid based on heat pumps are assessed based on monthly production data and relevant plans for future development. The emission intensities are further combined with the simulated energy use of the university campus future building stock to estimate the energy-related greenhouse gas emissions from the building stock in the period 2018 to 2050. The use of high temporal resolution on emission intensities was found to give lower emissions from the building stock than with average annual emission intensities. The absolute value of the emission intensity of district heat, together with how it varies throughout the year, is highly dependent on allocation choices in modelling the heat supply system. It is shown how different assumptions give different results for the carbon emission intensities and overall emissions towards 2050. This will again have implications for strategies regarding the deployment of new renewable energy solutions at the university campus in the years to come.

Key words

CO_2 emissions, emission intensities, energy use, building stock modelling, LCA, allocation

1 Introduction

1.1 Motivation/Background

A key strategy to mitigate climate change is to address the energy use and greenhouse gas (GHG) emissions from the building sector. The building sector consumes 32% of the world's final energy demand and emits 11% of the direct GHG emissions and a large share of indirect emissions [1]. The size of the indirect emissions is dependent on how much energy the building uses. It is also dependent on the type of energy carriers used, and how that energy is produced. A GHG emission intensity (g CO2-eq/kWh) is used to quantify these indirect emissions. The emission intensities of energy carriers are therefore of utmost importance when assessing the indirect emissions in building stock modelling.

The interconnection between the building sector and energy sector is complex. The energy systems are becoming more decentralized as building integrated energy production increases. The deployment of intermittent renewable energy is increasing both in the regional energy systems and in connection to buildings. In hours where the energy demand in a building is low, the locally produced energy can be exported to the grid. Local energy storage is expected to be a key technology for overcoming current challenges with peak power use and production. All these trends are characterized by a temporal variation that will increase the complexity in how we use energy in buildings and how we produce it.

The GHG emission intensity has traditionally been based on yearly averages[2]. It has however been common practice to assess the energy demand with an intra-year time-resolution. A higher time-resolution also for emission intensities would significantly increase the complexity of the calculations[3]. With increasing temporal dynamics in the energy system supplying buildings, a better understanding of the temporal variations in GHG emission intensities is needed, both for electricity and heat.

When assessing the GHG emissions related to energy carriers a differentiation must be made between attributional and marginal approaches in Life Cycle Assessment (LCA) inventory modelling. The attributional approach is characterized by the use of actual data from suppliers or assuming average technology data. Allocation is most often used to deal with multifunctional processes[4]. This is contrasted by consequential approaches where marginal data and the system expansion principle is used to estimate the consequences of effects and changes in the background economic system[4]. While attributional approaches are intended to capture the possible environmental impacts that can be ascribed to the foreground system during the whole life-cycle, consequential approaches intend to reveal the consequences a decision in the foreground system has for other systems and processes in the economy[5]. Life Cycle Inventory (LCI) databases offer inventories for electricity suitable for both marginal and attributional approaches [6], but disregards intra-year variations.

The regional complexity and interconnectivity of electricity networks complicates the GHG emission analysis of purchased power. Two approaches which are widespread is to assume that the emissions connected to purchased power is locally produced (Boundary 1), or that the imported electricity is entirely produced by the neighbouring exporting region (Boundary 2). These two approaches may lead to an under- or overestimation of the emission intensity of electricity in a region, which again may alter the results of GHG emission accounting. A third approach is to also consider the imports of a neighbouring exporting region (Boundary 3), which are proposed by Ling Ji et al. [7]. The same study has assessed the case of the Nordic power system and the results underline the need for a Boundary 3 approach[7].

The complexity of emissions connected to purchased electricity increases further when temporal variations also are considered. Recent studies assessing the intra-year temporal differences in the impact from electricity use have concluded that the temporal effects should not be disregarded[8-10]. Using a Boundary 1 approach, Roux et al. assessed the environmental impacts of electricity use in buildings using an hourly time resolution on production data. The study found that a use of a conventional yearly average carbon intensity for electricity will underestimate the GHG emissions by over 30% [9]. A study by Olkkonen and Syri has looked into the temporal and spatial marginal electricity mix in the Nordic power system towards 2030 [10]. Recent efforts are looking into the real time carbon intensity of the electricity mix, with both a production-based approach[11], and a consumption-based approach, namely the commercialized *Electricity Map* [12].

The literature assessing temporal variations in emission intensity for heating systems is scarce. A master thesis has assessed a real-time carbon intensity related to the district heating system in Stockholm. By using real-time production data of district heat, a real-time emission intensity was calculated using both marginal and average perspectives[13]. The temporal emission intensity of heat pumps is a field in lack of research. Since the emission intensity of the electricity supplied to the heat pump can vary with time[8-12], the emission intensity of the heat delivered by the heat pump can also vary. Another important aspect is the temperature-dependency for the coefficient of performance (COP) of a heat pump and how it affects the emission intensity [14].

1.2 Goal

The goal of this study is to examine temporal variations in the carbon intensity of energy carriers relevant for NTNU Gløshaugen, and how these are important for the estimation of overall GHG emissions towards 2050. The study will identify carbon intensities hourly for electricity and monthly for heat towards 2050. Four different energy carrier technologies will be assessed: 1) grid electricity, 2) district heating, 3) local electricity by PV, and 4) local heat by heat pumps. The study will be limited to only include emissions from the operational phase for local renewable energy, in line with how emissions from the operation phase is accounted in the forthcoming Norwegian standard prNS3720 [15]. This implies that embodied emissions in local renewable energy is excluded.

1.3 Problem formulation and research questions

Since the literature is scarce in the field of temporal GHG intensities, this study intends to give new insights that may drive the research further, both as a contribution towards improved GHG accounting and to methodology development. The following research questions were formulated:

What are the attributional emission intensities of relevant energy carriers at NTNU Gløshaugen now and in the near future, and how important is a high temporal resolution when estimating GHG emissions from this system?

What are the implications of the emission intensities of grid electricity and district heat for the strategy for deployment of local renewable energy at Gløshaugen?

2 Methods

This chapter will describe the case and the material used as a basis for the analysis. The methods used for establishing the temporal carbon emission intensities for the different relevant energy carriers are thereafter presented.

2.1 Case description

NTNU Gløshaugen is the main campus of the Norwegian University of Science and Technology (NTNU), located in the city of Trondheim in mid Norway. The current building stock consists of almost 300 000 m2 heated floor area. NTNU Gløshaugen is expected to grow with 92 000 m2 of university buildings as a new campus co-location project is realized during the next few years[16]. The energy demand of the current building stock is covered by grid electricity, district heating and a local heat grid. In 2016 the delivered energy to NTNU Gløshaugen was 62 GWh electricity and 21 GWh district heat. Some of the electricity was used to run local heat pumps supplying the local heat grid with 15 GWh[1].

The local heating grid is separated from the district heating grid through a heat exchanger. The heat exchanger allows for lower temperature in the local heating grid, which makes it possible to utilize low-temperature heat sources. The system is supplied by several heat pumps which of most have the dual functionality of cooling data centres at campus and providing heat to the local heat grid. This includes a high-temperature ammonia (NH_3) heat pump accounts for an estimated annual energy saving of 4-5 GWh[17].

The district heating system which is connected to the local heat grid, consists of 13 heat centrals, including a waste incineration plant producing 75-80% of the heat. The total production of heat has been in the range 573 - 635 GWh/year from 2015 to 2017. NTNU Gløshaugen has the same years bought 17 – 21 GWh/year, equivalent to some 3% of the total delivered heat from district heating in Trondheim. The district heating grid will develop towards a more renewable energy mix within 2020 [18]. After 2020, no tangible predictions are made for how the district heating grid in Trondheim will develop.

2.2 Emission intensity of consumed electricity from grid

The carbon intensity of the consumed electricity in the Norwegian bidding zone NO3 was modelled using an environmental system analysis approach. The regions and flows included in the model are shown in Figure 1. The analysis is based on statistical data[19-23], on physical

[1] Due to lack of data before in the beginning half of 2016, August 2016 to July 2017 is used to show the order of magnitude of the local heat pump production.

flows between regions, together with location and technology of production, and location of consumption. It does not take green certificates into consideration.

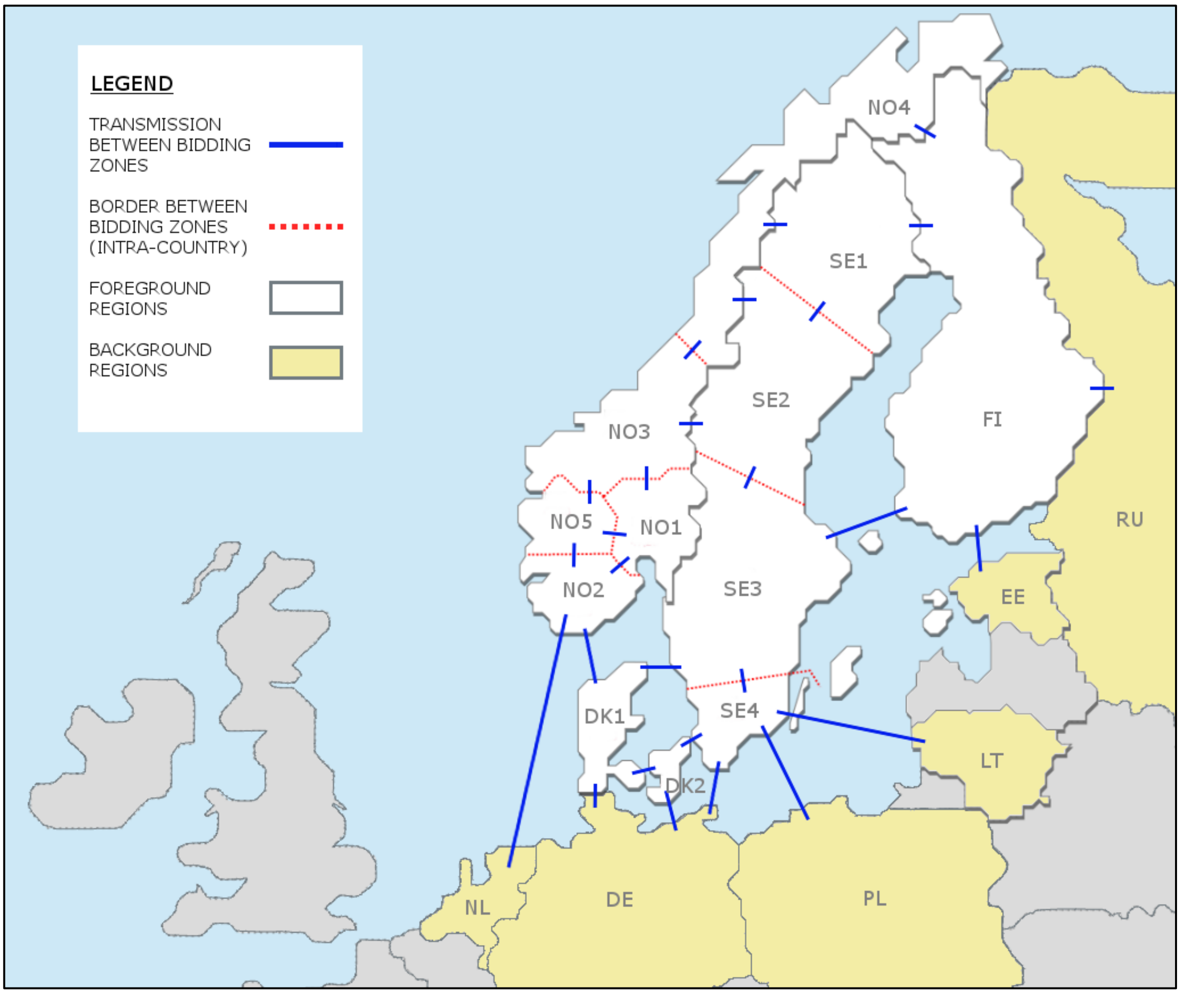

Figure 1: The modelled power system. Hourly data on imports/exports and production is used for the white foreground regions. The yellow areas are background regions with hourly data on production and exports to foreground regions. Grey areas are not regarded. Blue lines symbolize grid connections that are included in the model. The figure is a modification of Statnett's 'Nordic Power Flow' [24].*

**Note that the link between NO4 and RU is excluded.*

For the foreground regions, which consist of all bidding zones in Norway, Sweden, Denmark and Finland, hourly energy production technology data and hourly physical flow data provide inputs to the analysis. A cut-off is done for the background regions, where the only physical flow included is the one to the foreground region. This implies that imports from a background region is assumed to be the production mix in the respective background region.

For every hour, the emission intensity was calculated using the following equations. Firstly, the total output for each region at a specific time, x_t ,can be expressed by the Leontief Inverse as follows:

$$x_t = (I - A_t)^{-1} y \tag{1}$$

where x_i is the total output for hour t, I is the identity matrix, A_t is the requirements matrix for hour t, and y is the final demand vector consisting of a unit demand from NO3. A_t is quadratic, with the dimension of the foreground regions.

The hourly emission intensity without emissions from transmission and distribution (T&D) was calculated as follows:

$$E_t = e_{tech,t} T_{mix,t} x_t \tag{2}$$

where $e_{tech,t}$ is the emission intensity vector for the different technologies and background regions for hour t, $T_{mix,t}$ is the technology matrix, and x_i is the total output generated by the unit demand of 1 kWh consumed electricity in bidding zone NO3.

The total emission intensity of electricity, $E_{tot,t}$, is calculated by adding emissions from transmission and distribution (T&D), $E_{T\&D,t}$:

$$E_{tot,t} = E_t + E_{T\&D,t} \tag{3}$$

For details on the estimation of emissions from T&D, see S1.4 in supplementary materials.

Section S1.5 in supplementary materials will give the equations used in the contribution analysis.

2.2.1 Modified input data: Increased Wind

The emission intensity is calculated for two different cases: 1) using historical data, and 2) using modified historical data. The latter is intended to give a possible answer to the following question:

What if an increased amount of wind power could displace high-emitting technologies during the period 2015-2017?

To answer the question, the historical data is modified in line with S1.3 in the supplementary materials. It must be underlined that the question is hypothetical and the results with these assumptions is not intended to represent any real market in the past, present or future. Instead the results are intended to shed light on the potential impact an upscaling of wind power in NO3 can have on the emission intensity.

2.3 District heating

Statkraft Varme has provided historical production data for the years 2015, 2016, and 2017[25]. Together with expected changes in the district heating system[18], this was used to establish the production mix for every month towards 2020, further elaborated in supplementary materials, section S.2.

To calculate the emissions intensity of district heat, the technology share matrix was calculated first by using the equation:

$$T_{share,tech\_x,t} = \frac{P_{tech\_x,t}}{\sum_{tech} P_{tech,t}} \quad (4)$$

where $T_{share,tech\_x,t}$ is the technology share matrix for technology x at time t. $P_{tech\_x,t}$ is the production of technology x, while $\sum_{tech} P_{tech,t}$ is the total production. The total emissions for a given time $E_{DH,t}$ can be calculated using:

$$E_{DH,t} = \sum_{tech} T_{share,tech,t} \frac{E_{tech}}{\eta_{tech}} k_{a,tech} \quad (5)$$

where E_{tech} is the emission coefficient of the technology without considering the efficiency of the unit. η_{tech} is the efficiency of the technology. $k_{a,tech}$ is an allocation coefficient which is only relevant for the technology waste-to-heat.

The incineration of waste is the most important heat source in the district heating grid in Trondheim. The question is whether the emissions from the waste-to-heat plant should be allocated to waste-handling, district heating, or be allocated between the two by an allocation key. The three different allocation choices which are tested are summarized in Table 1.

Table 1: Summary of allocation methods for district heating.

Allocation method	**Share of emissions allocated to waste management (%)**	**Share of emissions allocated to district heating (%)**
Allocation to district heating	0	100
Allocation to waste handling	100	0
Allocation by economic value	62.5	37.5

2.4 Local renewable energy

The operational emissions from heat pumps are related to the electricity used to run the heat pumps. Although the hourly emission intensity is available for electricity, a monthly emission intensity will be calculated for delivered energy from heat pumps since the empirical production data for heat pumps from NTNU have a monthly time resolution only.

The monthly emission intensity of delivered energy by heat pumps, $E_{HP,t}$, is calculated using the following equation:

$$E_{HP,t} = E_{el,t} \sum_{x} \frac{c_{x,heat} k_{x,t}}{COP_{x,t}} \tag{6}$$

where $E_{el,t}$ is the emission intensity of the electricity at the time, $c_{x,heat}$ is the allocation coefficient to the heating for technology x, $k_{x,t}$ is the share of technology x at time t, and $COP_{x,t}$ is the coefficient of performance at a given time t for a given technology x. The COP can be calculated using the equation:

$$COP_{x,t} = \frac{Q_{del,x,t}}{W_{el,x,t}} \tag{7}$$

The share between the different technologies can be expressed by the equation

$$k_{NH_3,t} + k_{cold\&warm,t} + k_{warm,t} = 1 \tag{8}$$

Since the cold side of several of the heat pumps, including the NH3 heat pump, serve an unavoidable cooling function for the data centres and supercomputer, it was chosen to allocate all the emissions to the cold side for these heat pumps. This implies that the allocation coefficient to heating, $c_{x,heat}$, is equal to zero for both the NH3 heat pump and other heat pumps which are utilizing the cold side. For the heat pumps utilizing only the warm side, the allocation coefficient is equal to 1. The expression in Equation (6) is therefore simplified to:

$$E_{HP,t} = E_{el,t} \frac{k_{HPwarm,heat,t}}{COP_{HPwarm,t}} \tag{9}$$

The COP is assumed to vary through the year and be higher during the summer than the winter. It is a well-established connection that the COP decreases with decreasing temperature [14]. For further assumptions regarding heat pumps, see supplementary materials, section S3.

2.5 Estimation of total emissions from 2018 to 2050

The total emissions from the building stock at NTNU Gløshaugen are estimated using the calculated emission intensities and a preliminary output from the building stock model applied to NTNU Gløshaugen[26, 27]. The building stock model provides simulated delivered energy to NTNU Gløshaugen with an hourly time resolution during the whole analysis period. It must be underlined that the simulation which is used as input in this study was intended to be a demonstration of the model rather than an accurate simulation of the future energy demand at NTNU Gløshaugen. Therefore, the values are prone to large uncertainty, which should be kept in mind when reflecting on the results.

Based on the output from the building stock model and knowledge about today's energy system at NTNU Gløshaugen, an energy system covering the energy demand was assumed for calculating the total emissions. A simplified explanation of the system is presented in Table 2. See supplementary materials, section S5, for more details on intra-year distribution among the energy carriers.

Table 2: Assumed energy system in the estimation of GHG emissions from energy carriers at NTNU Gløshaugen 2018-2050. (HP = heat pumps)

Technology	**Delivered energy [GWh/year]**	**Comment**
PV	5.65	Estimated maximum potential on existing and new buildings.
Local HP	15	Based on current local HP system. Assumed a COP of 3.
District heating	17	Based on current level of DH.
Electricity	69 to 101	Assumed to cover growth in demand

Be aware that the result only includes GHG emissions from the operation phase of the local renewable energy, in line with prNS3720[15].

2.6 Sensitivity analysis

The sensitivity of selected parameters will be calculated using the sensitivity ratio, SR, given by the equation:

$$SR = \frac{(\Delta R / R_0)}{(\Delta P / P_0)} \tag{10}$$

The sensitivity ratio describes the relative change in the result $(\Delta R / R_0)$ with respect to the relative change in parameter $(\Delta P / P_0)$. R_0 is the initial result and P_0 is the initial parameter value [28].

The sensitivity ratio will be calculated for one year of GHG emissions from the building stock. The selected year was 2021 as future measures in both district heating and electricity grids will be implemented before the beginning of 2021. For details on assumptions, see supplementary material, section S6.

3 Results

The results will be presented for each energy carrier, including a contribution analysis. Thereafter, the emission intensities will be coupled against a possible future energy system at NTNU Gløshaugen. The sensitivity analysis results will finish the chapter.

3.1 Electricity

The hourly carbon emission intensity of consumed grid electricity during the period 2015-2017 in bidding zone NO3 is shown in Figure 2. The hourly carbon intensity varies between 18.2 and 56.1 g CO2-eq/kWh, while the average is 29.1 g CO2-eq/kWh.

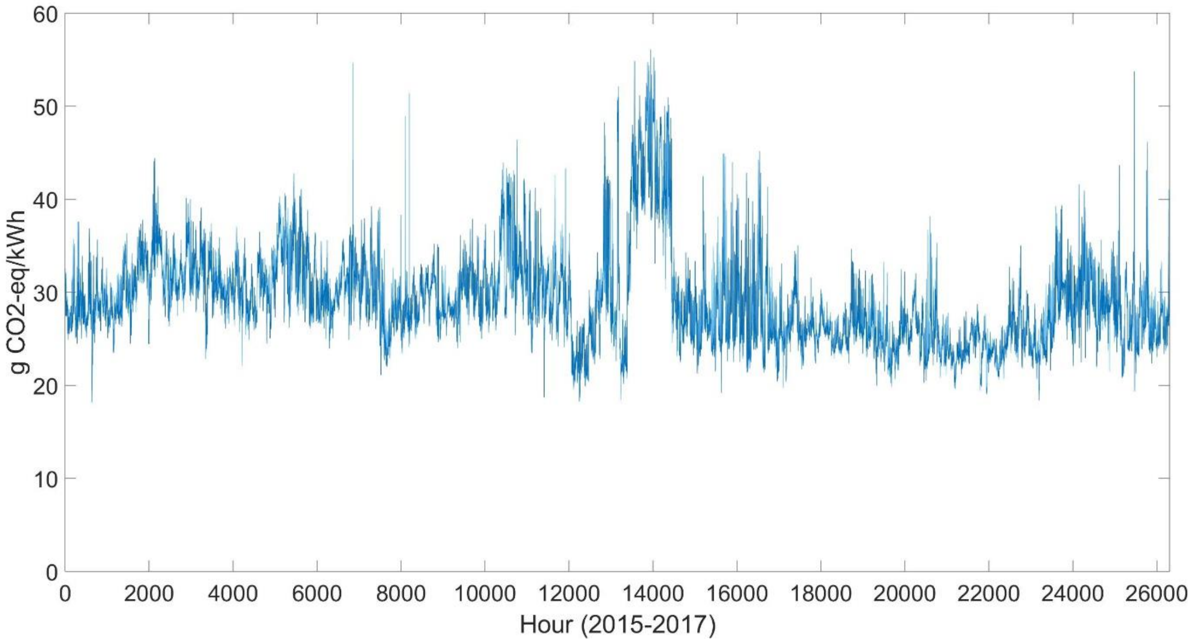

Figure 2: Hourly carbon intensity from consumed electricity in NO3.

The monthly emission intensity for each year during the analysis period 2015-2017 is shown in Figure 3. The monthly emission intensity ranges between 24.1 g CO2-eq/kWh in August 2015 and 39.4 g CO2-eq/kWh in July 2016.

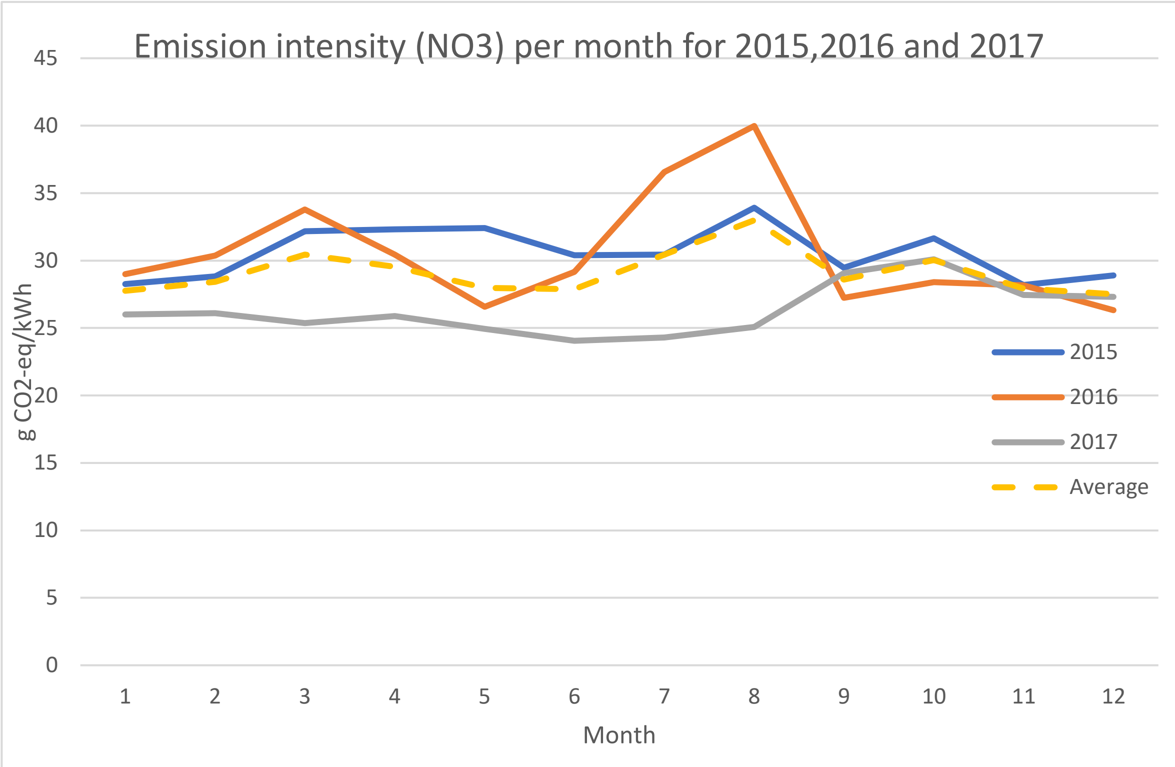

Figure 3: Emission intensity of electricity for the years 2015,2016 and 2017 in bidding zone NO3. The average emission intensity during the period is also plotted over the months.

To better understand why the emission intensity vary through and over the years, a contribution analysis has been done. Figure 4 shows how the different foreground regions contribute to the total emission intensity. One can see that the most important contributing region is NO3 itself, followed by the neighbouring regions NO4, NO5 and SE2, while the neighbouring region NO1 has a very small contribution to the total emission intensity in NO3.

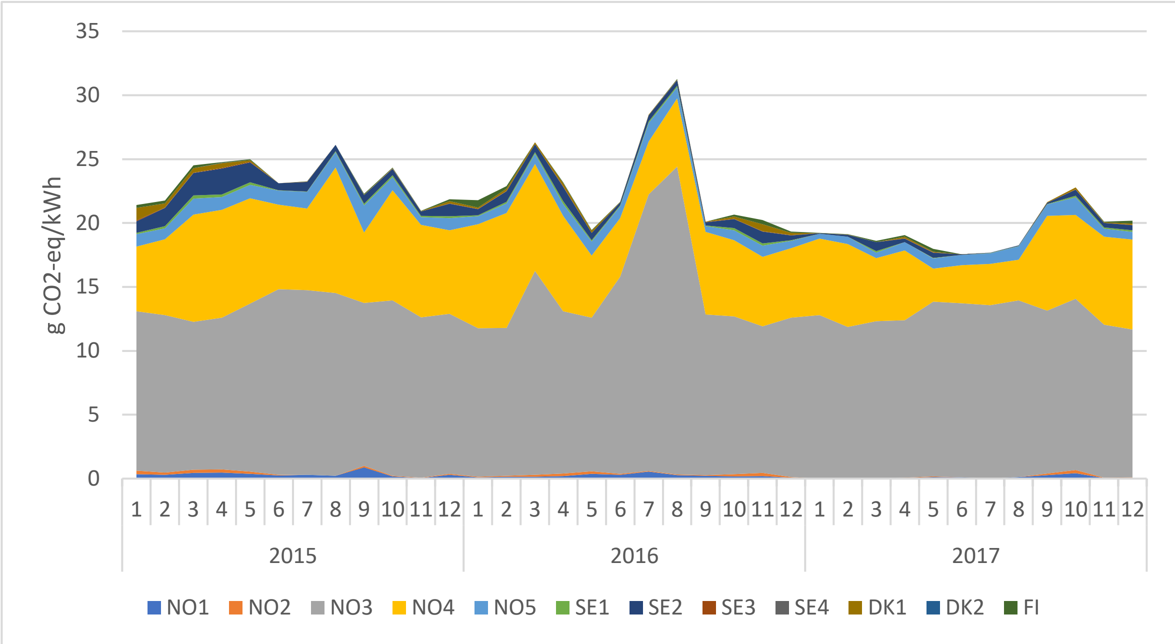

Figure 4: Emissions from electricity broken down to contribution by regions. Losses are not included.

Figure 5 shows how the different technologies are contributing to the total emission intensity. One can see that the most important technology is ‘Fossil Gas’, followed by ‘Hydro Power’ and ‘Onshore wind’. All three technologies are evident in the tier 0 region NO3 and are expected to make important contributions. Despite relatively small energy production from fossil gas, the category proves to be the most important because of its high emissions of carbon per energy unit.

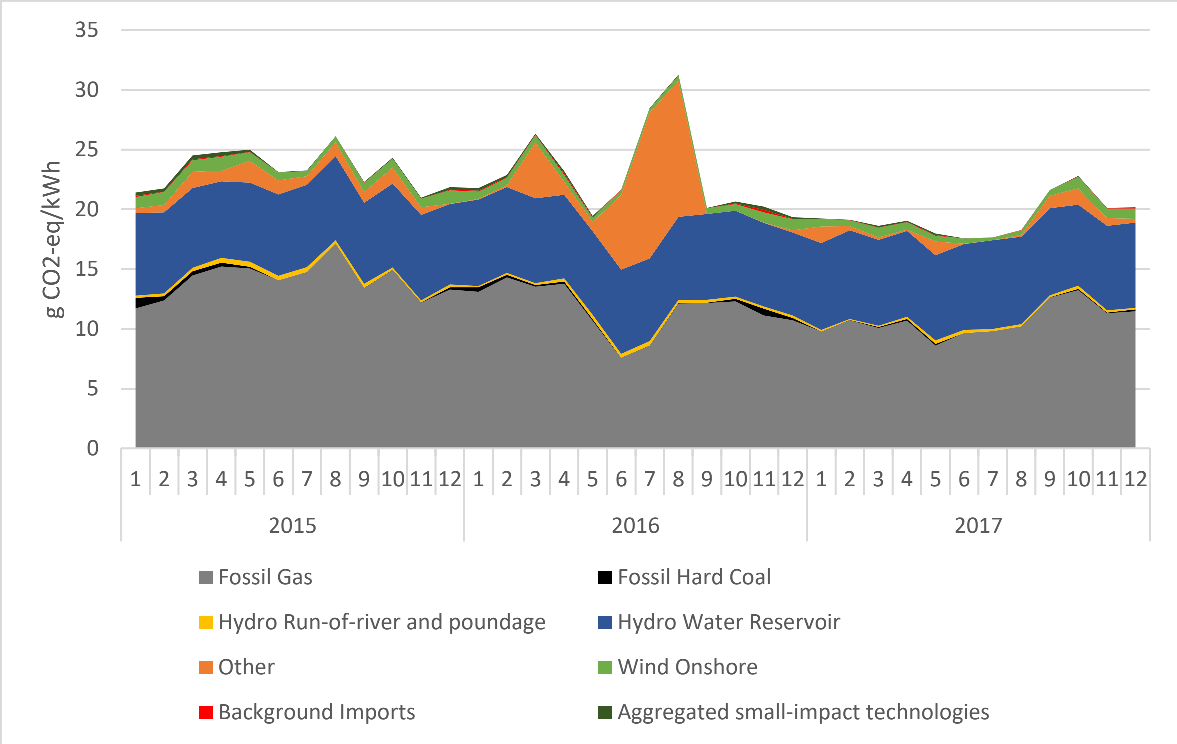

Figure 5: Emission intensity of electricity broken down by technology. Losses are not included.

The contribution of background regions to NO3 is small. Due to the many tiers between NO3 and the background regions, the impact in NO3 is close to negligible. In Figure 6 the contribution from the different background regions can be seen. When comparing the magnitude of emissions from background regions in Figure 6, with the foreground regions in Figure 4, one can see that all background regions has very small contributions to the total.

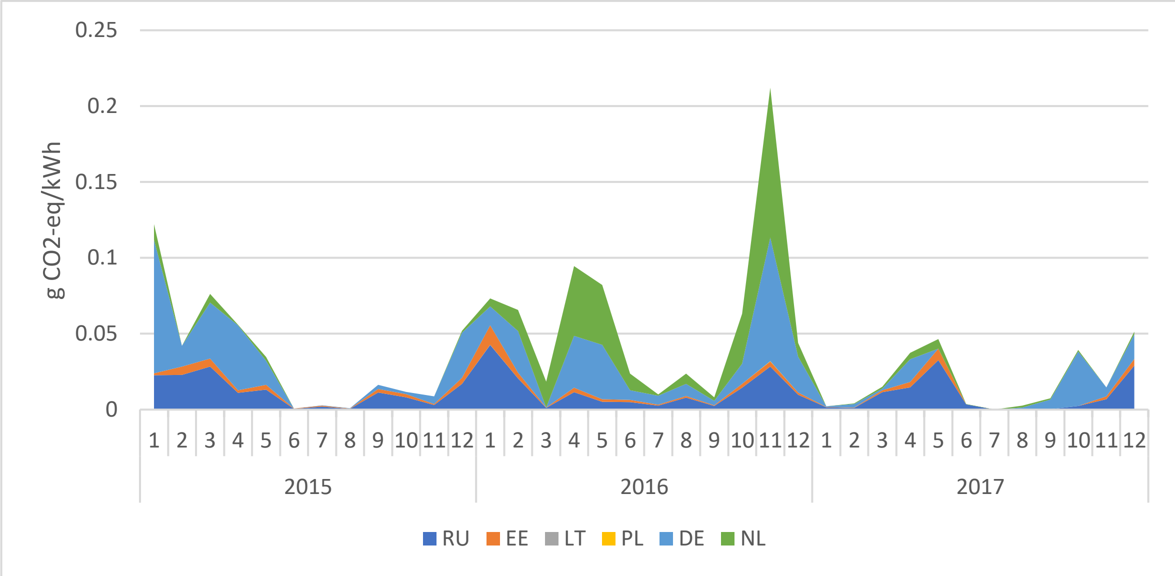

Figure 6: Contribution of imports from background regions.

An increased installation of onshore wind power, and the consequences for the electricity mix as assumed in the scenario Increased Wind, will lead to a decrease in the average emission intensity, with an average emission intensity of 19.1 g CO2-eq/kWh. The hourly emission with the increased wind power assumption can be seen in Figure 7.

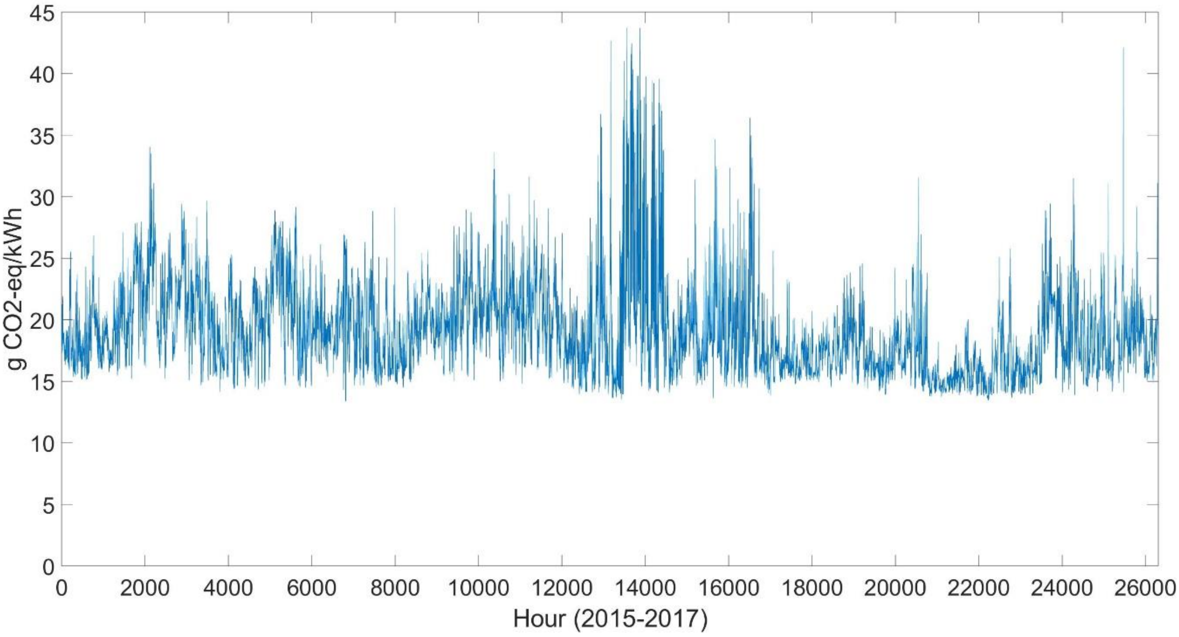

Figure 7: Increased Wind: Hourly carbon intensity for electricity consumed in NO3. The emission intensity uses the same historical input from the years 2015-2017 with modifications. The modifications include upscaled wind power production in the hours with historical wind production. The power demand in the assumed to be constant and the new wind power production displace other production or imports. It is assumed that the displacement follows a prioritized order. First, the gas power production in NO3 is displaced. If there still is a surplus of wind energy compared to the power demand, it will displace 'Other', imports, and lastly hydro power.

The Increased Wind assumptions also has the highest emission intensity during the hour 13000-15000 period of July to August 2016. By looking at the contribution by technology in Figure 8, compared to that in Figure 5, one can clearly see the increased contribution of onshore wind power. The impact of natural gas decreases but is still an important contributor. This is partly due to gas power production in NO3 in hours with too small wind production to displace the gas power production and partly because power still is imported from NO4 which has a relatively high gas power contribution in its production mix. Impact contributions from Other decreases significantly but cannot be totally displaced during the period with highest impact.

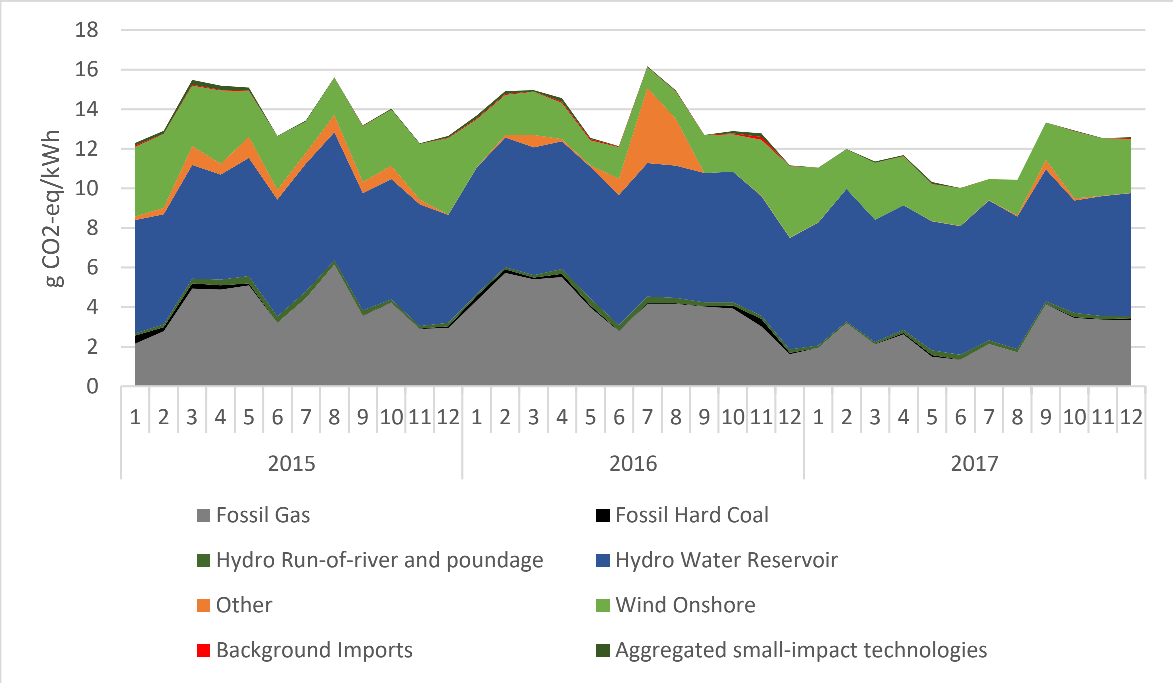

Figure 8: Contribution by technology to emission intensity of electricity, with Increased Wind. Losses are not included

The contribution by regions with the Increased Wind assumptions is shown in Figure 9.

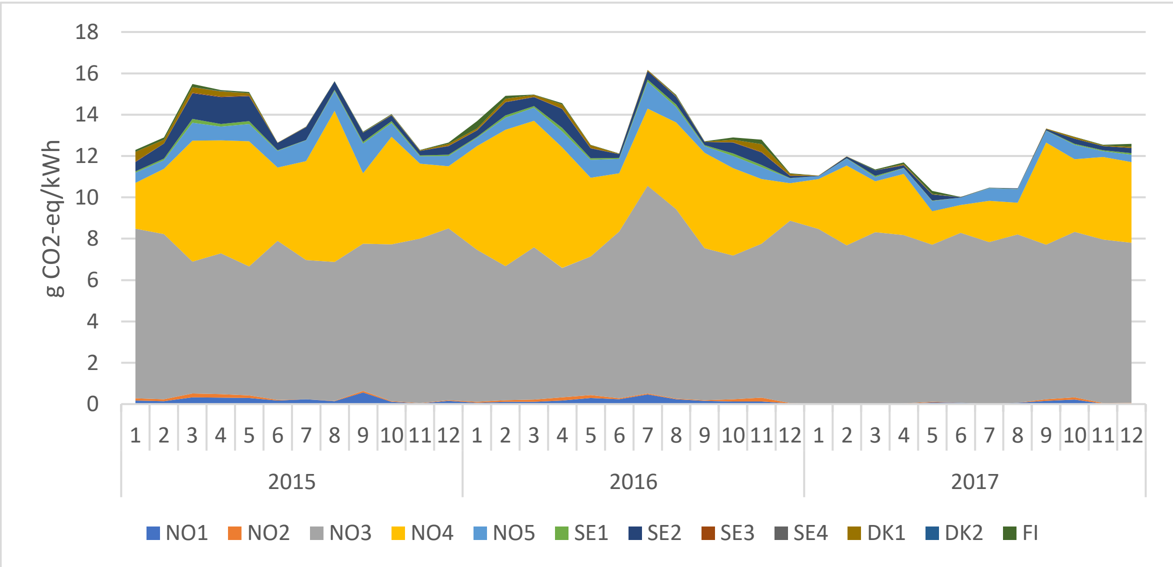

Figure 9: Contribution by foreground regions to the emission intensity of electricity, with Increased Wind. Losses are not included

3.2 District heat

The monthly emission intensity of district heat in Trondheim relies heavily on what assumptions are used to allocate emissions in the waste-to-heat power plant, since this is the most influential energy supply technology in the system. A comparison between the results with the three different assumptions can be seen in Figure 10. This clearly underlines the importance of allocation for the magnitude and intra-annual shape of the emission intensity of the district heat. The emission intensity of district heat is described in more detail in separate subchapters for each allocation method.

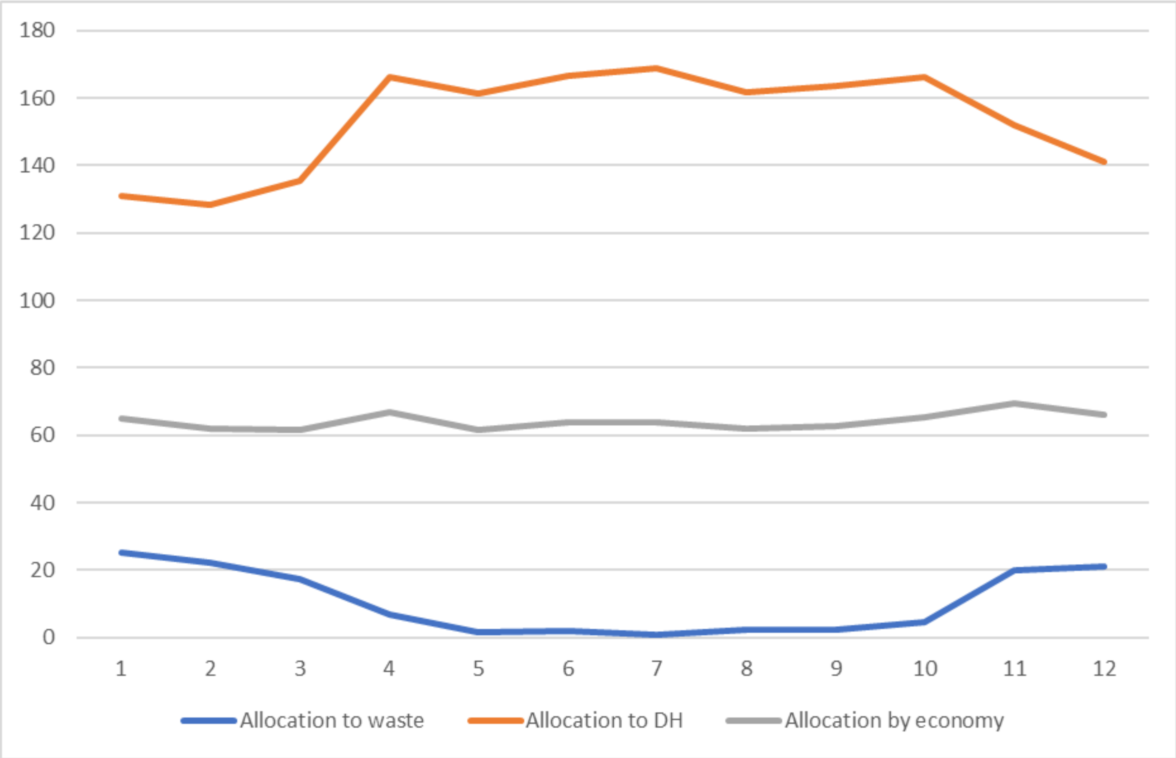

Figure 10: Emission intensity for district heat in Trondheim for year 2021 assuming three different allocation methods. Allocation to waste allocates all emissions to waste handling. Allocation to DH allocates all emissions from the waste-to-heat process to district heating. Allocation by economy allocates emissions between waste handling and district heating by an economic allocation coefficient.

3.2.1 Allocation of emissions to the waste handling system

Allocation of all GHG emissions from waste incineration to the waste handling system implies that the emission intensity for heat from waste has an emission intensity of 0 g CO2-eq/kWh. The emission intensity towards 2020 with this assumption can be seen in Figure 11. One can see that with 0 emissions from the dominating energy carrier waste, LPG dominates as the greatest contributor to the total emission intensity. The historic peak in January 2016 reached 88 g CO2-eq/kWh. The plans towards 2020 will lower the emission intensity to reach an average peak of 25g CO2-eq/kWh.

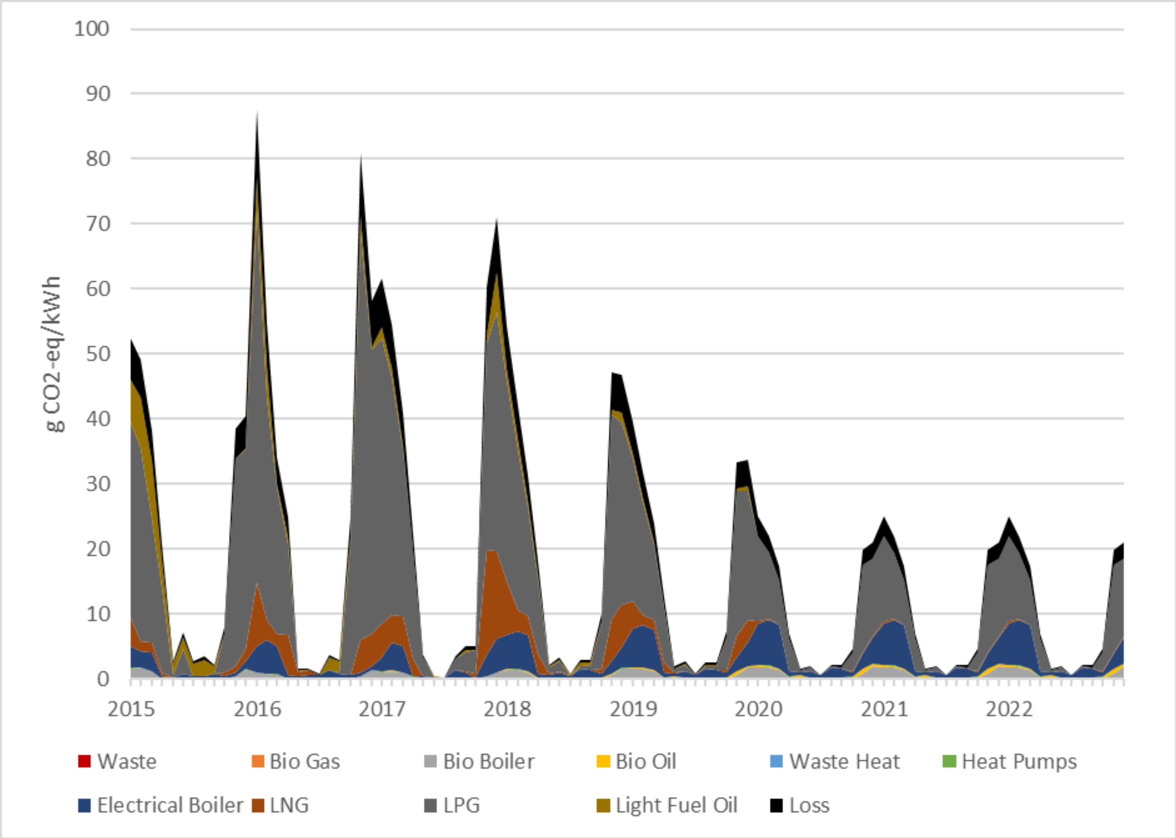

Figure 11: Emission intensity from district heat in Trondheim towards 2023 broken down by technology. Allocation to waste-handling is assumed.

3.2.2 Allocation of emission to the district heating system

Allocation of all GHG emissions from waste incineration to the district heating system implies that all emissions from the waste-to-heat process are allocated to district heating. This changes the results dramatically, as can be seen in Figure 12. With such an allocation the absolute magnitude of the emission intensity increases and is in the range between 128 -187 g CO2/kWh. Of particular interest is the seasonal shift of the annual emission intensity peak. One can see that with the increased decommissioning of fossil fuels in the system, the emission intensity peaks occur during the summer. This is because a relatively larger share of low-intensity energy, such as electrical boilers and biofuels, cover the power demand during the winter. This result would have great implications for policy making but does of course rely on the assumption of allocation.

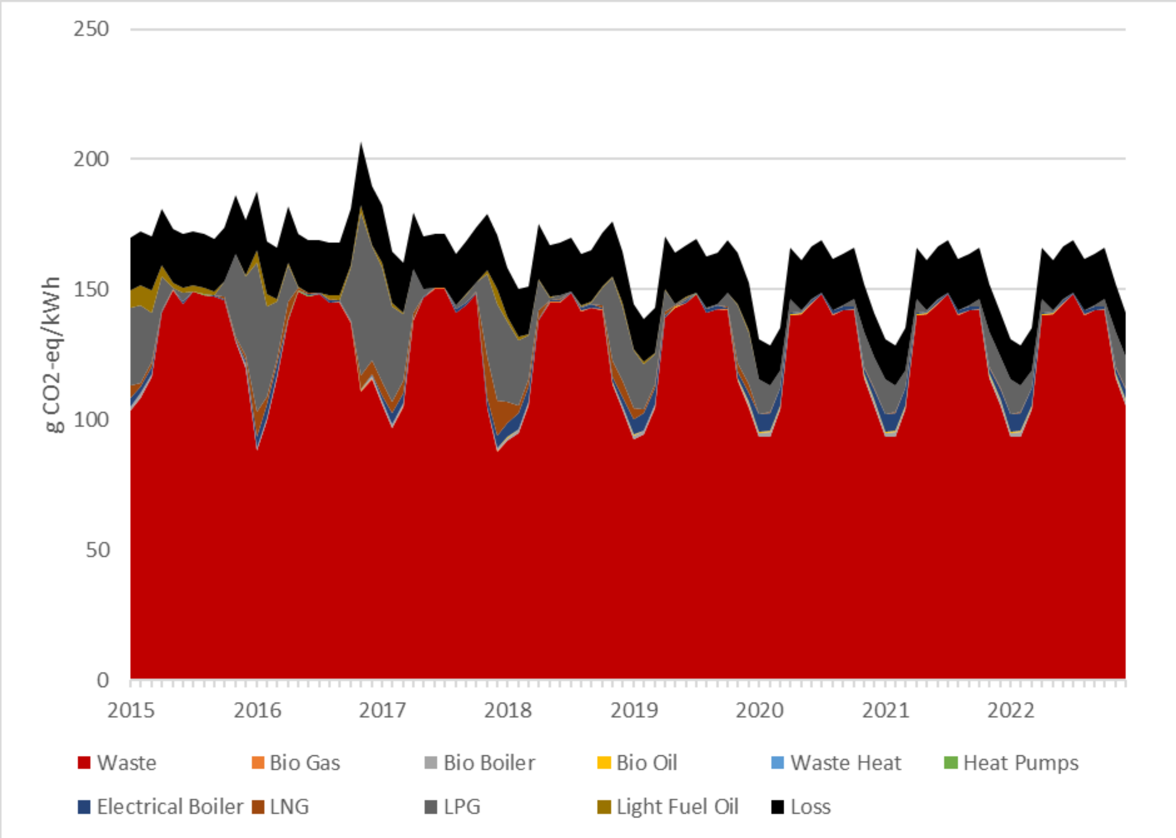

Figure 12: Emission intensity from district heat in Trondheim towards 2023 broken down by technology. Allocation to district heat is assumed.

3.2.3 Allocation of emission according to economic value

Allocation of emissions according to the economic value implies that the emissions from waste-to heat is shared between waste handling and district heating according to the economic allocation key as described in the methods chapter. The emission intensity with this assumption is shown in Figure 13. The emissions intensity ranges between 62-128 g CO2-eq. Given the historical data and the assumption the result is based on, the emission intensity peak occurs in November. This is due to the historical peak in November 2016 when the demand was covered by an extensive use of both fossil fuels and waste.

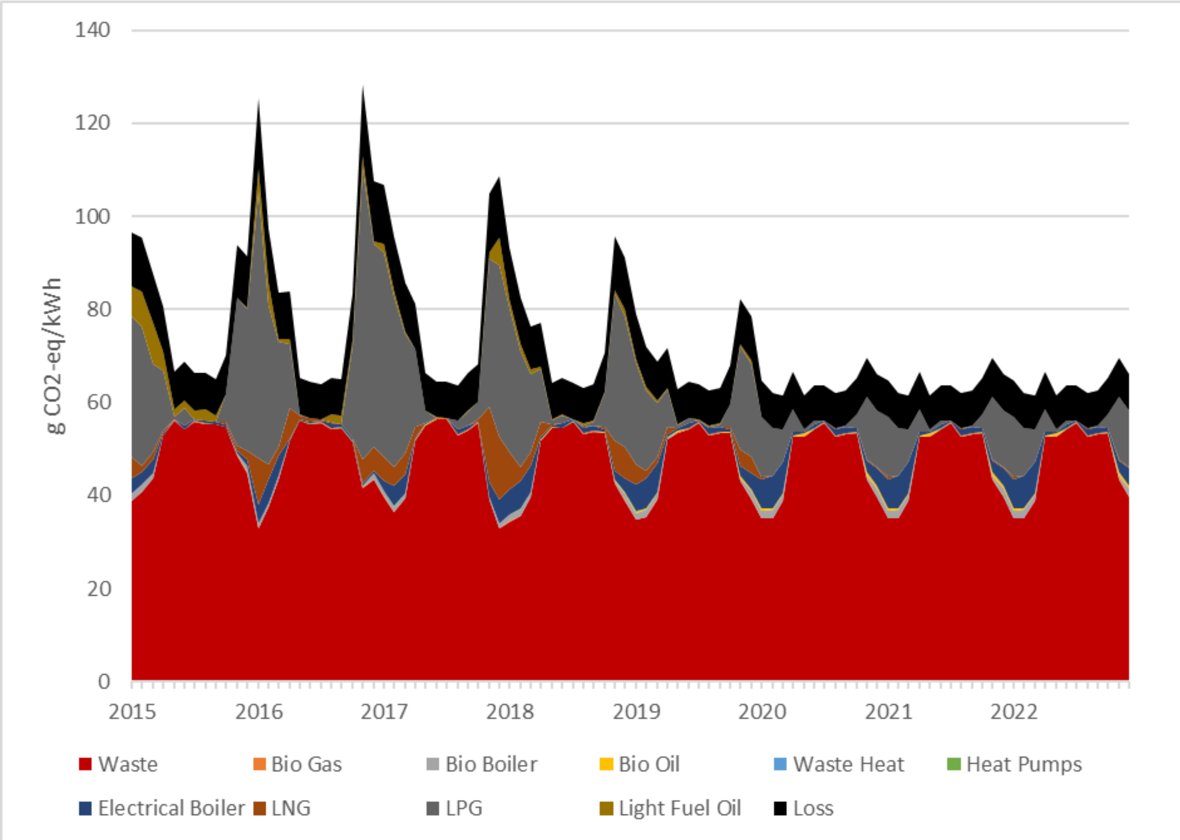

Figure 13: Emission intensity from district heating in Trondheim towards 2023 broken down by technology. Allocation by economy is assumed.

3.3 Local energy

The local heat grid will be a mixture of purchased district heat and locally produced heat from heat pumps. The emission intensity of delivered heat from heat pumps is shown for a year assuming the average electricity mix in NO3 in the period 2015-2017.

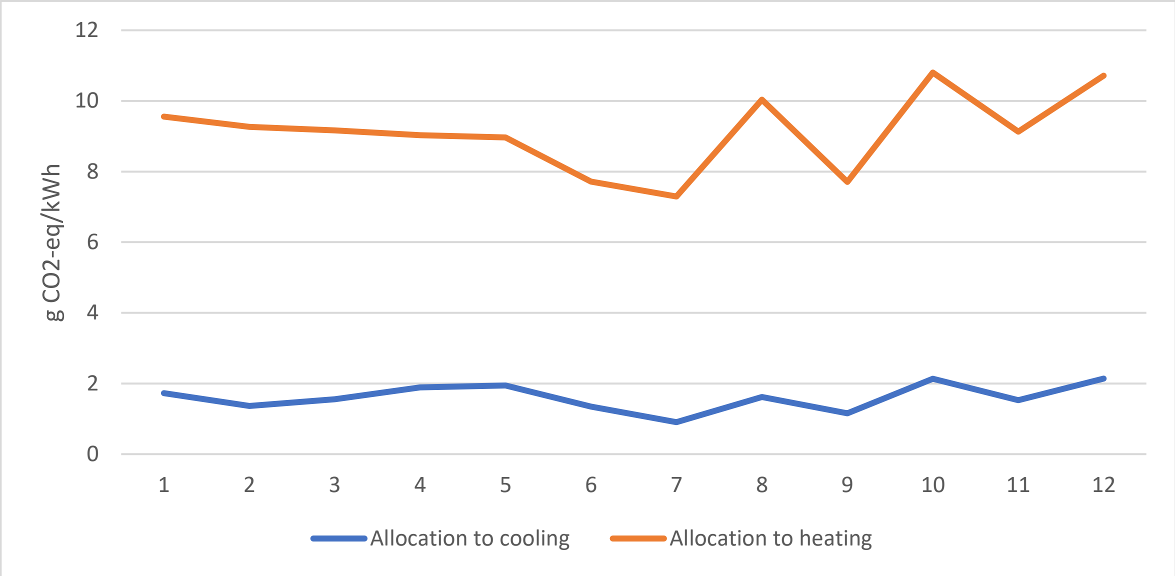

Figure 14: The emission intensity of delivered energy from the heat pumps over a year. Allocation to cooling is an assumption that all the emissions from heat pumps which serves both a heating and a cooling purpose are allocated to the cooling. Allocation to heating means that all emissions from heat pumps are allocated to heating.

3.4 Overall emissions from NTNU Gløshaugen towards 2050

To see the full implications of the results presented in the previous chapters, the emission intensity vectors must be linked to an energy demand profile. Assuming an energy system as described in section 2.5 and simulated hourly values for delivered electricity and heat to NTNU Gløshaugen, a total emission of 5073 ton CO2-eq was related to the energy demand in the year 2021. The total GHG emissions from 2018 to 2050 are presented in Figure 15, together with the share of energy carriers supplying the delivered energy.

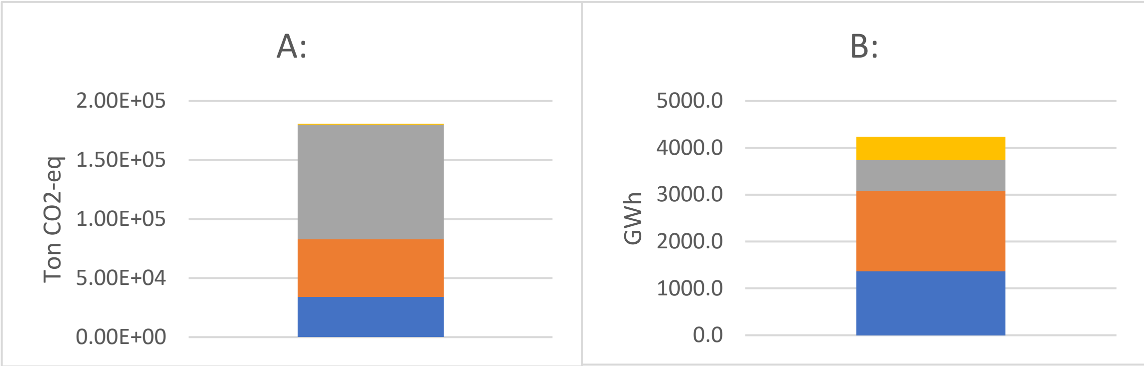

Figure 15: A: Emissions per energy carrier for NTNU Gløshaugen 2018 – 2050. The results in A is based on the assumed delivered energy by energy carrier in the period 2018-2050, shown in B.

3.5 Sensitivity analysis and uncertainty

A sensitivity analysis is carried out to display the sensitivity of selected parameters. The sensitivity ratio (SR) is calculated for the total emissions for 2021, and the relative sensitivity results are shown in Table 4. From the table one can see that the most important parameters affecting the total emissions in year 2021 are related to assumptions in the district heating system. An important reason for this is the high emission intensity of district heat, given the assumption of allocation of emissions from waste incineration to the generation of district heat in the Base Case. One can see that the total emissions are reduced by 50% if these emissions were allocated to the waste management system. This underlines the uncertainty in the results. Apart from district heat (DH) related parameters, the energy system supplying the campus is of great importance, with some of the higher SRs. In addition, some selected assumptions which cannot be assigned a parametric value were tested. These assumptions are shown in Table 3.

Table 3: Emissions for 2021 tested against assumptions

Assumptions	Emissions 2021 [ton CO2-eq]	Relative change	Explanation
Base case[2]	5073	-	See supplementary materials, S6
Increased wind assumption	4761	-6.1 %	Increased wind power in NO3
Aggregation to monthly (EL)	5223	+ 3.0 %	Monthly emission intensity for el
Aggregation yearly (EL)	5286	+ 4.2 %	Yearly emission intensity for el
Aggregation yearly (DH)	5273	+ 4.0 %	Yearly emission intensity for heat

[2] See supplementary material, section S6, for further explanation

Table 4: Sensitivity ratio for selected parameters.

Parameter	Emissions 2021, [ton CO2-eq]	Sensitivity Ratio, SR	Change in parameter
Base case[3]	5073	-	-
Delivered el. specific electricity	5164	0.17975	10%
Delivered el to heat	5194	0.24060	10%
Delivered DH	5363	0.57452	10%
Delivered local heat	5075	0.00512	10%
Delivered from PV	5058	-0.02909	10%
Allocation DH to economy	3474	0.50032	-63%
Allocation DH to waste-incineration	2514	0.50432	-100%
Allocation Local Heat	5193	0.00487	488%
COP Local Heat	5070	-0.00466	10%
Emission factor 'Other'[4]	5030	0.00901	-92.8%

[3] See supplementary material, section S6, for further explanation
[4] 'Other' is a production category in electricity data from ENTSO-E.

4 Discussion

4.1 Implications of results

From NTNU's perspective, the results show that a strategy to reduce GHG emissions from energy use is highly dependent on emission intensities and the assumptions behind the calculated values. The allocation assumption for district heat is especially important.

With an allocation of emissions to district heating, a clear strategy would be to limit use of district heat at NTNU Gløshaugen. This assumption clearly promotes increased renewable energy at campus. The substitution effect would also be significant, if the campus were able to export heat during hours with high production. The technical feasibility of this is, however, something that needs to be assessed. The current solution with heat pumps, supplying a low-temperature heat grid, limits the potential to export surplus heat to the higher-temperature district heating grid. This technical barrier may be overcome, by using high-temperature heat sources such as a bio-fueled CHP. Another solution which would limit the use of district heat is to shave power peaks by deploying local heat storage. Heat pumps have highest COP-factor at high surrounding temperatures, which is the time when there is the least heat demand. A load shift, both on daily and yearly basis, could therefore utilize more of the local heat and decrease the use of district heat. The deployment of ground-source heat pumps may also be a good opportunity to increase the heat production during the coldest months. This technology is less affected by the surrounding air temperature and has a more stable COP-factor throughout the year[14]. Whether this is a viable option for NTNU Gløshaugen must be assessed in geological studies. A positive implication of high COP-factors during the summer is the increased possibility to avoid district heating during the summer months, when emission intensity reaches its peak for district heat with this allocation method.

If the emissions from waste incineration on the other hand is allocated to the waste management system, the use of district heat appears in a completely different manner. With the assumed energy system, the total emissions for one selected year (2021) would decrease by 50% (see section 3.5). This is significant and underlines the importance of allocation choices. With this assumption, the emission intensity peaks during winter, which suggests that the potential for seasonal peak shaving by local seasonal heat storage can be an important measure to limit emissions. The peaks reach a value of 25 g CO2-eq/kWh during winter months after the expected emission-reducing are deployed within 2020. During the summer months, the emission intensity is close to zero. This assumption does therefore not promote increased deployment of local renewable energy production, since district heat is assumed to have very low emissions. This allocation assumption is in line with the views of the district heat supply industry who also promotes district heat as a renewable energy resource.

A third allocation option for waste-to-heat is to allocate by economic value. This assumption leads to a quite flat emission intensity curve with small relative changes within the year (after 2020). The emission intensity in the range between 60 and 70 g CO2-eq/kWh implies a smaller potential for reducing GHG emissions by seasonal storage than with the other two allocation methods. The assumption will still promote the deployment of local renewable energy production, because of the absolute size of the emission intensity.

The emission-saving potential from PV-production is rather limited. Firstly, since the emission intensity of electricity is relatively low, the savings by reducing electricity delivered from the grid becomes relatively small. The same reason reduces the potential for substitution effects, or negative emissions[29], by exporting locally produced power to the grid. Another important point is that the emission intensity of PV was considered to be zero, in line with prNS3720. If PV are to be compared to other technologies in a decision-making context, it is important that embodied emissions also are included for PV to make a fair comparison. According to de Wild Scholten the lifecycle emissions of PV is in the range of 20-81 g CO2-eq/kWh, when assumed produced in China and with an irradiation of 1700 kWh/m2[30]. The irradiation in Trondheim is substantially lower, with 884 kWh/m2 annually[31]. Without further assessing the life cycle emissions of PV installed in Trondheim, one can assume that the average emission intensity of electricity will be lower than electricity from PV. This is especially likely if the Increased Wind results are considered. One should therefore avoid to only optimize for the operation phase and be careful not to counteract the emission-savings in the operation phase by increased embodied emissions. In a lifecycle perspective, the results do not promote local PV.

A marginal approach would however likely lead to another conclusion regarding local PV. Instead of substituting grid electricity with an average GHG intensity of around 30 g CO2-eq/kWh, one could with a marginal approach argue that the locally produced electricity substitute fossil power on the European continent [3]. An approach with lower resolution on regions, would also possibly lead to other conclusions regarding PV, since a Norwegian electricity emission intensity could be higher than the emission intensity in NO3.

The sensitivity analysis showed that the use of hourly emission intensity for electricity and monthly emission intensity for district heating, lead to lower emissions than if annual average emission intensities were used. This finding is important because it differs from the literature where low time resolution were found to underestimate emissions[9]. This suggests that whether high time-resolution leads to an increase or decrease in accounted emissions are dependent on region.

4.2 Applicability to other projects

The electricity system modelling principle that is developed in this study is in principle applicable to any region in an interconnected electricity network. One important factor which however must be carefully considered, is the system boundary. The cut-off done in this study has proven to be reasonable, considering that the contribution from the background regions hardly reached 1.5% of the total emission intensity of the consumed electricity in NO3. The situation would however be different for other regions, for example for NO2 (southern Norway), as this bidding zone has a closer connection to mainland Europe, eventually also UK, and system boundaries should be reconsidered accordingly. An alternative would, however, be to model the whole interconnected grid without cut-offs. For case studies looking at one specific region, a cut-off approach may be a reasonable.

The methods used for the other technologies are applicable to other projects if local factors are included in the analysis.

4.3 Strengths and weaknesses with the work

It is highly problematic to estimate the future development based on historic data. This is especially true for complex systems as the electricity system, because of the wide and uncertain range of parameters which affects the flow and production of electricity at a specific time. Long time horizons and the use of a high time resolution lead to high uncertainties in the emission intensity of the electricity mix at a specific point in time. The approach does still lead to some important findings. Even though the numerical values of the results have large uncertainty and are not intended to represent a given time in the future, the study demonstrates a promising method to calculate emission intensities for several energy carriers. This method could be applied with better quality by using data from energy model simulations of the future energy system, using scenarios that anticipate specific changes in the energy system. The approach used to capture the most important expected change, Increased Wind, demonstrates how the results can change with different input into the model. The results also demonstrate some of the intra-year variations of emission intensities. As literature in this field so far is rather scarce, this might be an important contribution.

Emission factors for the different electricity-producing technologies are assumed to be independent of region. This assumption affects the result. Regionalized emission factors would, theoretically, give a more accurate production mix in each region, which again would lead to more accurate emission intensity for purchased power in NO3. The impact on the result of regionalized emission factors are, however, still believed to be small. Current cut-off methodology shows that regions such as Germany have a very limited impact on the electricity mix in NO3. The increased complexity of calculations regionalized emission factors would lead to, may justify the use of the current method with emission factors independent of region.

The emission intensity of electricity used in the calculations for the total GHG emissions from NTNU Gløshaugen's building stock is an average emission intensity based on three historical years, and this averaging is done to limit uncertainty, but the approach has a weakness. By taking the average of three historic years, one loses the some of the dynamics that the study was intended to display the importance of. The peaks become lower and the curve becomes flatter. The effect of this approach is therefore comparable to using annual average emission intensities. A better approach would be to base the analysis on actual high-resolution model simulations for the future electricity system.

To be able to compare energy sources on a fair basis, the life cycle emissions should be equally included for all technologies. A limitation in this study is the high emphasis on emissions from the operation phase for local renewable energy. A more detailed study on embodied emissions of local renewable energy solutions will be possible when relevant technology concepts are proposed and specified.

There are also large uncertainties in what the future energy system will look like, both at a local, regional, and international level. The energy sector is especially prone to be influenced by politics. Since a range of opportunities are plausible for the future energy system and how it is operated, the analysis would benefit from a range of scenarios.

4.4 Future research

The data retrieved from ENTSO-E raises questions that are yet to be answered: Where does the power production from fossil gas in NO3 occur? What energy production technology is being reported in the category 'Other' for NO3? It is assumed that the reported energy production from 'Fossil Gas' is correct despite no valid reference is found for what or where this production is. It is also assumed that the power production in the category 'Other' has the same emission intensity as power production from natural gas to avoid underestimating the emission intensity. The mobile gas power plants at Tjeldbergodden and Nyhamna are plausible sources for 'Natural gas’ and ‘Other’, but whether this is the actual case should be clarified to improve the reliability of the results.

Future research should take the analytical method further by applying data from energy system simulations. A possible opportunity for the electricity system is to use simulations from EMPS [32] or TIMES [33], to give more realistic scenarios of the future. It shall however be underlined that even with scenarios from mentioned models, large uncertainty is embodied in the results. This is especially due to the complexity of the energy system, the long time horizons and the high influence politics have on the energy systems. A range of scenarios should be run to grasp the range of opportunities for future emission intensities.

While this study has used an attributional LCA approach, there is a need for also conducting a marginal LCA approach. A marginal approach could lead to different insights regarding local energy solutions and might also be even more relevant in a decision-making context. While an attributional approach is sensible when the relative economic size of an object is small[34], a marginal approach can be more suitable in the opposite case. This is especially relevant for the district heating system, as NTNU Gløshaugen is a large customer of Statkraft Varme.

A possible future research topic is to integrate a time-varying emission intensity profile with the building stock model and the underlying IDA-ICE simulations. This is beneficial because it would ensure consistency, which presently is not possible to verify. It would also link the emission intensities with simulated energy systems, their production profiles, and the buildings’ energy demand. When new information about the future energy system at NTNU Gløshaugen arrives, this topic can be taken further.

5 Conclusions

Temporal carbon intensities for electricity, district heat and local renewable heat in the Norwegian city Trondheim is investigated. Current findings suggest that the carbon intensities of purchased electricity vary with time due to varying production technology and varying degree of imports from other regions. The emission intensity of district heat is expected to decrease in the coming years due to measures to phase out fossil fuel, and the intra-year variation in emission intensity is significant. Allocation of emissions in waste-to-heat incineration plants supplying district heating grids is a key aspect and can have large implications for strategies regarding deployment of local renewable energy. High time-resolution on emission intensities did in this case lead to lower total emissions than with a use of annual averages.

While the study has provided new insights in how emission intensities vary with time, a lot of questions remain unanswered. A large range of opportunities are plausible for how future energy systems will develop and be operated. Further research should seek to fully comprehend these possibilities by basing calculations on simulations with high time-resolution.

A possible application of time varying emission intensities of energy carriers is to use it as optimization parameters in real-time energy system operation planning. This possibility is expected to be further assessed in following research.

6 Acknowledgements

This research paper was written as MSc. thesis at NTNU. I would like to thank my two supervisors Christian Solli and Helge Brattebø for their guidance.

Supplementary material

This document is supplementary material to the research paper *Temporal Carbon Intensity of Current and Future Energy Carriers at NTNU Gløshaugen*. It will provide details on the underlying data, methods, and the assumptions which are made in the research paper.

S1 Electricity

S1.1 Data

The data sets which was prepared for the analysis consists of 18 production matrices, 1 for each region. The physical flow is gathered in import matrices for every one of the 12 foreground regions. All these matrices have at least hourly time resolution. The data was collected from ENTSO-E [19, 20], Svenska Kratnät [21, 22] and ERI RAS [23].

A graphical representation is made for the matrices which are most relevant for the emission intensity in NO3. Figure 1 shows the imports to NO3 from neighbouring regions for all hours in the years 2015 to 2017, while Figure 17 shows the exports from NO3 to neighbouring regions in the same period. Figure 18 shows the production broken down by technology for all hours in the period 2015 to 2017. If comparing the three graphs, pay attention to the y-axis.

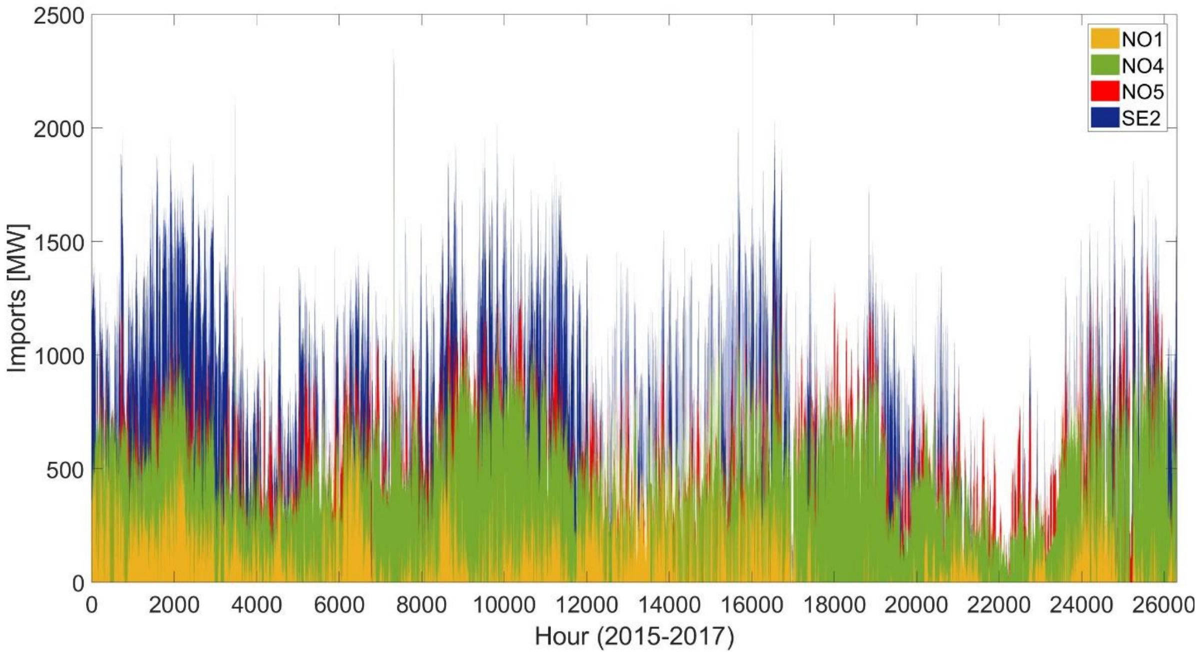

Figure 16: Physical flow of electricity to NO3 from neighbouring regions for all hours in the years 2015, 2016, and 2017.

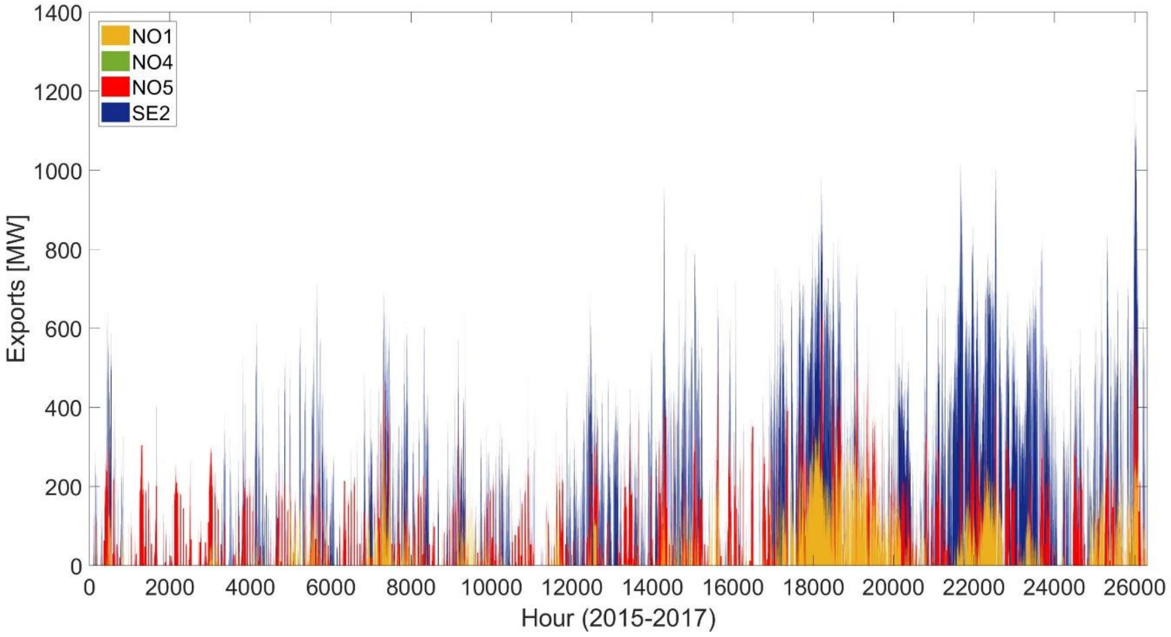

Figure 17: Physical flow of electricity from NO3 to neighbouring regions for all hours in the years 2015, 2016 and 2017.

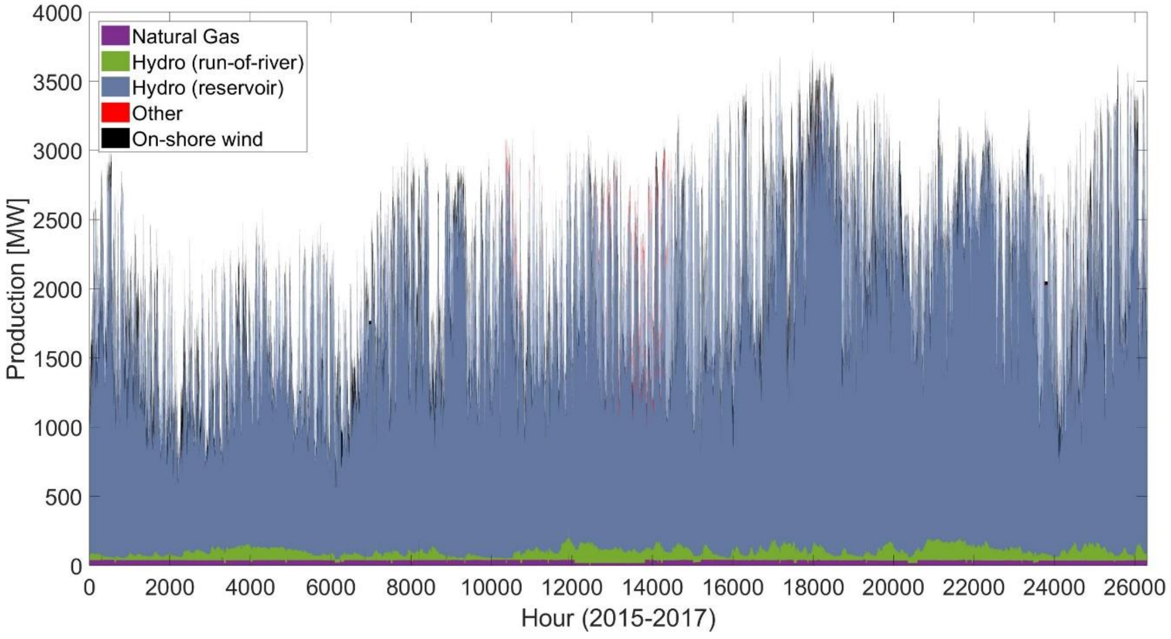

Figure 18: Production of electricity in NO3 by technology for all hours in the years 2015, 2016 and 2017.

S1.2 Missing data

All regions except the Swedish regions (SE1, SE2, SE3, SE4) are based on data from ENTSO-E. ENTSO-E does not provide sufficient energy production data for the Swedish regions. It was decided to use data from Svenska Kraftnät (SVK), the Swedish TSO, instead. Production data for 2015 up until April 2017 were collected from SVKs statistics[22]. Production data for May 2017 to December 2017 were collected from Mimer [21], since at the time of data collection, the data were unavailable in SVKs statistics.

The energy data from SK is subdivided into other energy producing categories than the ENTSO-E data source. There are for example no differentiation between different types of thermal power plants which are all aggregated into the category Thermal Power. It was decided to disaggregate to ENTSO-E categories by using an allocation factor based on IEAs energy production statistics for Sweden 2015. The same allocation is done for all four regions (national average), since no higher resolution is available.

The data collected from ENTSO-E contains cells which do not contain any data. These cells are marked with “N/A” (missing data) or “n/e” (not expected data)[35]. The data sets do also include cells with errors. These cells were adjusted differently dependent on whether it was production data or import data.

For import data it was decided to adjust cells with N/A, n/e or an error by setting it equal the previous cell. This causes uncertainty in the results but is still assumed to be a better assumption than to replace missing data by 0.

For production data n/e essentially means that an energy source is not installed in the specific bidding zone. Therefore, cells containing n/e were set to 0. Cells containing N/A or errors were treated the same way as for imports, by setting it equal the previous cell.

S1.3 Assumptions

The emission intensity for electricity is assumed to be the same for every year from 2018 to 2050. This emission intensity is assumed to be the average of the hourly emission intensities of the years 2015, 2016, and 2017.

For the Increased Wind Scenario, it is assumed that the increased wind power will displace other energy production. The displacement follows a specified order and will displace the high-emitting energy sources first. The displacement is done in the following order:

1. Electricity from natural gas
2. Electricity from 'Other'
3. Electricity imported from other regions
4. Electricity from hydro power

If there is still surplus wind energy after it has displaced electricity from natural gas, the surplus electricity will displace as much as possible of 'Other'. Similarly, if it still is surplus wind electricity after all 'Other' is displaced, it will continue with imports, and so on.

S.1.4 Transmission & Distribution

The emissions from T&D, $E_{T\&D,t}$ were estimated on an hourly basis:

$$E_{T\&D,t} = E_{GRID} + E_{LOSS.t} \tag{11}$$

where E_{GRID} is assumed constant with time and represents the emissions from 1) overhead lines and structures, 2) cables, 3) transformers and switchgear, 4) installation and operations and maintenance, 5) end-of-life. This is in line with Arvesen et al.[36], where E_{GRID} were calculated to be 4.45 g CO2-eq/kWh [36]. The additional emissions from power loss $E_{LOSS,t}$ is calculated by the equation:

$$E_{LOSS,t} = E_{LOSS,literature} k_{corr,t} \tag{12}$$

where $E_{LOSS,literature}$ is the annual average loss from Arvesen et al. assuming a Norwegian electricity mix[36]. This value is scaled up or down for each hour using the correction constant ratio:

$$k_{corr,t} = \frac{E_t}{E_{NO,ecoinvent}} \tag{13}$$

where $E_{NO,ecoinvent}$ is the emission intensity for Norwegian high voltage market mix collected from Ecoinvent 3.2[37].

S.1.5 Contribution analysis

The contribution analysis is done by matrix manipulations to get the desired dimensions. In this case a contribution analysis for technology was done by keeping the technology dimension in the emission intensity result. For contribution by technology $E_{Ctech,t}$, the following equation was used:

$$E_{Ctech,t} = e' t_t x_t \tag{14}$$

where e is the emission factor row vector, $t_t x_t$ is the diagonalized vector of the product of t_t (technology vector) and x_t which is the total output vector.

The regional dimension was kept, so the contribution by region, $E_{Creg,t}$, could be assessed. This was done using the equation:

$$E_{Creg,t} = e' t_t x_t \tag{15}$$

where the only difference is that the diagonalization only includes x_t.

S2 District heating

S2.1 Data

The emission intensity for district heat is based on data retrieved from Statkraft Varme [25] and their report *Data for Breeam certification for customers of Statkraft Varme in Trondheim – 2018* [18]. The historical energy mix is shown for 2015 – 2017 on monthly basis in Table 6. The expected future energy mix (after 2020) is assumed to be equal to the one shown in Table 5.

Table 5: District heat production for 2020 with efficiencies and energy in fuel

Energy Source	**Efficiency (%)**	**Energy production (GWh)**	**Energy input (GWh)**
Waste incineration	100	524.0	524.0
Biogas	90	4.1	4.6
Electricity to HP	100	1.3	1.3
Waste heat	100	4.2	4.2
Briquettes	85	25.6	30.1
Electric Boilers	98	83.1	84.8
LPG	90	16.5	18.3
LNG	90	0.4	0.4
Bio-oil	90	18.1	20.1
LFO	90	-	-

Table 6: Energy mix for district heat in Trondheim for the years 2015, 2016, and 2017.

2015	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Sum**	**Share**
Waste incineration	54 025	46 095	46 392	46 307	37 162	30 670	24 960	21 874	28 745	42 614	48 374	52 535	479 753	83.7 %
Bio gas	246	119	116	150	144	252	162	283	288	271	218	244	2 493	0.4 %
Bio boiler	5 372	4 575	2 997	0	0	0	0	0	0	0	985	3 952	17 881	3.1 %
Heat pumps	484	390	335	243	205	249	306	129	185	321	328	210	3 385	0.6 %
Elelctric boilers	8 984	5 646	5 385	652	150	784	150	198	554	493	913	2 905	26 813	4.7 %
LNG	1 337	366	356	108	1	0	0	0	0	101	208	481	2 959	0.5 %
LPG	7 884	6 340	3 800	2 138	43	393	-118	-16	0	864	5 964	6 731	34 023	5.9 %
LFO	1 556	1 508	1 615	611	208	170	155	170	109	3	8	51	6 163	1.1 %
Sum	***79 888***	***65 038***	***60 996***	***50 209***	***37 913***	***32 518***	***25 615***	***22 637***	***29 880***	***44 667***	***56 998***	***67 109***	***573 469***	

2016	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Sum**	**Share**
Waste incineration	55 595	49 340	49 391	47 756	33 039	26 195	21 798	25 529	27 487	49 375	52 641	53 090	491 236	78.3 %
Bio gas	252	125	134	62	0	134	283	283	360	372	396	312	2 713	0.4 %
Bio boiler	3 740	2 585	1 876	0	0	0	0	0	0	0	1 200	3 943	13 344	2.1 %
Heat pumps	316	215	318	332	260	306	265	324	294	336	373	214	3 552	0.6 %
Elelctric boilers	13 527	12 865	7 972	837	387	478	150	691	687	1 088	1 092	1 113	40 887	6.5 %
LNG	3 504	850	463	1 225	90	66	11	10	0	5	1 385	1 325	8 934	1.4 %
LPG	18 141	8 494	4 821	2 412	21	0	0	0	6	3 630	14 901	10 083	62 509	10.0 %
LFO	1 439	1 102	100	176	21	9	0	148	147	168	565	79	3 954	0.6 %
Sum	***96 514***	***75 576***	***65 074***	***52 800***	***33 817***	***27 187***	***22 508***	***26 985***	***28 981***	***54 974***	***72 553***	***70 159***	***627 130***	

2017	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Sum**	**Share**
Waste incineration	53 322	46 824	49 655	49 888	36 472	28 233	24 866	24 216	26 157	48 349	51 502	49 132	488 616	76.9 %
Bio gas	335	354	418	432	450	432	372	446	432	418	425	446	4 960	0.8 %
Bio boiler	3 307	3 696	2 653	501	0	0	0	0	0	0	1 200	3 456	14 813	2.3 %
Bio oil	0	192	100	71	185	0	2	2	0	96	487	276	1 411	0.2 %
Waste heat	407	302	265	374	220	14	0	299	111	165	185	324	2 666	0.4 %
Heat pumps	164	154	142	243	22	0	0	0	0	0	0	0	725	0.1 %
Elelctric boilers	6 361	12 062	11 552	190	347	52	50	1 165	842	143	8 981	15 690	57 435	9.0 %
LNG	1 462	1 151	1 211	531	0	1	0	0	1	101	4 502	4 278	13 239	2.1 %
LPG	11 092	8 889	6 091	3 018	361	7	3	151	281	601	7 843	10 319	48 656	7.7 %
LFO	420	324	110	1	0	10	0	0	17	0	329	1 567	2 778	0.4 %
Sum	***76 870***	***73 947***	***72 197***	***55 249***	***38 056***	***28 750***	***25 294***	***26 279***	***27 841***	***49 874***	***75 453***	***85 489***	***635 299***	

S2.2 Assumptions

The assumptions for district heating is listed in Table 7.

Table 7: Assumptions for establishing monthly emission intensities for district heat from 2018 to 2050.

Number	Assumption	Assumption regarding years
1	Calculated monthly electricity emission intensity is used for electric boilers and heat pumps.	2015, 2016, 2017
2	Negative values in Table 6: Energy mix for district heat in Trondheim for the years 2015, 2016, and 2017. are assumed to be zero.	2015, 2016, 2017
3	Increase in annual production between 2017 and 2020 is assumed to be linear.	2018, 2019, 2020
4	The shape of the intra-annual production mix curve is assumed to be equal to the shape of the average intra-annual production mix curve for 2015 to 2017.	2018, 2019, 2020
5	Average emission intensity (2015 to 2017) for electricity is assumed.	2018 and onwards
6	The same district heat emission intensity is used for every year after 2020.	After 2020
7	Emission intensities as recommended by Norsk Energi [38], adjusted for efficiency. Exception: See assumption 8.	All
8	Emission intensity for waste incineration from Lausselet et al. [39].	All

S3 Local Heat grid

6.1 Assumptions

Some assumptions are done to calculate the emission intensity for local heat from heat pumps. The assumptions are based on historical data.

The COP is assumed to vary throughout the year as shown in table Table 8.

Table 8: COP-variation throughout the year.

Month	COP
January	2.72
February	2.79
March	2.76
April	2.85
May	2.74
June	3.12
July	3.66
August	3.93
September	3.49
October	2.55
November	2.96
December	2.43

The share of energy supplied by heat pumps which are only used for heating are assumed to vary through the year as shown in Table 9.

Table 9: Share of energy from heat pumps only utilizing warm side.

Month	Share of energy from heat pumps only utilizing warm side (%)
January	18
February	15
March	17
April	21
May	22
June	17
July	10
August	16
September	15
October	20
November	17
December	20

S4 Local PV

Two different studies have assessed the PV potential for NTNU Gløshaugen, one providing an hourly production profile for PV on new buildings [31], the other providing a monthly production profile for PV on existing buildings[40]. The monthly production is assumed to be distributed over the hours in the months, similarly to the hourly production profile.

To show distribution of production through the year, a monthly aggregated graphical representation of the PV-production through the year is shown in Figure 19.

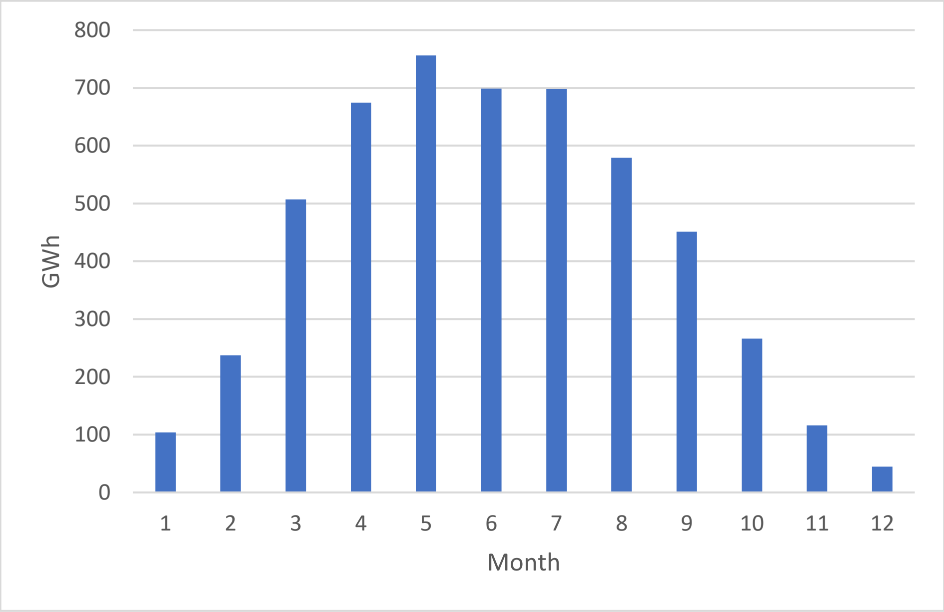

Figure 19: Monthly aggregated electricity production from local PV. Maximum potential at current and future buildings.

To show how the PV is produced during the hours of a day, the estimated production on May 1st is shown in Figure 20.

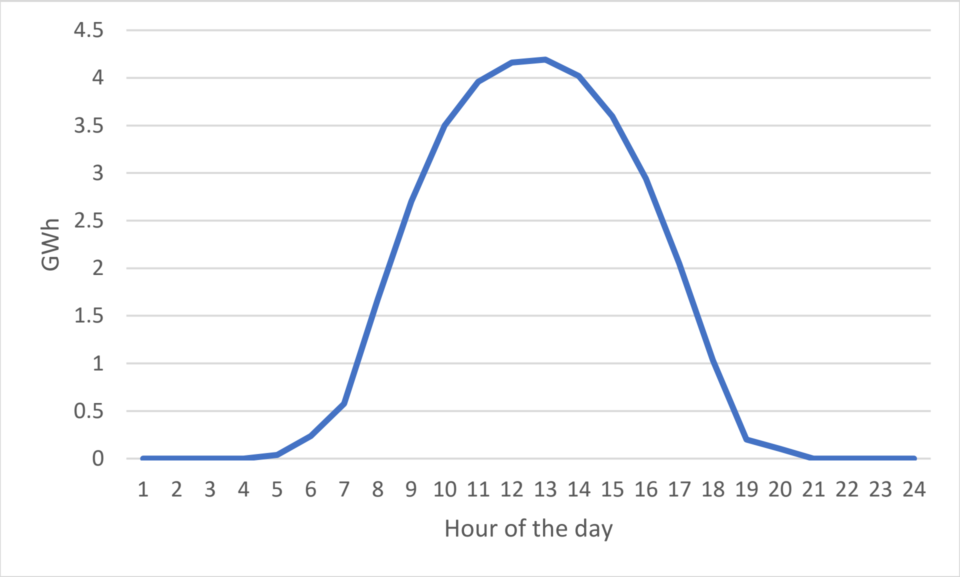

Figure 20: PV production for all hours of a day. This example is May 1st.

S5 Energy system

The local energy system in based on output from the building stock model. The output contained five matrices with supplied energy, each one supplying energy to a specific purpose. Each matrix showed the hourly delivered energy for all years (dimension: hour X year). The five matrices were:

- HVAC, aux
- EL, Equipment
- EL, Lighting
- Heating
- DH cold

Due to low transparency in how these results were attained through modelling in IDA ICE and the building stock model, some assumptions were made.

- ‘DH cold’ was assumed to be a mixture of district heat and locally produced heat from heat pumps.
- ‘Heating’ was assumed to be covered by 100% electricity.
- ‘Heating’ was assumed to be delivered heat by electricity, excluding electricity used in heat pumps. The latter is instead an input in ‘DH cold’

With these assumptions, which presently is unverifiable, the energy system described in Table 2 were established to cover the energy demand from 2018 to 2050.

The intra-annual variations in how the energy carriers cover the heat demand is shown in Figure 21 with year 2021 as an example.

The intra-annual variations in how PV and grid electricity covered the specific electricity demand is shown in Figure 22 with year 2021 as an example.

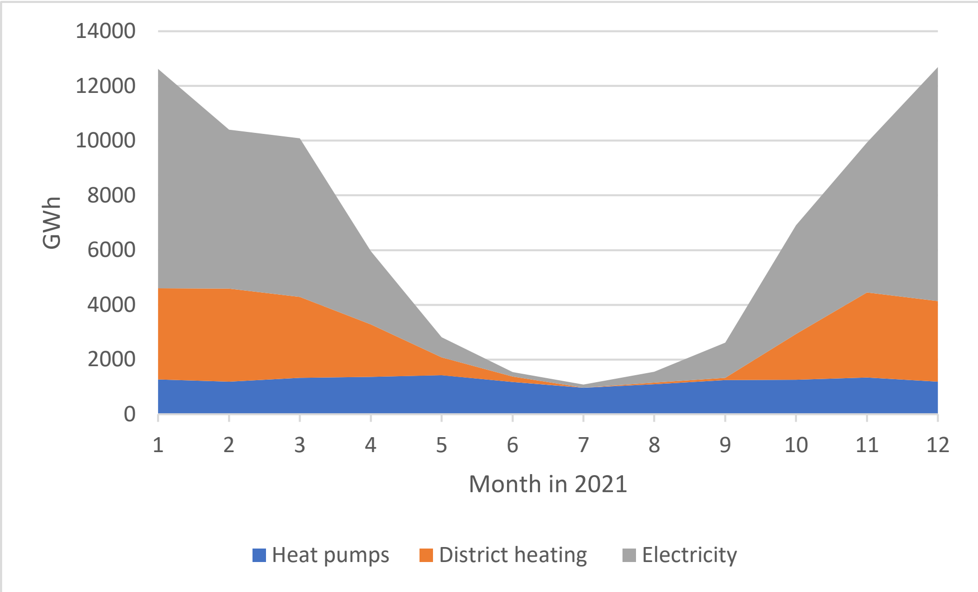

Figure 21: Delivered heat to NTNU Gløshaugen per month per technology in 2021.

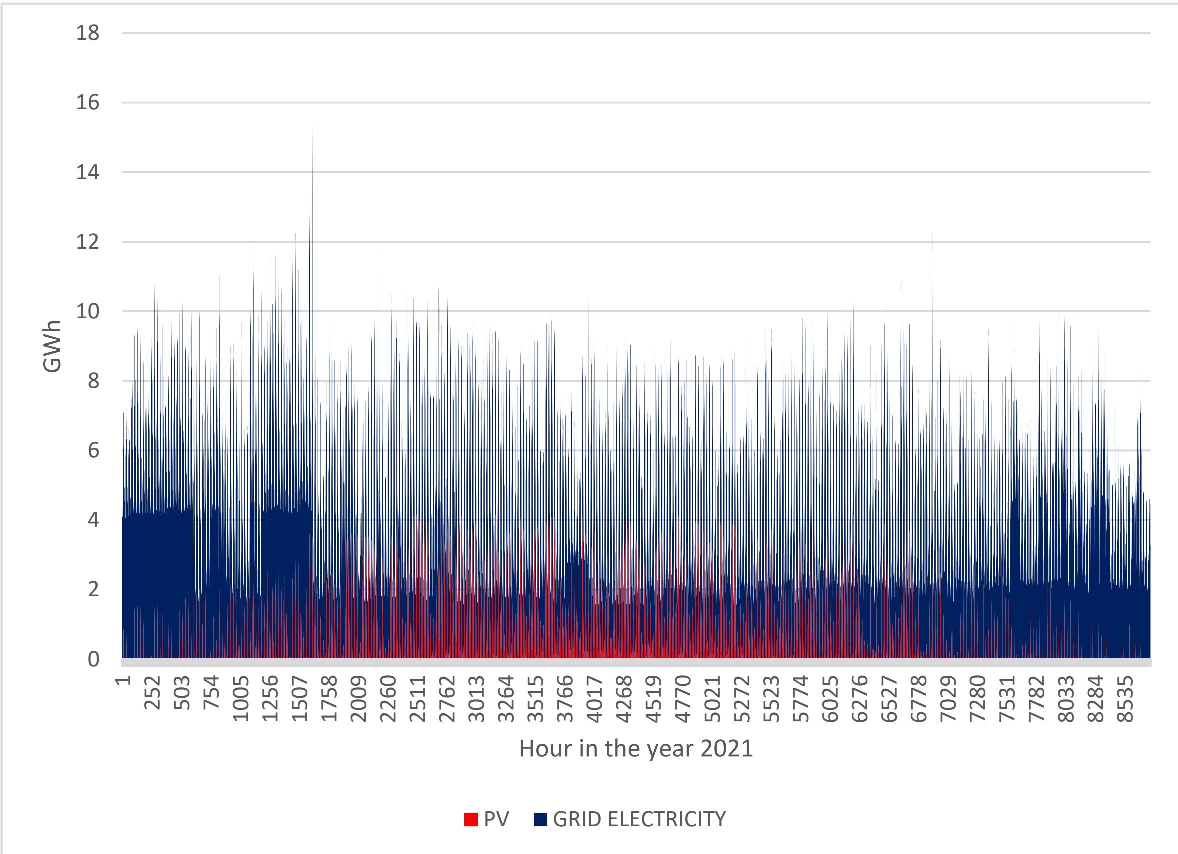

Figure 22: Delivered electricity for electricity specific purposes to NTNU Gløshaugen per hour per technology in 2021.

S6 Sensitivity analysis

The sensitivity analysis tested some selected parameters towards the initial result. The initial results were based on the initial parameters, following the assumptions in Table 10.

Table 10: Assumptions for base case

Number	**Assumption**
1	The energy system is as described in Table 2 and section S5.
2	The average hourly emission intensity for the years 2015, 2016, and 2017 based on historical data were used.
3	The emission intensity for district heating is assumed to be the monthly average for an arbitrary year after 2020 (same is assumed for every year beyond 2020).
4	The emissions from waste incineration are allocated to district heating.
5	The emissions from electricity used in heat pumps are allocated to cooling, for heat pumps utilizing both the warm and cold side.
6	Average COP is 3.
7	The emission intensity for the electricity production category ‘Other’ is 530 g CO_2-eq/kWh, equal to the one of natural gas

S7 Emission intensities

The emission factors were decided by choosing the most relevant region for each technology. The emission factor for hydropower was based on LCI-database values for Norwegian hydropower. This approach will limit the uncertainty in the results, while keeping the complexity of calculations on a relatively low level. Table 11 shows the emission intensities used in the study. For electricity, Ecoinvent[37] was used when possible.

Table 11: Emission intensities used in the study.

Technology	**GWP (g CO2-eq/kWh)**	**Reference**	**Specification**
Electricity generation			
Biomass	59	Ecoinvent	Electricity, high voltage [12]| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Alloc Rec, U
Fossil Brown coal/lignite	1223	Ecoinvent	electricity, high voltage/electricity production, lignite/DE/kWh
Fossil Coal-derived gas	700	Assumed	Assumed to have small influence, guess.
Fossil Gas	529	Ecoinvent	Electricity high voltage {DK}| heat and power co-generation, natural gas, conventional power plant, 100 MW electrical | Alloc Rec U
Fossil Hard Coal	1266	Ecoinvent	Electricity, high voltage {DK}|heat and power co-generation, hard coal| Alloc Rec, U
Fossil Oil	1000	Ecoinvent	Electricity, high voltage {DK}| heat and power co-generation, oil | Alloc Rec, U
Fossil Oil Shale	1266	Electricity Map	Assumption in Electricitymap[12]
Fossil Peat	1071	Ecoinvent	Electricity, high voltage {FI}| electricity production, peat | Alloc Rec, U

Technology	GWP (g CO2-eq/kWh)	Reference	Specification
Electricity generation (continued)			
Geothermal	38	Literature	Kommalapati et al. [41]
Hydro Pumped Storage	47	Ecoinvent	electricity, high voltage/electricity production, hydro, pumped storage/NO/kWh
Hydro Run of River and poundage	5	Ecoinvent	Electricity, high voltage {SE}| electricity production, hydro, run-of-river | Alloc Rec, U
Hydro Water Reservoir	8	Ecoinvent	Electricity, high voltage {NO}| electricity production, hydro, reservoir, alpine region | Alloc Rec, U
Marine	50	Literature	Kommalapati et al.[41]
Nuclear	13	Ecoinvent	Electricity, high voltage {SE}| electricity production, nuclear, pressure water reactor | Alloc Rec, U
Other	529	Assumed	Assumed equal to Fossil Gas
Other renewable	38	Assumed	Average of renewable
Solar	144	Ecoinvent	Electricity, low voltage {DK}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Alloc Rec, U
Waste	0	Ecoinvent	Electricity, for reuse in municipal waste incineration only {DK}| treatment of municipal solid waste, incineration | Alloc Rec, U

Technology	GWP (g CO2-eq/kWh)	Reference	Specification
Electricity generation (continued.			
Wind Offshore	18	Ecoinvent	Electricity, high voltage {DK}| electricity production, wind, 1-3MW turbine, offshore | Alloc Rec, U
Wind Onshore	14	Ecoinvent	Electricity, high voltage {DK}| electricity production, wind, 1-3MW turbine, onshore | Alloc Rec, U
District heating			
Waste	153	LCA	Lausselet et al.[39]
Bio Gas	14	BREEAM documentation	Statkraft Varme[18]
Bio Boiler	21	Report	Norsk Energi[38]
Waste heat	0	Report	Norsk Energi[38]
Heat pump	-	Calculated	
Electrical Boiler	-	Calculated	
LNG	243	Report	Norsk Energi[38]
LPG	274	Report	Norsk Energi[38]
LFO	289	Report	Norsk Energi[38]

References

[1] Lucon O, Ürge-Vorsatz D, Ahmed AZ, Akbari H, Bertoldi P, Cabeza LF, et al. Chapter 9 - Buildings. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, et al., editors. Climate Change 2014: Mitigation of Climate Change IPCC Working Group III Contribution to AR5: Cambridge University Press; 2014.

[2] Itten R, Frischknecht R, Stucki M, Scherrer P, Psi I. Life cycle inventories of electricity mixes and grid. 2012.

[3] Andresen I, Lien KM, Berker T, Sartori I, Risholt B. Greenhouse gas balances in Zero Emission Buildings – Electricity conversion factors revisited. ZEB Project Reports. sintefbok.no: SINTEF; 2018.

[4] Sonnemann G, Vigon B. Global Guidance Principles for Life Cycle Assessment Databases. Paris/Pensacola: UNEP/SETAC Life Cycle Initiative; 2011.

[5] European Comission - Joint Research Centre - Institute for Environmend and Sustainability. International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. First Edition ed. Luxembourg: Publications Office of the European Union, 2010.

[6] Moreno Ruiz E, Valsasina L, Fitzgerald D, Brunner F, Vadenbo C, Bauer C, et al. Documentation of changes implemented in the ecoinvent database v3. 4. ecoinvent. Zürich, Switzerland. 2017.

[7] Ji L, Liang S, Qu S, Zhang Y, Xu M, Jia X, et al. Greenhouse gas emission factors of purchased electricity from interconnected grids. Applied Energy. 2016;184:751-8.

[8] Khan I, Jack MW, Stephenson J. Analysis of greenhouse gas emissions in electricity systems using time-varying carbon intensity. Journal of Cleaner Production. 2018;184:1091-101.

[9] Roux C, Schalbart P, Peuportier B. Accounting for temporal variation of electricity production and consumption in the LCA of an energy-efficient house. Journal of Cleaner Production. 2016;113:532-40.

[10] Olkkonen V, Syri S. Spatial and temporal variations of marginal electricity generation: the case of the Finnish, Nordic, and European energy systems up to 2030. Journal of Cleaner Production. 2016;126:515-25.

[11] Dandres T, Farrahi Moghaddam R, Nguyen KK, Lemieux Y, Samson R, Cheriet M. Consideration of marginal electricity in real-time minimization of distributed data centre emissions. Journal of Cleaner Production. 2017;143:116-24.

[12] Tomorrow. Electricity Map. 2018.

[13] Reniers J, Nilsson A, Brandt N, Olsson M. Analysis of a real-time signal for greenhouse gas emissions of district heating consumption. 2015.

[14] Petrović SN, Karlsson KB. Residential heat pumps in the future Danish energy system. Energy. 2016;114:787-97.

[15] Standard Norge. FORSLAG TIL Norsk Standard prNS3720 Metode for klimagassberegninger for bygninger (Method for greenhouse gas calculations for buildings). prNS3720: Standard Norge; 2017.

[16] Kunnskapsdepartementet. Veien videre for campus NTNU. regjeringen.no: Statsministerens Kontor; 2018.

[17] Stene J. Grønn IT - unikt høytemperatur kjøle- og varmepumpeanlegg ved NTNU. https://www.tekniskenyheter.no/varmepumper/varmepumper/gronn-it-unikt-hoytemperatur-kjole-og-varmepumpeanlegg-ved-ntnu, 12.06.182015.

[18] Statkraft Varme AS. Data til bruk i Breeam-sertifisering for kunder av Statkraft Varme i Trondheim - 2018. https://www.statkraftvarme.no/globalassets/2-statkraft-varme/statkraft-varme-norge/dokumentasjon-breeam-trondheim-2018_2.pdf, 06.04.2018: statkraftvarme.no; 2018.

[19] ENTSO-E. Cross-Border Physical Flow. In: ENTSO-E, editor. https://transparency.entsoe.eu/transmission-domain/physicalFlow/show, 20.05.182018.

[20] ENTSO-E. Actual Generation per Production Type. In: ENTSO-E, editor. https://transparency.entsoe.eu/generation/r2/actualGenerationPerProductionType/show, 20.05.182018.

[21] Svenska Kraftnät. Produktionsstatistik. In: Kraftnät S, editor. https://mimer.svk.se/ProductionConsumption/ProductionIndex, 04.06.182017.

[22] Svenska Kraftnät. Statistik per elområde och timme. In: Svenska Kraftnät, editor. https://www.svk.se/aktorsportalen/elmarknad/statistik/, 24.05.182017.

[23] Veselov F. Russian electric power sector overview. Conference Russian electric power sector overview, Moscow.

[24] Statnett. Nordic Power Flow. GIMP. http://statnett.no/en/Market-and-operations/Data-from-the-power-system/Nordic-power-flow/, 08.06.182018.

[25] Gangaune SS. Brenselsmiks pr mnd 2015-2017. In: AS SV, editor.2018.

[26] Næss JS. Gløshaugen_resultater0706. In: Næss Js, editor.2018.

[27] Næss JS, Sandberg NH, Nord N, Vestrum MI, Lausselet C, Woszczek A, et al. Neighbourhood building stock model for long-term dynamic analyses of energy demand and GHG emissions. General model description and case studies. . Research Centre on ZERO EMISSION NEIGHBOURHOODS IN SMART CITIES; 2018.

[28] Sandberg NH, Sartori I, Vestrum MI, Brattebø H. Using a segmented dynamic dwelling stock model for scenario analysis of future energy demand: The dwelling stock of Norway 2016–2050. 2017.

[29] Fufa SM, Schlanbusch RD, Sørnes K, Inman MR, Andresen I. A Norwegian ZEB Definition Guideline. SINTEF Academic Press; 2016.

[30] De Wild-Scholten MJ. Energy payback time and carbon footprint of commercial photovoltaic systems. Solar Energy Materials and Solar Cells. 2013;119:296.

[31] Woszczek A. Analysis of energy use and greenhouse gas emissions at the future building stock at the NTNU campus Gløshaugen 2018.

[32] SINTEF. EMPS - multi area power-market simulator. https://www.sintef.no/en/software/emps-multi-area-power-market-simulator/, 15.06.182018.

[33] IEA ETSAP. Overview of TIMES Modelling Tool. https://iea-etsap.org/index.php/etsap-tools/model-generators/times, 20.06.182018.

[34] Frischknecht R, Stucki M. Scope-dependent modelling of electricity supply in life cycle assessments. The International Journal of Life Cycle Assessment. 2010;15(8):806-16.

[35] ENTSO-E. What Is The Meaning Behind „N/A“, „N/E“ And "-" Values In The Data View? https://entsoe.zendesk.com/hc/en-us/articles/115000153723-What-is-the-meaning-behind-N-A-n-e-and-values-in-the-data-view-, 20.05.182018.

[36] Arvesen A, Hauan IB, Bolsøy BM, Hertwich EG. Life cycle assessment of transport of electricity via different voltage levels: A case study for Nord-Trøndelag county in Norway. 2015.

[37] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment. 2016;[online](21(9)):pp 1218-30.

[38] Otterlei ET. Klimaregnskap for fjernvarme, Felles utslippsfaktorer for den norske fjernvarmebransjen – Oppdatering 2013. Norsk Energi / Norsk Fjernvarme; 2014.

[39] Lausselet C, Cherubini F, del Alamo Serrano G, Becidan M, Strømman AH. Life-cycle assessment of a Waste-to-Energy plant in central Norway: Current situation and effects of changes in waste fraction composition. Waste Management. 2016;58:191-201.

[40] Rennan IM, Søraas AEH, Johansen KBH. Renewable energy solutions for the Gløshaugen Campus (NTNU). 2018.

[41] Kommalapati R, Kadiyala A, Shahriar MT, Huque Z. Review of the life cycle greenhouse gas emissions from different photovoltaic and concentrating solar power electricity generation systems. Energies. 2017;10(3).