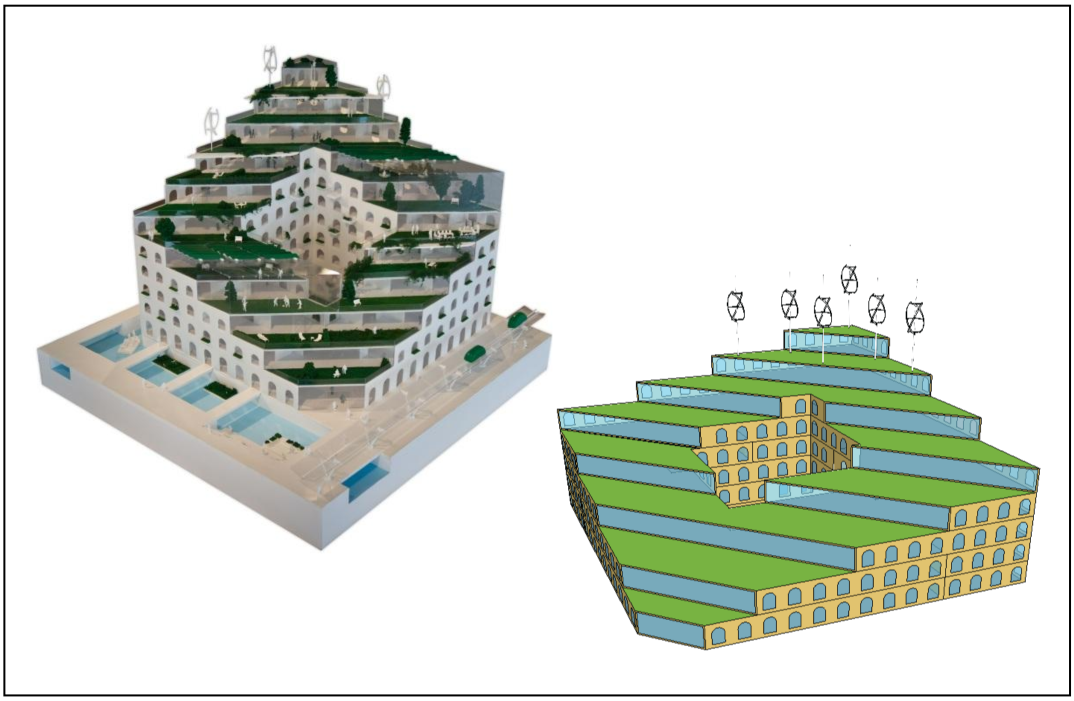

An energy assessment of a multifunctional building

Master of Science Thesis [in Innovative Sustainable Energy Engineering]

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Division of Energy Technology
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Göteborg, Sweden, 2012
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Cover:
The multifunctional building modelled on scale and on the computer © 2011 Super Sustainable.
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Preface

Clearly, using renewable energies is not only from a climate change point of view a wise objective (IPCC, 2011); at the same time the depletion of our fossil fuels leads to a dead-end. The path to this sustainable earth is currently initiated, but is equally a hurdle to be taken. I am a strong believer that the Sustainable City can be the ignition to the transition process, which is the reason I started this Master thesis.

The Sustainable City should however not be newly built, it arises by transforming and re-engineering existing cities (Lehman, 2010). Moreover, the perspective of niche market development (Geels, 2005; Kemp et al., 1998), where technologies are fed in small markets, will enforce the expansion of Sustainable Cities. They can act as 'lighthouses for eco-innovation' for the country itself and possibly the world, from where the technologies can develop (Cooke, 2011).

Nowadays, the emphasis on Sustainable Cities is set more and more, evidenced by e.g. the European Green City Index, an assessment of Sustainable Cities (in Europe) by the Economist Intelligence Unit (2009). This thesis will only treat one puzzle piece of the Sustainable City: the concept of a net-energy building. Nevertheless, I hope it will also contribute its bit, in order to attain this Sustainable City, something we should all be aiming for.

The rest of this part is dedicated to the people that made me complete this thesis, but even more so acquire the title of Master of Science. It is without saying that my parents Clemens and Anneke have contributed the most both in a financial and mental way, to back me up, when I was getting into troubled water. Besides that I would also like to thank them for making it possible for me to explore my interests in both engineering and linguistics, which could be seen as a somewhat unusual combination. Many thanks, it will make me the diverse person I want to be, for the rest of my life.

For this thesis alone, I would like to thank all the people that have helped with small bits for me to come to the end result. I knew it was not an easy way to take, to start up your own Master Thesis, but the words of Cecilia Hedenstierna (student counsellor at Chalmers) are still in my mind: "If you are enthusiastic for what you are doing, I am sure you will manage and finish on time".

Therefore, my appreciation goes to Joakim Kaminksy, architect within Kjellgren Kaminsky Architecture, who gave me the opportunity to work on the thesis subject without any restrictions. As a second, I have had a lot of help from Emil Nyholm, PhD student at Chalmers, who was willing to think with me about the application of a solar model on the multifunctional building, which was very much cherished.

I would also like to mention the people at the Building Services Engineering department who have been discussing the passive house with me, including giving ways to address the actual energy modelling. It supported me in looking at the thesis from an engineer point of view, an indispensable feature. On the other hand, the talk I had with Jaan-Henrik Kain, member of the organisation Mistra Urban Futures and researcher at Chalmers' architecture department, has also inspired me to think a bit more about the non-technical aspects to the topic, not less essential.

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Summary

The awareness of sustainability has struck Swedish cities, proven by various documents that have popped up describing and making targets for social, economic and environmental sustainability. In Göteborg the area around the Göta river is brought to the attention, since restructuring/renovating the district would lower the ecological footprint, by making the city more compact.

A plan by the non-profit organisation Super Sustainable to enforce this development is the foundation of this Master thesis. The voluntary architects propose a passive housing concept – the multifunctional building – in which shops, offices and apartments are smartly located to lower the energy use and increase the energy efficiency, in the end aiming at a net zero-energy state.

This thesis tries to assess the multifunctional building by both determining the energy demand and energy supply side of the building. It is energy modelled with EnergyPlus and OpenStudio to determine on the one hand the heat need for hot water and on the other hand the need for household and space heating/cooling electricity. The supply side is based on on-site renewable energy production techniques and is represented by calculations on wind, solar and waste energy.

It is concluded that the concept of the multifunctional building does not function as well as was thought. Next to that turns out that the energy demand (especially for electricity) is too high to be covered by the proposed mix of renewable energies. The results for the demand are in line with what is known about state-of-the art passive housing apartments. Nevertheless could the supply be upgraded by including a geothermally based heat and power production. Above all, for shops and offices more reliable academic data is needed, such that a better overall assessment can be performed.

The report is written in English.

Keywords: Passive house, Net zero-energy building, On-site renewable energy production

Table of Contents

1. Introduction

A building that is creating enough energy to supply for its own energy demands. It is an idea that may already have originated in the 1920s and revisited in the 1970s. Only recently the concept has gained momentum, resulting in the first net zero-energy buildings all over the world (Hernandez & Kenny, 2011).

The definition of a net zero-energy building can be wide however. Torcellini et al. (2006) talk about 4 different variants, where either the source (building production energy), the site (every-day energy use), the costs or the emissions are governing. Also is the term zero-energy building (thus without 'net') an ambiguous synonym to the concept, since only zero would imply that no energy is used at all.

For this master thesis a building will be analysed that belongs to a proposal for a Sustainable City in the city of Göteborg (English: Gothenburg) in Sweden. The plan of the non-profit organisation Super Sustainable suggests a building, which will have to attain the state of net-zero energy by renewable energy production on-site. Moreover, intends the building - the so-called multifunctional building - to integrate shops, offices and apartments reducing the energy demand.

1.1 The objective and its limitations

The aim of this thesis is therefore to get an answer to:

Is the multifunctional building within the plan of Super Sustainable for a Sustainable City in Göteborg an example of a zero net-energy building?

A limitation to the aim is that it will follow the 'site' variant according to Torcellini et al. (2006). In other words, the analysis will only look at the energy balance of the building when in use, not at the construction energy, nor costs or emissions.

Another restraint is that the energy assessment for the building will only be applicable to the city of Göteborg. Both the calculations performed for the demand and supply will be location dependent. Extrapolations to other circumstances should therefore be carefully made.

In order to increase the validity of the answer, it will be strived for to obtain hourly quantitative results (both demand and supply side), such that factors as intermittency (e.g. wind energy), seasonal variation (building cooling vs. heating), peak load and others are taken into account properly.

1.2 Methodology

Before the energy balance assessment is performed an introduction to the plan for a Sustainable City in Göteborg will be given in chapter 2. The issues that exist within the Gothenburg area will be treated and the according projects that have been initiated. Finally, the benefits of the plan of Super Sustainable will be highlighted and the multifunctional building will be introduced.

The proposed building will subsequently be analysed both for its energy demand side (chapter 3) and its energy supply side (chapter 4). The paper written by

Wang et al. (2009) which reports about a net-zero energy building in the United Kingdom has been an example for the structure of this thesis.

Concerning the energy demand, the architects of Super Sustainable suggested the multifunctional building to abide by the Swedish Passive Housing regulations (FEBY, 2009) to reduce the call for energy. The ideas of these rules will first be explained according to the licentiate thesis of Janson (2008), such that they will serve as an important input for the demand assessment.

The actual energy demand of the multifunctional building will then be mainly computer modelled using the programs EnergyPlus and OpenStudio. The first is a US government program simply calculating for a wide range of input data. The second is even so run by the US government and implements the options of EnergyPlus, giving a convenient overview. Besides that has OpenStudio a plug-in for Google Sketchup, the design program in which the building dimensions have been supplied.

Household electricity and space heating/cooling (electricity) are mostly based on Swedish research input and calculated by the mentioned EnergyPlus, although the computations for the latter will be clarified using Jonsson & Bohdanowicz (2010). The third and last energy need of the multifunctional building, hot water demand (heat), is computed in MS Excel. The research of Wall (2006) on energy efficient terrace houses in Sweden is later used to compare all obtained results.

The proposed renewable energy mix is based on both Wang et al. (2009) and Marszal et al. (2011). For on-site energy production they talk about PV panels and wind turbines; in Marszal et al. municipal waste is also discussed as an off-site supply. The latter will however for this thesis be seen as an on-site supply, since the waste is produced at the multifunctional building itself.

These three renewable energies have been chosen to investigate, since they seemed the most encouraging before the research started. The use of solar thermal collectors was also discussed by Marszal et al., but not considered as important.

Electricity produced by wind energy has been calculated using the basic wind power formula, implementing wind data obtained for Göteborg. Concerning the wind turbine, has been chosen to calculate with state-of-the-art designs, to get realistic and feasible results. The eventual outcomes have been computed with the mathematical program Matlab/Simulink. Finally, the total amount of placed wind turbines is based on roof inspection.

For solar energy global radiation and temperature data for Göteborg have been applied to a PV panel algorithm by Huld et al. (2011) using Matlab/Simulink. This is justified, since the researchers have been able to produce a method for which reasonable electricity production results for a generic crystalline PV module can be obtained. Subsequently, assumptions have been made for the possible size of the solar panel area on the roof of the multifunctional building, based on shadow overcast behaviour.

Finally, for municipal waste a basic estimation is made using Swedish data on waste incineration. This analysis will result in an hourly back-up for both heat and electricity. To wrap up, also a calculation on the non-profitable use of wave energy will be shown. This energy production method was within the plan of Super Sustainable, which is the reason why it was investigated, although it does not resemble on-site energy production (according to Torcellini et al, 2006).

Concluding, in chapter 5 energy balances for both heat and electricity will be drawn up for the multifunctional building, off-setting the hourly demand to the hourly supply. The questioned viability of a net zero-energy building for the specific case study will be addressed, thereby answering the objective of this Master thesis. Next to that, attention will be paid to a discussion and reflection of the performed work and indications for extended/further research.

2. Case study: Göteborg

Sweden is ready to face the challenge of sustainability. Cities have started to write reports about how to increase the share of renewables (e.g. in Malmö; Malmö Stad, 2008), set targets for social sustainability (S2020 in Göteborg) and increase the use of public transport (also in Göteborg; K2020, 2009). It resulted in the advancing to several sustainable areas, such as in Mora, Norrköping and Mönsterås and even in the development of a Sustainable City in the Västra Hamnen area in Malmö (the neighbourhood Hyllie; E.ON, 2011).

According to a report of Göteborgs stad (2007) the dare for Göteborg is to reduce its current ecological footprint. The report speaks about a footprint of 5.5 hectare per inhabitant, which amounts to a total of about 2.9 million global hectares (for 519,399 inhabitants in the city area), an area which equals the size of Västra Götaland, the region it is situated in. Making the city more compact would be the solution, but it is both a river and the deserted bank areas that form a significant barrier.

2.1 Developing the abandoned industrial area

The river Göta Älv which splits Göteborg in a northern and a southern part has been more an obstacle than an asset after the shut-down of the free port in the 80s of the last century (Sepehr, 2010). The municipality is aware of this and numerous parties have started various projects, where the development of the city is mainly focused on the area Frihamnen (see figure 2.1, marked red), but also on all the other former harbour areas (marked blue).

Figure 2.1: An overview of the central neighbourhoods around the Göta Älv.

One of those projects is "Centrala Älvstaden/Älvstranden" which is currently developed by both Älvstranden Utveckling AB and the Municipality of

Gothenburg, in order to integrate and connect the city over the water. The project covers all the area around the Göta Älv, such as Frihamnen, Lindholmen, Kvillebäcken, Ringön and Gullbergsvass. The main vision is to rejuvenate the former harbour and make it more sustainable.

Another approach is that of Mistra Urban Futures (consortium of amongst other Chalmers University of Technology and Göteborgs stad), which is a centre for sustainable urban development. For the area Frihamnen Roth et al. (2011) propose a three-way plan, which is addressing future climate change. Three possible scenarios of Attack, Defend and Retreat are discussed, where e.g. floating buildings are put forward to tackle sea level rise. Similar is the Master thesis of Sepehr (2010), which is besides adaptation to flooding, focusing on public transport and the development of green areas.

2.2 The river city island

The plan of the think-tank Super Sustainable (volunteering architects based in Göteborg) is slightly different compared to the ones discussed in the section before. To decrease Göteborgs ecological footprint densification of the city centre (less transport, smaller distances travelled) is the keyword. Although the mentioned plans in the last section strive for this too in their own way, the hurdle of connecting the city over the river is never taken. Next to that the intention is to have a self-sustaining city area concerning the use of energy, which for the other plans has not been an objective. Wind, solar and wave power are put forward to satisfy for the energy demand in the Sustainable City.

The Sustainable City plan, a river island on the Göta Älv, includes not only a connection of the north to the south, but also the placement of apartments and offices, which is needed seen the projected growth in population and jobs in Göteborg for 2020 (30,000 homes and 40,000 workplaces; Göteborg City Planning Autorithy, 2009). The architects have also chosen for a structure of floating buildings, which is however placed in between Lindholmen and the City Centre (the pink area in both figure 2.1 and figure 2.2). Whether this is a better and more viable choice than the construction of supporting pillars underneath the houses is not clear, but beyond the scope of this report.

Figure 2.2: A close-up of the planned Sustainable City placed between Lindholmen and the City Centre © 2011 Super Sustainable.

It is for these reasons that the plan of Super Sustainable is chosen to be the subject of this Master thesis. Although it is hypothetically planned to be realized in 2050, the assessment for the Sustainable City (and thus the multifunctional building) will be done according to the present day's standards. This will not only facilitate the calculations, but in this way it will also show whether or not such a building can be achieved presently.

2.3 The city lay-out

The buildings and roads of the Sustainable City have been constructed such that the transition from land to water fits into the current infrastructure and atmosphere of Gothenburg. The Sustainable City itself has a diverse lay-out, where the emphasis is on green, but also on combining functions. The city map in figure 2.3 shows for example several public buildings on the north side of the inner canal, which have a park as a rooftop (one of them: the purple zoomed-in building). Next to that, the city is filled with buildings integrating shops, offices and apartments, referring to the concept of the multifunctional building which will be explained in the next section (the red zoomed-in building).

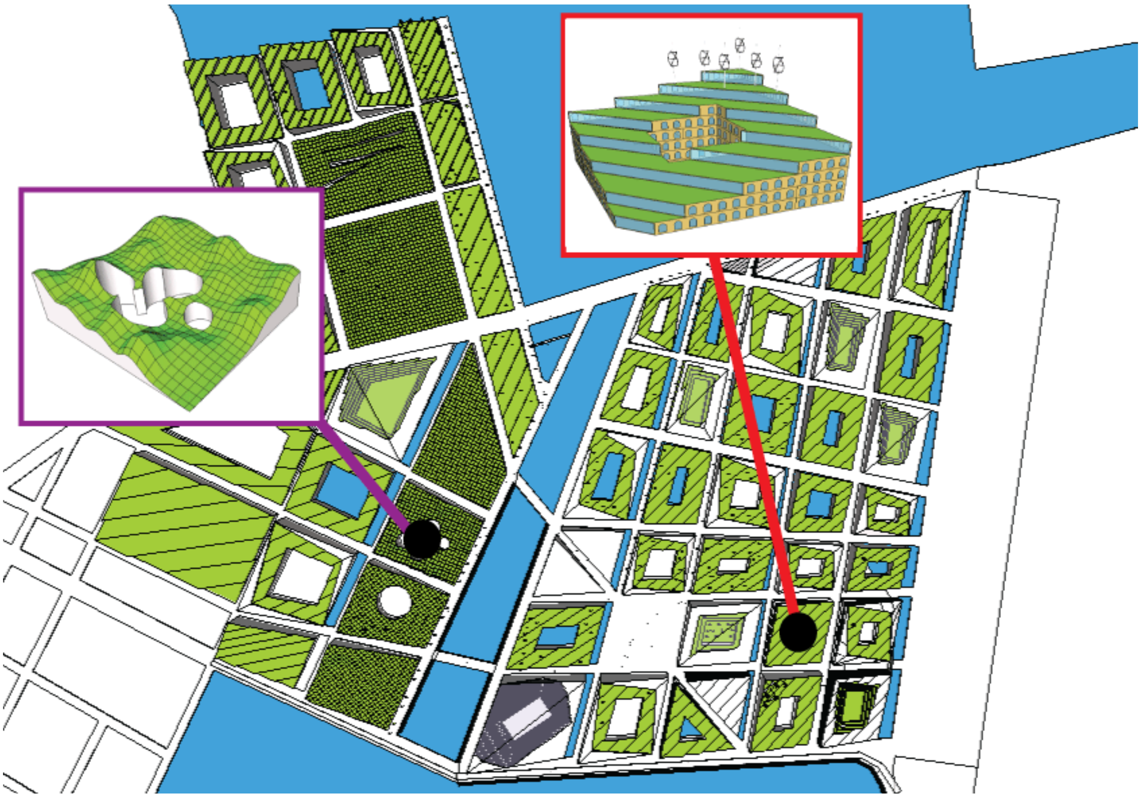

Figure 2.3: A map of the Sustainable City with two highlighted buildings: a rooftop park building (purple) and the multifunctional building (red).

Based on the inner floor areas of all the buildings, estimations can be made concerning the population size and the availability of office and shop space. According to figures from the city of Stockholm (Johnson, 2010) 1.7 people were living in a multi-family apartment with an average size of 66 m^2, which seems reasonable for Göteborg (Sweden's second biggest city, after Stockholm). Using this as a conversion factor, it is computed that the total living area of the apartments (325,666 m^2) results in 8,388 persons occupying the dwellings.

Using the average office size in Sweden determined by Cushman & Wakefield (2006; 1 person per 18 m^2) the overall office space of 76,716 m^2 accommodates 4262 employees. Finally, the shopping area amounts to 89,784 m^2.

2.4 The multifunctional building concept

The buildings and their lay-out are the most important part of the Sustainable City plan, because they have been shaped for a specific aim. Apart from the fact that they will follow Swedish Passive Housing regulations (this will be explained in section 3.1), have they been constructed stepwise, such that they provide an optimal implementation of solar panel placement and can be used for leisure and agriculture. Besides this, the orientation of the buildings to the south increases the uptake of solar gains and provides natural light to the apartments (see figure 2.4).

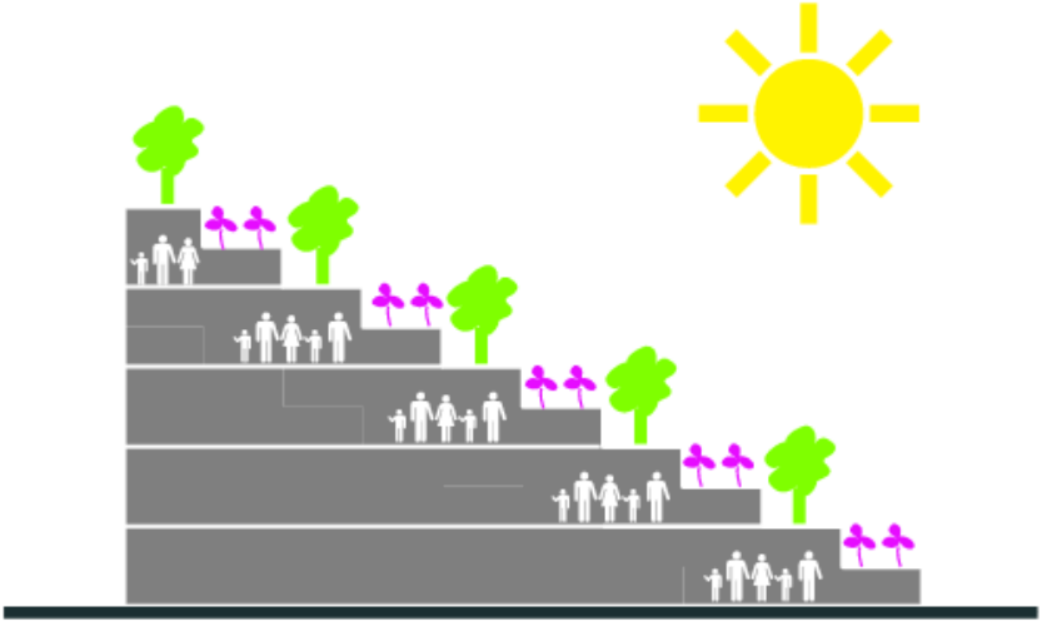

Figure 2.4: The buildings are stepwise built for solar panel placement, to increase the solar gains and provide natural sun light to the apartments © 2011 Super Sustainable.

The buildings are not only used for residential purposes, but also for office space and shops, which is supposed to give unapparent opportunities for energy savings. According to Super Sustainable do offices and boutiques require cooling, whereas apartments (in Sweden) mostly require heating: an air-to-air heat exchange system between the two would lower energy use. Moreover, the positioning of the apartments on the south side of the buildings strengthens this vision, whereas working places and shops remain cool on the north-side of the building (see figure 2.5).

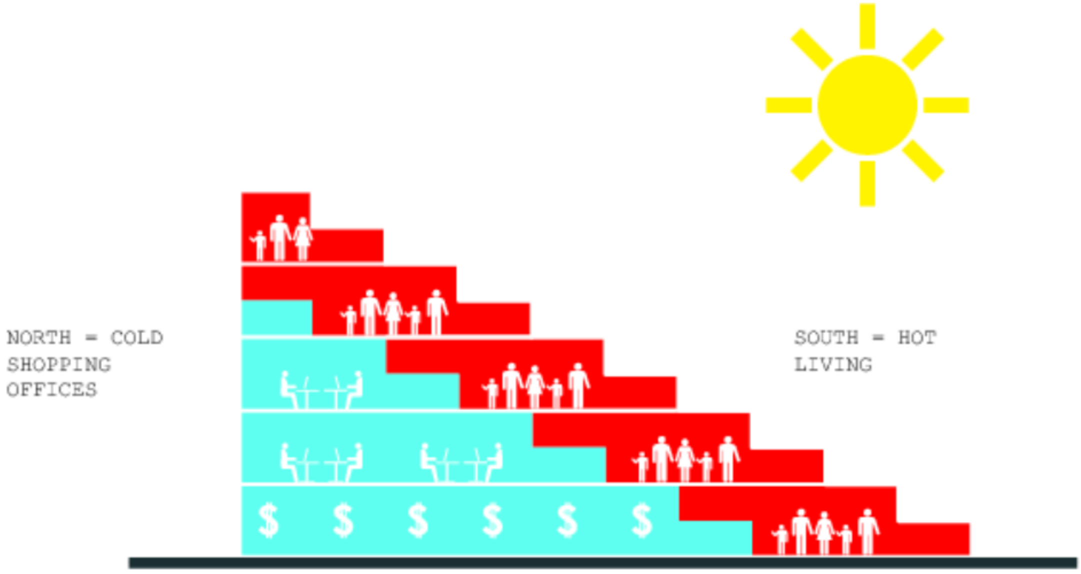

Figure 2.5: The buildings are stepwise built with shops and offices on the north side (colder areas) and apartments on the south side (warmer areas) © 2011 Super Sustainable.

2.5 The wind-mill building

The multifunctional building concept explained in the last section has three types to be found in the Sustainable City: the greenhouse-building (figure 2.6, left), the solar power building (figure 2.6, right) and the wind-mill building (figure 2.7, as previously shown in figure 2.3). The first has an inner court yard comprised out of several flights, which is used as a greenhouse to grow crops, the second is a building that is constructed mainly for solar power and the third is mostly used for wind power.

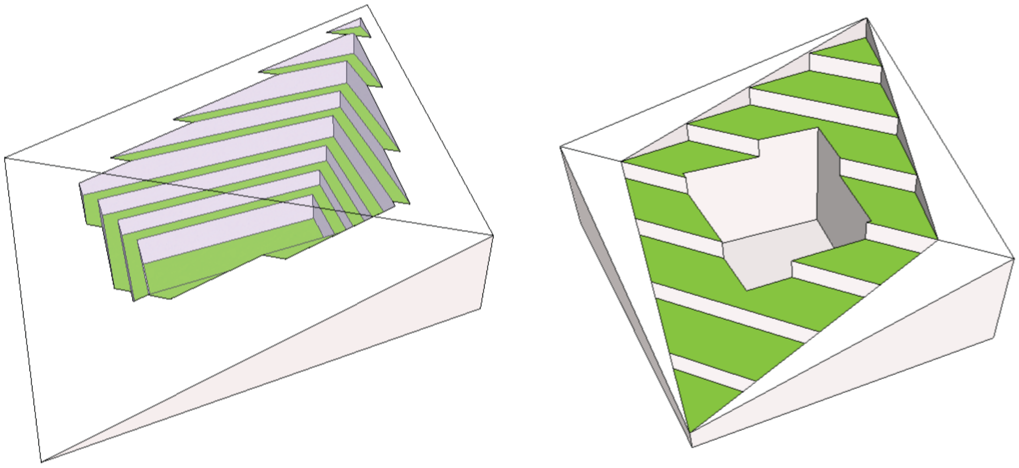

Figure 2.6: To the left the greenhouse building, where the inner court yard is used to grow crops. To the right a solar panel building, where the sides and some flat parts on the roof are used for power from the sun.

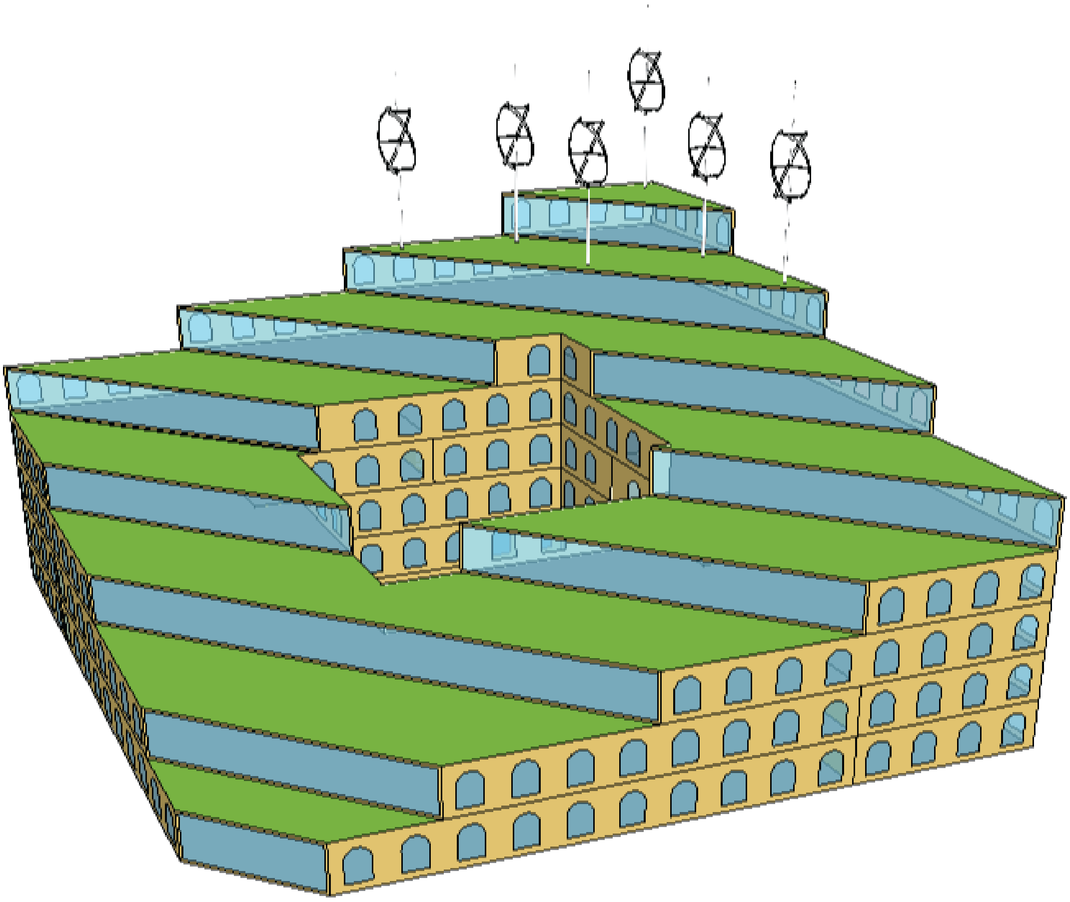

Figure 2.7: The wind-mill building, where the upper part of the building is designated for wind power.

Since all three types are based on the same concept, it has been chosen to elaborate on just one (the wind-mill building). On the other hand, it would be interesting to see, how the greenhouse building is coping with a preferred high indoor temperature (typically 24°C during the day; Coelho et al, 2005), but this is limited by the time frame of this thesis.

SPECIFICATIONS – Wind-mill building (figure 2.7)

85 apartments (145 persons), divided over four two-storey apartments:

- 6 apartments on the fourth and upper part (7th and 8th floor)
- 24 apartments on the third part (5th and 6th floor)
- 38 apartments on the second part (3rd and 4th floor)
- 27 apartments on the first and lower part (1st and 2nd floor)

68 working places in the office area (3rd, 4th and 5th floor) and 2459 m^2 of shopping area (1st and 2nd floor)

The flat roofs facilitate:

- use of windmills on the 7th and the 8th floor
- partly solar panels and agricultural/leisure purposes

3. Energy demand of the multifunctional building

In this chapter the energy demand of the multifunctional building (type: wind-mill building) will be discussed. As an introduction, some lines will be dedicated to the principle of Passive Housing, the voluntary (Swedish) regulations which all of the Sustainable City buildings will follow. Thereafter, in section 3.2, the set values for the energy modelling program OpenStudio will be shown. Finally, in section 3.3 the hourly energy demand will be determined for the wind-mill building, by interpreting the building's energy model.

3.1 Introduction to the passive house

Passive housing is a technique which originated from 1988, when Professor Bo Adamson at Lund University and Dr. Wolfgang Feist (Institute for Housing and the Environment, Germany) developed the concept (Halse, 2005). The main idea of a passive house is that it is well-insulated and airtight, such that mechanical ventilation is the primary factor for heating and cooling and assuring the air quality.

The temperature regulation of the building is mainly performed by a ventilation system that has an air-to-air heat exchanger that uses warm exhaust heat to warm up the incoming fresh air. No other heating systems (e.g. radiators) are required, also because passive solar gain and heat gain from persons and household appliances are smartly used. The insulation of a Passive House makes sure that the warmth stays inside; the outer walls are three times as thick as a conventional building (New York Times, 2010). Plus, the windows have triple pane glazing, with coated glass, which gets the emissivity down from 0.9 to 0.2, even so preventing energy transfer through the windows.

According to Schneider & Hermelink (2006) the users of passive houses are pleased with the thermal comfort of the building. At the same time the energy use for space heating is reduced with 80% and the total energy consumption with 50%. Overheating is one of the bigger drawbacks of passive houses, but can be counteracted satisfactorily. Mlakar & Štrancar (2011) say that opening the windows during hot summer days, shading of southern and western windows and keeping internal energy sources as low as possible are sufficient to keep the indoor climate comfortable.

For passive housing, documents have been developed to verify if a house is complying with the rules. These regulations are different for every country and are voluntary. In Sweden the guidelines have been set by the Forum för Energieffektiva Byggnader (FEBY, 2009). The most important rule is that a building should not exceed an energy demand of 55 kWh/m^2 per year. This is however excluding the household electricity which is used for electric appliances and for lighting. The value is applicable to the south climate zone in Sweden, in which Göteborg is located. It should be emphasized however that for offices and shops regulations do not exist yet, such that no conclusions can be made.

3.2 Three energy needs

The multifunctional building will be energy modelled using the computer program OpenStudio (whilst making use of EnergyPlus), which has a plug-in for the design program Google Sketchup. OpenStudio is known for its user-friendly interface, whereas EnergyPlus is taking care of the modelling; both are originating from the Energy Department of the US Government. The combination of these programs will later on result in an hourly energy demand for the wind-mill building primarily, but also for any other generic building in the Sustainable City. This hourly energy need is based on three factors, which are electricity, hot water demand and heating/cooling need.

3.2.1 Electricity demand

The first one, electricity demand, is fairly easy to calculate, because the only values needed are the use of electrical appliances per area or person and a certain schedule of use throughout the day.

It will be assumed that the template data (for 2009 Energy Efficient Buildings in the US) for electricity in OpenStudio can be applied on Sweden, such that the maximum is set to 3.88 W/m^2, 9.36 W/m^2 and 3.12 W/m^2 for an apartment, office and shop respectively, and a day schedule is provided (what fraction of the maximum is used). The lighting is not included, since it is based on the actual need for artificial light, when natural daylight is present. Its maximum is 3.49 W/m^2, 9.69 W/m^2 and 12.38 W/m^2 (apartment, office, shop, respectively) and has a similar fractional day schedule.

3.2.2 Hot water demand

The second factor, hot water demand, is not provided in the program as a template. It will be assumed that the need for hot water in offices and shops is two times smaller (Koiv et al., 2010), which makes the estimation become fairly simple then. Both Widén et al. (2009) and Lundh et al. (2008) give that the use for hot water per person in Sweden in a multi-family apartment is 6.5 kWh and 7.4 kWh for a weekday and a weekend day respectively. Widén et al. also provide the schedule per hour for one day, which looks like figure 3.1.

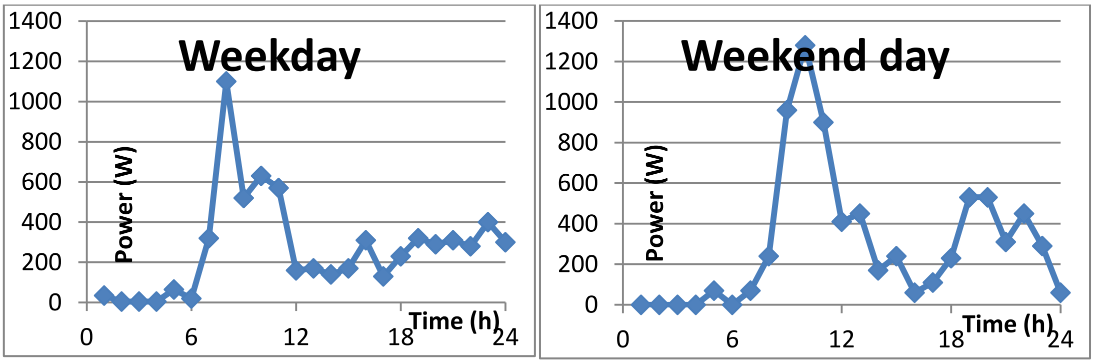

Figure 3.1: The hot water demand per weekday and weekend day for an apartment in Sweden (Widén et al., 2009).

If a quick calculation is done for how much water is used per year, this results into $(6.5 \cdot 5 + 7.4 \cdot 2)/7 \cdot 365 = 2{,}466$ kWh/person/year or 43.10 kWh/m^2 (Widén et al, 2009). However, FEBY (2009) advises to take the water volume $V_{VV} = 18$ m^3 as an annual value per person, such that the energy used E_{VV} can be computed, using [1] (where A is area):

[1]

Which using Johnson (2010) results into:

$E_{VV} = 18 \cdot 1.7 \cdot 55 / 66 = 25.5$ kWh/m^2/year

It is clear that the water use in Widén et al. (2009) is higher than the standard for passive housing. It will therefore be assumed that the schedule of use is the same, but that all values for the water use will be smaller with a multiplying ratio of 25.5/43.10. It seems justified to do this, because the studies do not take into account the measures that are taken to keep the passive housing standard (maximum temperature, maximum flow). Above all, a study of Wall (2006) shows that Swedish energy efficient houses have a monitored hot water demand of 24.1 kWh/m^2/year.

As a final point, FEBY (2009) also provides a distribution of warm water throughout the year. The use looks roughly like figure 3.2, which will also be included in the hourly energy demand for hot water.

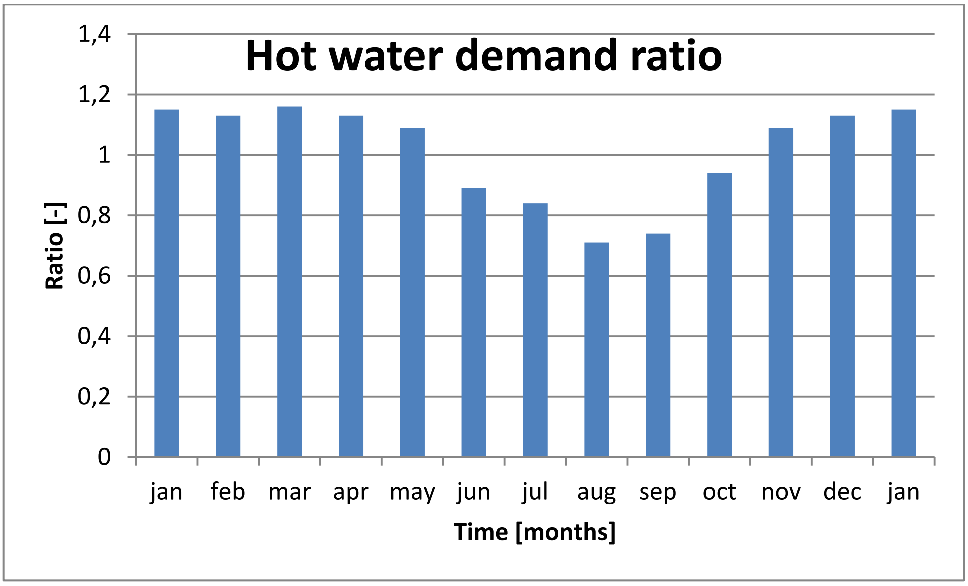

Figure 3.2: The hot water demand ratio for the whole year for an apartment in Sweden (FEBY, 2009).

3.2.3 Heating/cooling demand

The third factor, the heating and the cooling need is a bit more complicated. Although OpenStudio will use more elaborated formulas in its model, the explanation of the various factors will happen according to Jonsson & Bohdanowicz (2010), which is not wrong, but more basic. The heating/cooling demand for them is based on the following simple formula:

[2]

where
and

The meaning of the single terms in equation [2] will be explained within the coming subsection. Above all, the values used within OpenStudio to model the multifunctional building will be given and argued.

TRANSMISSION HEAT LOSS

The transmission losses are based on the equation:

[3]

Where U is known as the overall heat transfer coefficient, A stands for the inner area of the building floors and t_i and t_o are the indoor and outdoor temperature, respectively.

All the walls, floors and roofs have the U-values as in table 3.1, which have been based on average values of the two multi-family building projects Värnamo and Frillesås studied in the PhD thesis of Janson (2008). The U-value for windows (in the same table) is complying with the demand of FEBY (2009), since it is lower than 0.90 W/(m^{2}K). On the other hand, the construction materials used to attain the U-values are not of relevance within this thesis. The standard options within OpenStudio have been chosen, but 350 mm insulation has been added where necessary to acquire the passive housing standard (based on both Wall, 2006 and Janson, 2008).

In the plan of Super Sustainable green rooftops were also included, to reduce the energy demand for space heating/cooling. Literature learns us however, that this effect is very small, if not negligible for newly built houses (Castleton et al., 2010; Niachou et al., 2001). The effect is only visible for older buildings that are poorly insulated. Rainwater management and urban habitat creation for birds for example, are however many of the advantages concerning green roofs (Villarreal & Bengtsson, 2005), but not applicable to the analysis of this thesis.

Table 3.1: U-values and materials used in OpenStudio for the energy model.

	U-Value W/(m^{2}K)	Construction Material
Exterior Wall	0.082	100 mm Brick, 200 mm Concrete, 350 mm Insulation, Air, 19 mm Gypsum
Ground Floor	0.085	200 mm Concrete, 350 mm Insulation
Interior Wall	2.58	19 mm Gypsum, Air, 19 mm Gypsum
Exterior Roof	0.081	100 mm Concrete, 350 mm Insulation, Air, Acoustic tiles
Exterior Window	0.880	3 mm Coated, 13 mm Air, 3 mm Coated, 13 mm Air, 3 mm Coated
Interior Floor	1.449	100 mm Concrete, Air, Acoustic Tile

Although FEBY (2009) specifies a designed indoor temperature (20°C), at which the power of the space heating for apartments should comply, it does not reflect the indoor temperature preferred by residents. Ekberg (2007) says that the temperature should be somewhere between 20 and 24°C in winter (23 and 26°C in summer), whereas Jönsson (2009) claims that the annual average lies at 21.65°C. Also Janson (2008) reports that residents like to have the thermostat at somewhere between 21 and 22 degrees. Therefore, it is decided to see what effect both 22°C (based on literature) and 20°C (based on FEBY, 2009) have on the energy demand of the apartments.

Concerning offices and shops, the architects of Super Sustainable thought that they would require less heat in their indoor air. For offices however Nicol & Humphreys (2007) state that 22.6°C is the optimal indoor temperature, whereas Fang et al. (2004) say that subjects feel themselves neutral in a 23°C environment. It makes it fair to say that an apartment should not be warmer than an office; it is even the other way around. For this Master thesis, it will however be assumed the same (22°C), which also has to do with the fact that temperature differences within a passive house are difficult to maintain (Janson, 2008).

For shops Diederichsen et al. (2007) report the indoor temperature to be fairly high: 22-26°C. Morgan and de Dear (2003) conclude a similar temperature range, which is 22-24°C. It is clear that also for shops, a higher temperature is wished for than expected. For similar reasons as for the offices, a 22 degrees thermostat will now be applied on the shops.

It means that the concept of cool parts on the north side and warm parts on the south side is hereby disproved. One could even say that the positioning of apartments versus shops and offices should be the other way around. However, for economic reasons the same indoor temperature in the whole building is anyhow favourable, since energy transfer by internal losses plays a big role, if several rooms have to be kept at different temperatures (Janson, 2008). It should also be noted that a set-back of temperature in shops and offices during the night does not give any significant energy reductions (Hastings, 2004).

The outdoor temperatures are based on a weather file for Göteborg Landvetter, the local international airport. The file is not valid for a specific year, but applicable for any year, since it is based on data from 1961-1990. Although this will not be in line with the approach used in the rest of the report (see Chapter 4), it will still be used. Not only is more data available, but most important, the file is ready to use for the program OpenStudio.

The assumption will be made that the ground temperature of the buildings will be similar to the outdoor air, since it is not sure what the effect will be of water in contact with the ground floor of the multifunctional building. Water has the property to be cooling slower than soil, such that the temperature will be higher in winter times and lower in summer times compared to soil. Next to that, the surface temperature is influencing the building and not so much the complete water volume as a whole. It seems the outdoor air effect thus has more influence on the temperature of the water, such that this assumption is justified.

VENTILATION AND INFILTRATION HEAT LOSS

The other part of the heat losses exists of the ventilation losses and the infiltration losses. The first, which is caused by losses involving the ventilation system, and the second, which is caused by losses involving infiltration of outside air, are quite similar. They can both be estimated by the following equation:

[4]

In this equation ρ is the density of air (1.2 kg/m^3) and c_p is the specific heat of air ($1.0 \cdot 10^3$ J/(kgK)), whereas the indoor and outdoor temperature are the same as explained before. The volume flow rate however is calculated in two ways. For ventilation it is based on both the area and the people present (FEBY, 2009), according to equation [5]:

[5]

Where A_{temp} is the area that is heated/cooled and n_{max} is the maximum amount of people projected in the building. This results into a value for air changes per hour (ACH) of 0.55 for apartments (in agreement with Janson, 2008) and 2.78 and 0.76 for shops and offices respectively.

The ACH should be 0.05 for infiltration (Janson, 2008), such that the infiltration volume flow rate can be computed using [6], where V is the volume of the building:

—— [6]

SOLAR IRRADIATION HEAT GAIN

Jonsson and Bohdanowicz (2010) propose the following equation for solar irradiation:

[7]

The solar gain (q_v) calculations in OpenStudio are based on irradiance data and the direction of the sun (extracted from the aforementioned weather file). Jonsson and Bohdanowicz assume the value ε (emissivity) to be 0.9 as a standard for clear glass. Because also the windows need to comply with the passive housing standard, coated glass with an emissivity of 0.2 has been chosen (Sunergy, 2011). The value A_w is equal to the area of the windows in the multifunctional building.

PEOPLE HEAT GAIN

The amount of energy gained by the presence of people is depending on three different factors. In the first place the amount of people present per area has to be known. As stated earlier, Johnson (2010) accounts for 1.7 people per 66 m^2 for apartments, which equals to 0.02576 people per m^2. For offices, 1 person has 18 square meters available, which implies 0.05556 people per m^2 (Cushman &

Wakefield, 2006). For shops the facts from the local shopping mall Nordstan are used, which results in 0.3355 people per m^2 (Nordstan, 2010).

As a second factor, it is important to know what the occupancy schedule of the persons is. The individual templates in OpenStudio will be assumed to be applicable for all three functions within the building.

Thirdly, the activity of these people will have to be taken into account, which addresses the metabolism of the people present. For apartments this will be considered to be 117 W, for offices and shops 132 W. These values are all based on Jonsson and Bohdanowicz (2010) and they have been averaged for every human being.

LIGHTING AND ELECTRICAL EQUIPMENT HEAT GAIN

Lighting and electrical equipment also produce heat when being used. In EnergyPlus it is considered that the power needed to operate is equal to the heat gain produced. Although this might not be completely true, seen e.g. light produced leaving the building through a window, it will be accepted as an assumption.

This however entails that FEBY's maximum for 4 W/m^2 of internal heat gain (for both people, lights and electric equipment) for an apartment will be exceeded. The values written in subsection 3.2.1 already amount to 7.37 W/m^2 when both lighting and electric equipment are at its maximum; for people only this would be 3.01 W/m^2.

Anyhow, no lower values for heat gains by people, lighting and electrical appliances will be assumed, thereby violating this regulation. This is both justified by Wall (2006) who already claims that the amount of electrical appliance used and their energy effectiveness is underestimated. On the other hand, FEBY's 70 W metabolism for people (versus 117 W average based on Jonsson and Bohdanowicz, but also Allard & Ghiaus, 2005) in apartments seems to be on the low side, thereby making the 4 W/m^2 unattainable.

3.3 The computer model

The idea behind the buildings in the Super Sustainable plan has been disproved in the last section, both because of fundamental reasons, but also out of practical and economic ground. On the other hand the integration of functions in a passive house has not been done so far and neither has the step-wise built shape been given much attention in current research. It is the reason why the energy model for the multifunctional building still will be pursued in this thesis. This section will show how the computer model of the wind-mill building looks like, based on the input of section 3.2.

3.3.1 Thermal zones

Since OpenStudio is a computer program, which is still in its early development, many bugs and crashes appear in the program. This is especially stimulated by designing a fairly difficult model, which is the case for the wind-mill building. For this reason the building is not modelled directly as a whole, but it is decided to divide it up in its thermal zones. These thermal zones are so-called within the program and could be seen as the parts of the building that have a similar function (shops, offices or apartments) and are on the same storey. It results into the fact that this particular building has 14 thermal zones, visualised in figure 3.3 and 3.4. It should be noted that three thermal zones exist on the fourth floor, of which two are apartments (F4A1 and F4A2).

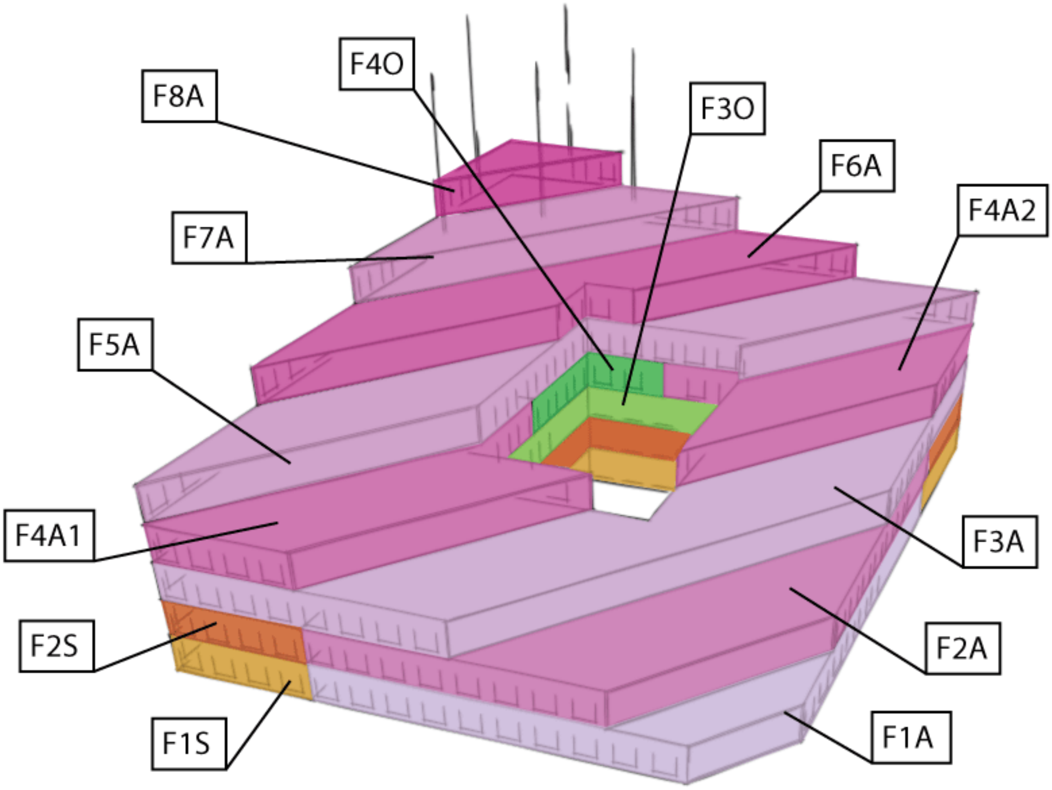

Figure 3.3: The windmill building and its thermal zones - top view - where F = floor, # = storey, A = apartment, O = office, S = shop.

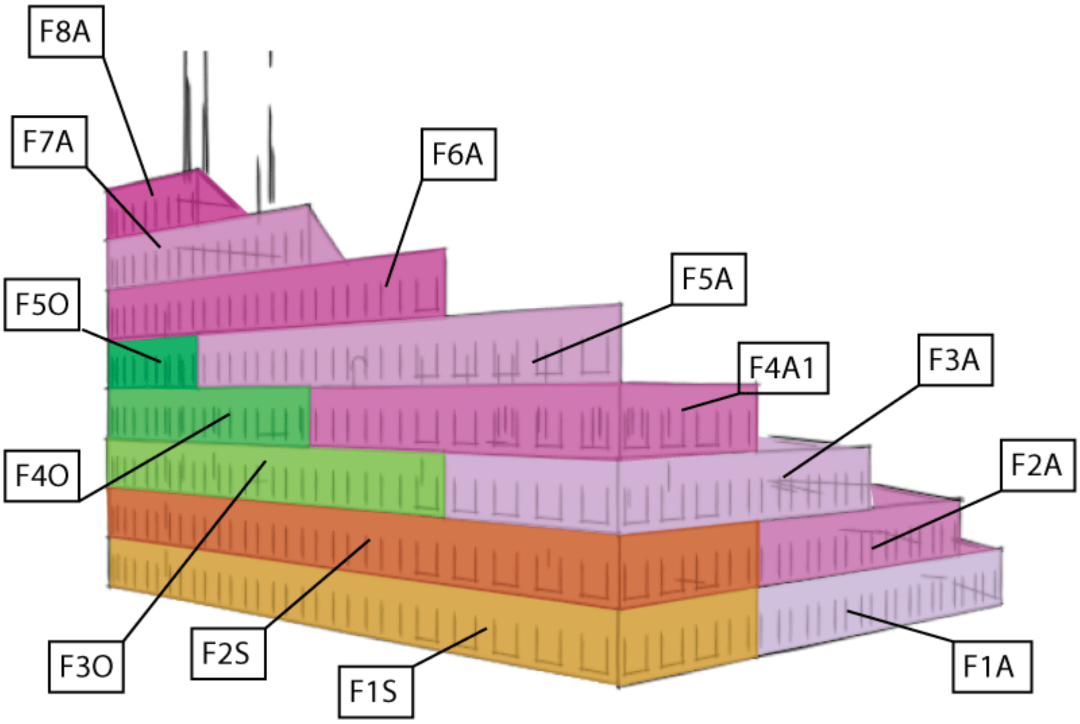

Figure 3.4: The windmill building and its thermal zones - side view - where F = floor, # = storey, A = apartment, O = office, S = shop.

3.3.2 Building model

In order to elaborate on how 14 energy models of the thermal zones can add up to one model of the complete building, one thermal zone (F1A) will be used to explain the approach, see figure 3.5. In the figure the walls with windows are considered as exterior walls that interact with the outside conditions. On the other hand, the walls that do not have windows are interior walls, which interact with adjacent thermal zones. Because the temperature in the whole building will be the same (subsection 3.1.3), these walls have been set to adiabatic.

Just as the exterior walls is the roof (in red) in contact with the outdoor conditions, whereas the grey ceiling/floor is an internal floor between apartments (adiabatic). The ground floor is considered as an exterior floor and thus coping with outside boundary conditions.

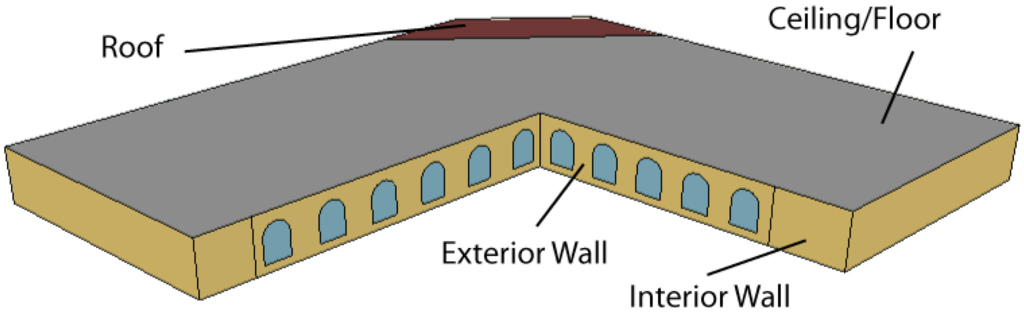

Figure 3.5: Thermal zone F1A, part of the wind-mill building.

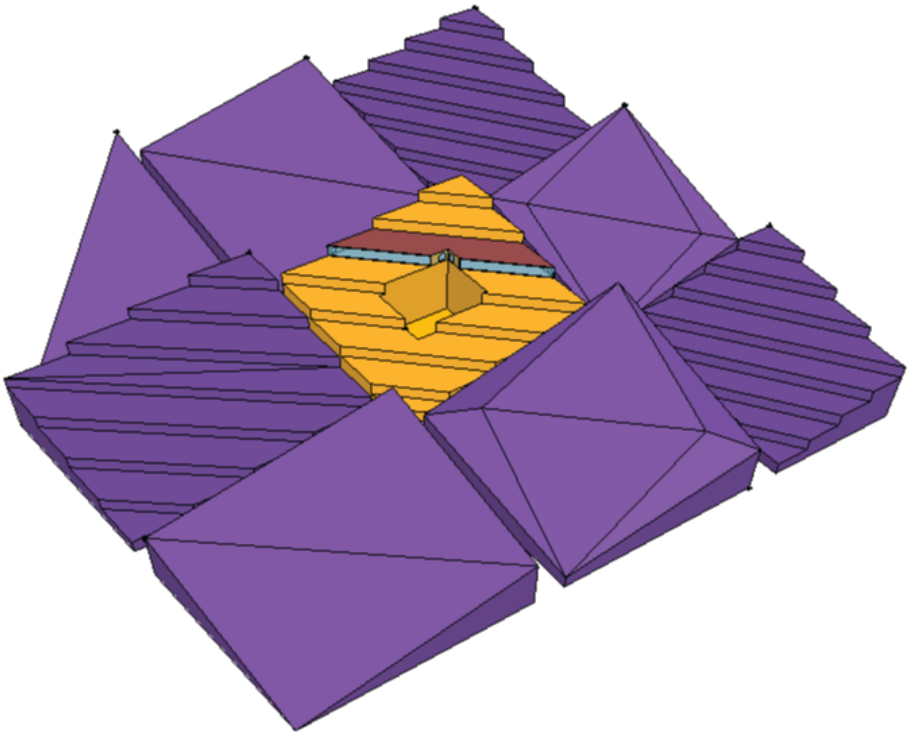

Figure 3.6: The surroundings of the wind-mill building modelled as purple shading surfaces. The building itself is a yellow shading surface and the particular thermal zone modelled is F6A.

To reflect the presence of other buildings in the vicinity of this particular building, these objects have been included in the model as (purple) shading surfaces, see figure 3.6. Besides that, has the building itself also been included as a (yellow) shading surface for the thermal zones that do not take part in the particular modelling run for one specific thermal zone (in this case F6A), to perfectly account for possible wind and sun conditions on and around the building.

3.3.3 Ventilation system

In the building will be one type of ventilation system, which is based on figure 3.7. Starting at the supply side (following the arrow) is to be found an air exchange with outside, in order to maintain air quality (oxygen level). On the other hand also an economizer is installed, which will make sure that the exhaust heat from the system is kept inside, to reduce heating in winter (or cooling in summer). Next in line are an electric cooling coil and an electric heating coil keeping the temperature constant. Although the cooling part in the Swedish regulations for a passive house is non-existent (read: should not be used), its presence has been justified, to account for extreme overheating in the shopping area, on hot summer days. Finally, the fan is in the duct to move the air in an auto-sized design flow.

At the demand side is the system split into single-duct branches, each branch distributing air to a thermal zone (indicated with “zone”). The branches come together again at the zone mixer, such that from there on the cycle repeats itself.

It should be noted however that there will exist at least three of these ventilation systems, for every function one. This is due to the fact that the demand schedule for an apartment is different than for a shop: shops need at least 10 times as much ventilation flow (based on people occupancy), to make sure that indoor air quality is maintained. Nevertheless will the different ventilation systems mix their exhaust air, in order to keep the temperature stable.

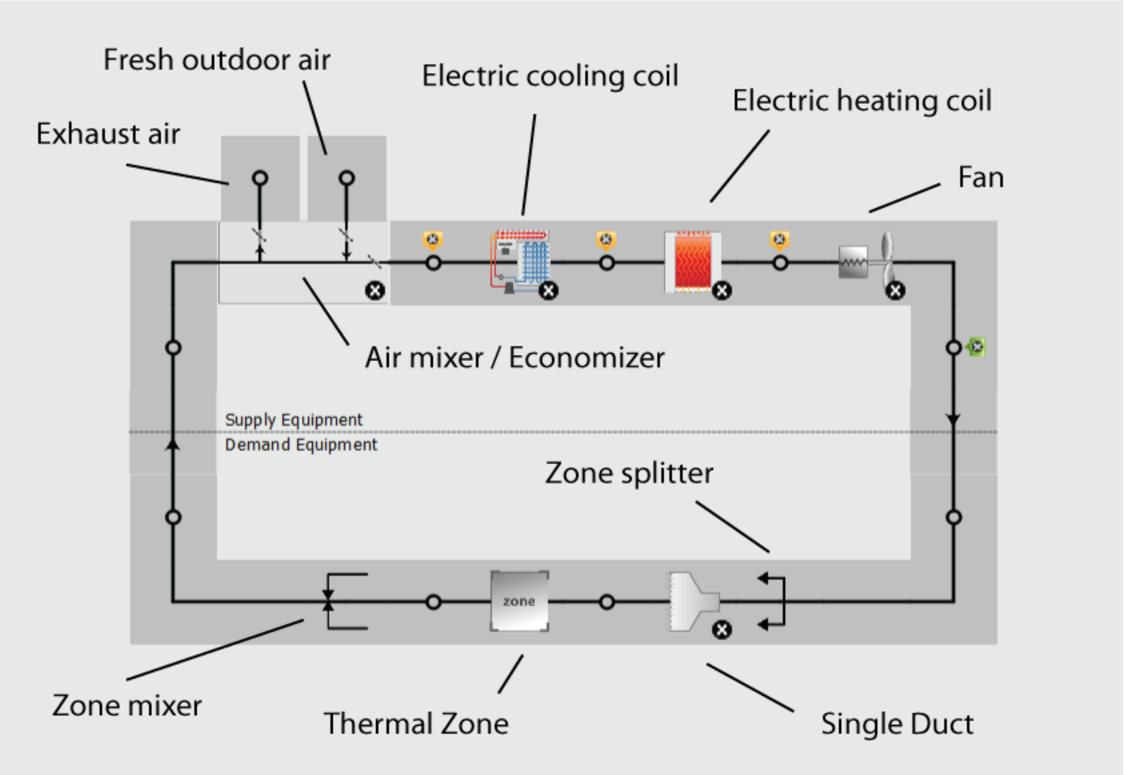

Figure 3.7: The ventilation system used within the multifunctional building.

3.4 The energy modeling results

In this section the annual results for the energy modeling of the complete windmill building will be shown. It means that for a whole year (8760 hours) all three energy needs for every thermal zone have been computed. For electricity both the energy needed for lights and electric equipment is presented, whereas for the heating/cooling need also accompanying electric fan use is given. Except for the hot water demand (heat), all energies given refer to electricity.

As has been argued in subsection 3.2.3 the results will be obtained for two temperatures: both 20°C (following FEBY, 2009) and 22°C (according to literature). The outcomes for the first have been presented in table 3.2, for the second in table 3.3.

Besides a table for both temperatures, visual interpretations of some of the data will be given. Heating need, cooling need, lighting demand and electrical equipment demand have been drawn in the figures 3.8 through 3.11, respectively. Concerning the colors holds that, the darker the color, the higher the demand. It should also be noted that the drawings hold for both cases, since the 22°C case is mainly a magnification/diminution of the 20°C case.

The subsections 3.4.1 (the energy demand at 20°C) and 3.4.2 (the energy demand at 22°C) will now discuss the acquired results. For the first, some special attention will be given to comparing the outcome with the Swedish Passive Housing regulations.

3.4.1 Energy demand at 20 degrees Celsius

Concerning the electricity need table 3.2 shows us that the lighting demand and electrical equipment demand for the whole building are quite similar with 23.18 and 23.79 kWh/m^2. The averages are quite high, due to the large use of lighting in shops on the one hand (see figure 3.10) and the large use of appliances in offices on the other hand (see figure 3.11).

The average for the overall electricity need for apartments is however computed to be 31.21 kWh/m^2, which is slightly lower than the 31.8 kWh/m^2 for the energy efficient terrace houses in the research of Wall (2006). Besides that recommends FEBY (2009) that a multi-family building should have an electricity use of 1,040 kWh/year/household + 300 kWh/year/person. Interpreting Johnson (2010) it is computed that 1,040 + 300 · 1.7 = 1,550 / 66 = 23.48 kWh/m^2 is what should be strived for ideally. It is not a regulation demand, but it suggests that the used values for lighting and appliances could be taking energy-efficiency into account a bit more.

The hot water demand for apartments which is 25.5 kWh/m^2 of heat is not a surprise (see section 3.2.2). Neither is it a value which is unattainable. Wall (2006) showed that it is possible to obtain 24.1 kWh/m^2 of energy needed to heat the water in monitored houses, although this is partly heat and electricity. In other words, this value will even be slightly lower, if efficiency losses from electricity to heat are included.

For the space heating/cooling demand 40.34 kWh/m^2 per year is on the high side, mainly because of the presence of the shops (see figure 3.8). It is logical the shops need a lot of heating in winter in Sweden, since the infiltration/ventilation rate is high, both by people entering the shops via exterior doors and because of maintaining the indoor quality. Above all, the thermal zone

F8A needs quite some cooling (see figure 3.9), which makes sense if in summer time it is not blocked from any sun, high up the building. On the other hand, for apartments, the space heating/cooling need average is computed to be 14.74 kWh/m^2 per year with a maximum peak load of 10 W/m^2, which again is similar to the findings of Wall (2006). In combination with the hot water demand (14.74 + 25.5 = 40.24 kWh/m^2), it does comply with the maximum energy demand of 55 kWh/m^2 (excluding household electricity).

Total amount of electricity needed per year per area:	87.31 kWh/m^2
Total amount of heat needed per year per area:	19.2 kWh/m^2
Total amount of electricity needed per year:	1,497 MWh
Total amount of heat needed per year:	330 MWh

3.4.2 Energy demand at 22 degrees Celsius

Concerning the results for the case where the temperature is set 2 degrees higher, some difference is to be seen compared with the previous. Lighting and electrical appliances will be assumed to be the same, as will the hot water demand. On the other hand, the demand for heating is going up, whereas the demand for cooling is going down. Fan use decreases slightly compared to the 20°C case. The overall heating/cooling demand does increase from 40.34 kWh/m^2 to 44.46 kWh/m^2.

But how does this affect the Swedish Passive Housing Regulations? The new average for apartments for space heating/cooling is 10.93 kWh/m^2, which is actually a reduction compared to the previous case. It is however a logical conclusion, since cooling for apartments alone was the only concern (see figure 3.9). Thus, with a higher indoor temperature required, the need for cooling disappears partly for the apartments.

Total amount of electricity needed per year:	91.43 kWh/m^2
Total amount of heat needed per year:	19.2 kWh/m^2
Total amount of electricity needed per year:	1567 MWh
Total amount of heat needed per year:	330 MWh

Table 3.2: The electricity demand (except for hot water, which is heat) for all 14 thermal zones of the wind-mill building for an indoor temperature of 20°C.

Thermal zone	Lights [kWh/m^2]	Electric Equipment [kWh/m^2]	Electricity [kWh/m^2]	Hot Water Demand [kWh/m^2]	Fan [kWh/m^2]	Heating [kWh/m^2]	Cooling [kWh/m^2]	Space Heating/Cooling [kWh/m^2]
F1A	9.88	22.33	32.22	25.5	2.83	0.03	3.28	6.14
F1S	44.97	14.40	59.37	12.8	10.35	83.96	11.23	105.54
F2A	9.47	22.33	31.81	25.5	3.54	0.00	4.61	8.15
F2S	44.90	14.40	59.30	12.8	10.31	83.43	11.31	105.06
F3A	7.57	22.33	29.90	25.5	4.85	0.01	7.13	11.98
F3O	30.69	41.90	72.59	12.8	7.38	0.43	7.02	14.84
F4A1	8.66	22.33	30.99	25.5	6.40	0.00	9.72	16.13
F4A2	9.02	22.33	31.35	25.5	5.75	0.04	8.61	14.40
F4O	30.64	41.90	72.54	12.8	7.32	0.43	7.01	14.76
F5A	8.93	22.33	31.26	25.5	6.35	0.01	9.70	16.06
F5O	30.65	41.90	72.55	12.8	7.06	0.41	6.93	14.40
F6A	8.47	22.33	30.80	25.5	9.11	0.02	13.78	22.91
F7A	8.00	22.33	30.33	25.5	17.53	0.26	26.33	44.12
F8A	7.37	22.33	29.71	25.5	44.87	3.22	64.83	112.93
Average	**23.18**	**23.79**	**46.97**	**19.2**	**7.47**	**23.76**	**9.11**	**40.34**

Table 3.3: The electricity demand (except for hot water, which is heat) for all 14 thermal zones of the wind-mill building for an indoor temperature of 22°C.

Thermal zone	Lights [kWh/m^2]	Electric Equipment [kWh/m^2]	Electricity [kWh/m^2]	Hot Water Demand [kWh/m^2]	Fan [kWh/m^2]	Heating [kWh/m^2]	Cooling [kWh/m^2]	Space Heating/Cooling [kWh/m^2]
F1A	9.88	22.33	32.22	25.5	2.10	0.17	2.41	4.67
F1S	44.97	14.40	59.37	12.8	7.40	114.81	8.23	130.44
F2A	9.47	22.33	31.81	25.5	2.68	0.01	3.45	6.14
F2S	44.90	14.40	59.30	12.8	7.33	112.52	8.27	128.12
F3A	7.57	22.33	29.90	25.5	3.62	0.01	4.97	8.60
F3O	30.69	41.90	72.59	12.8	5.58	0.73	5.16	11.47
F4A1	8.66	22.33	30.99	25.5	4.82	0.00	6.86	11.68
F4A2	9.02	22.33	31.35	25.5	4.27	0.07	6.15	10.50
F4O	30.64	41.90	72.54	12.8	5.53	0.73	5.14	11.40
F5A	8.93	22.33	31.26	25.5	4.75	0.02	6.82	11.59
F5O	30.65	41.90	72.55	12.8	5.30	0.69	5.06	11.05
F6A	8.47	22.33	30.80	25.5	6.85	0.03	10.40	17.28
F7A	8.00	22.33	30.33	25.5	13.21	0.33	19.67	33.21
F8A	7.37	22.33	29.70	25.5	34.16	3.96	49.75	87.88
Average	**23.18**	**23.79**	**46.97**	**19.2**	**5.51**	**32.31**	**6.65**	**44.46**

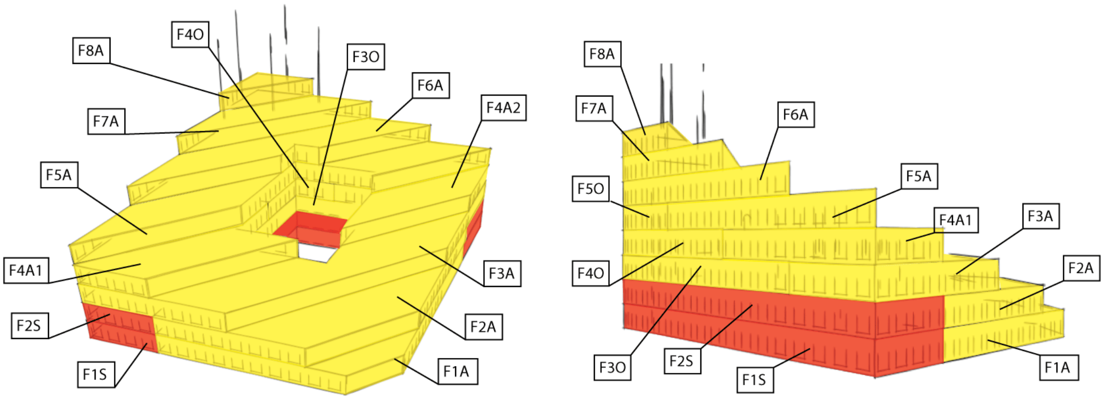

Figure 3.8: The heating demand for the wind-mill building per thermal zone.

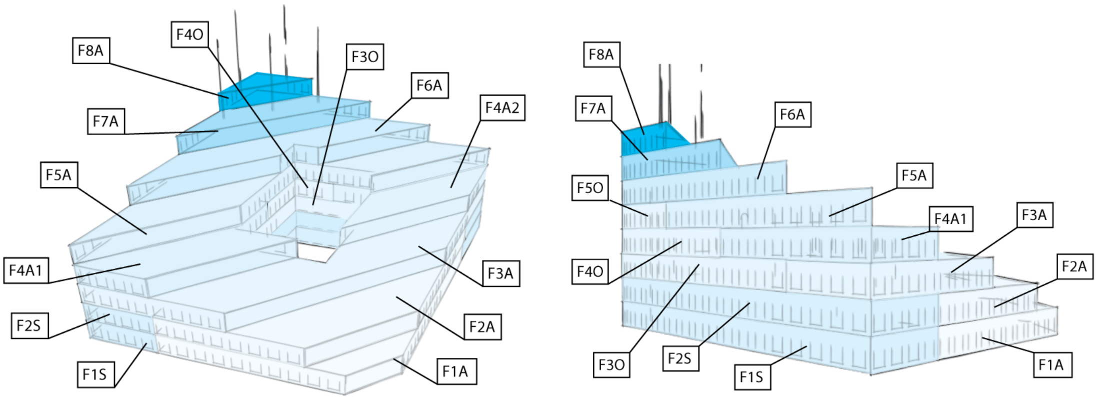

Figure 3.9: The cooling demand for the wind-mill building per thermal zone.

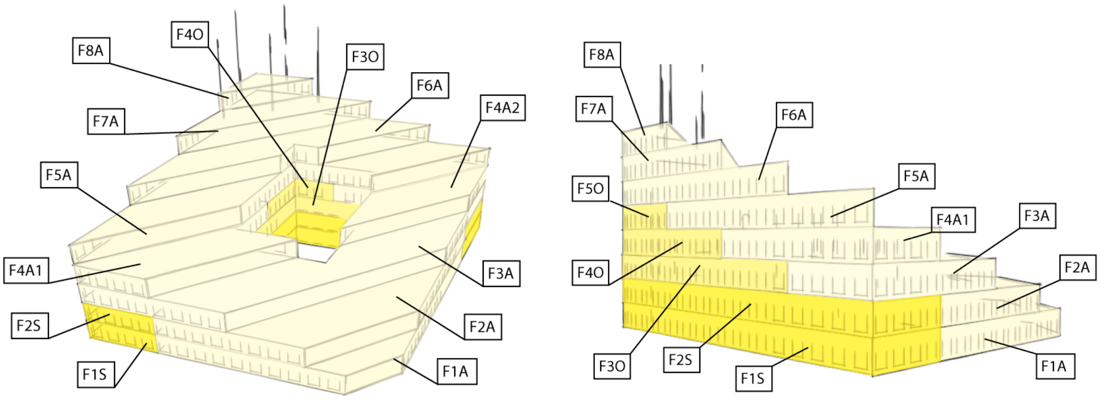

Figure 3.10: The lighting demand for the wind-mill building per thermal zone.

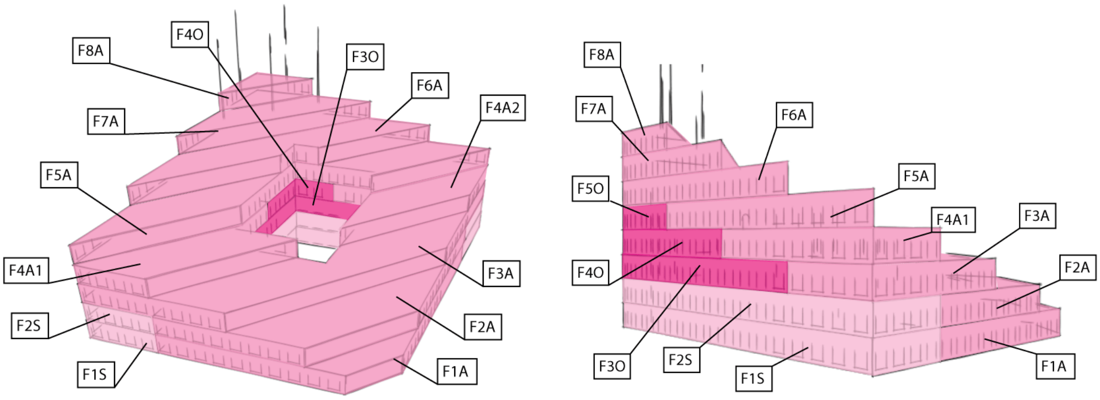

Figure 3.11: The equipment demand for the wind-mill building per thermal zone.

4. Energy supply of the multifunctional building

In this chapter the energy supply for the multifunctional building will be calculated. In the original plan for the complete Sustainable City, wind power (section 4.1) and solar power (section 4.2) were included, which can be directly applied and attached on the building itself. Both wave power (section 4.3) and municipal waste energy (section 4.4) will be assessed too, although their energy supply holds for the Sustainable City as a whole and not just for one building in specific.

4.1 Wind energy

To determine the possible wind energy generation this section will start with describing and analyzing how the wind site looks like and what kind of wind turbines could be used. After that, a yearly model (in Matlab/Simulink) for one wind turbine will be given in subsection 4.1.3. Finally, an estimation of the energy supplied by the windmills for the multifunctional building will be made.

4.1.1 The wind site

An evaluation of the wind site is necessary, since the occurring wind speeds largely determine the possible energy supply. Wind data at the spot is unfortunately not available, but the local energy company Göteborg Energi was able to provide data from a wind site at a 40 meter height located at Risholmen, the harbour outside of Göteborg.

Although the location of the SC is not located at the sea, but on the river, it will be assumed that the given data can be used to make an estimate for the generation of wind energy. The reason for this is the height of the wind data being similar to the height at which the windmills will be placed on the buildings.

The data provided is an average measurement for every hour of the day for a 10 year period from 2002 until present. For simplicity reasons the data in the year 2011 (i.e. 8760 measurements) will be used to process. The typical Weibull distribution of the wind speed in 2011 is shown in figure 4.1.

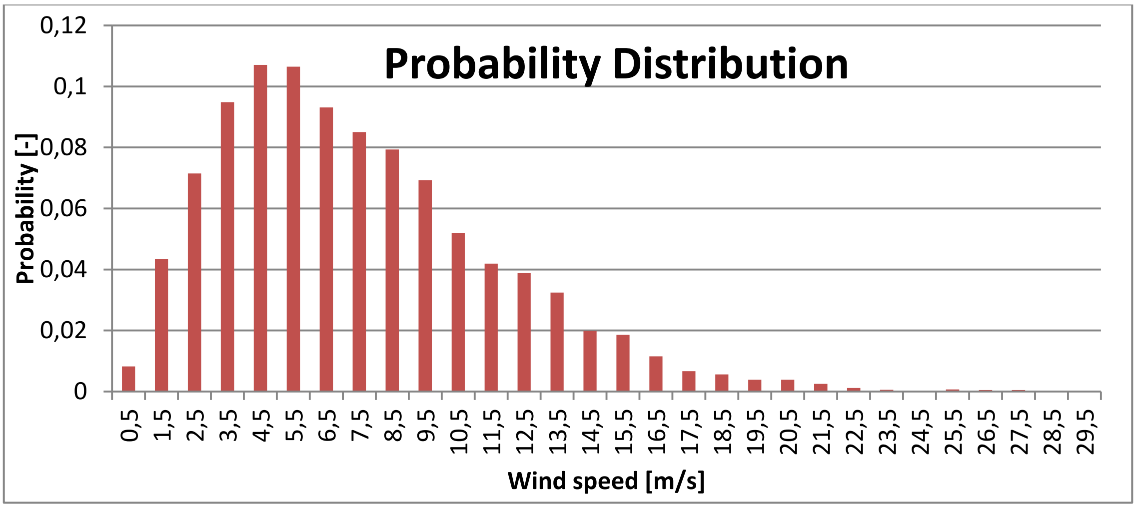

Figure 4.1: Weibull probability distribution of the wind speeds at the SC site at 40 meter height.

The average wind speed can be calculated to be 7.4648 m/s, which will be rounded off to 7.5 m/s for further convenience.

4.1.2 Two different wind turbines

The original plan of Super Sustainable included two types of wind turbines. The first type is an urban designed small wind turbine which is located on the roof of the buildings. The other is an airborne wind turbine, very much alike a kite, which is attached to the buildings. Both types will be discussed here.

ROOF LOCATED WIND TURBINE

In urban areas big turbines are not appreciated because of both the height and the noise pollution. But putting smaller wind turbines on the ground will not have any effect, because of the wind being blocked by buildings. Next to that, wind conditions are different: lower average wind speeds and high turbulence levels (Mertens, 2002). The most logical option seems to put wind turbines on the roof.

According to Mertens (2002) especially vertical axis wind turbines (VAWT) show to have a benefit from the wind conditions on the roof. This results from the fact that the wind flow is separating at the leading roof edge, which will allow a flow to continue in an angle of 45 degrees with the horizontal roof. For normal horizontal axis wind turbines this leads to stalling, whereas for VAWT this gives a 20% benefit compared to normal on ground conditions. Furthermore has the VAWT the advantage of wind direction independence, such that it does not need to be positioned in the wind (like a HAWT).

Figure 4.2: An example of an H-Darrieus turbine: the UGE-4K © 2012 Urban Green Energy.

This led to the development of so called H-Darrieus turbines in the last decade (see for an example figure 4.2). An overview of the most important commercial turbines of this type are shown in table 4.1 (data from the manufacturers: Turby (2006), Quiet Revolution (2011) and Urban Green Energy (2011), respectively).

Table 4.1: Specifications of commercial H-Darrieus turbines.

	Turby	**QR5**	**UGE-4K**
Annual Energy [kWh]	3500 (at 14 m/s)	12,729(at 7 m/s)	11,000 at (7.5 m/s)
Diameter [m]	2.0	3.1	3.0
Height [m]	8.9	11	10.6
Swept area [m^2]	10.87	15.5	13.8

AIRBORNE WIND TURBINE

The second type of turbine being proposed is an airborne wind turbine. This specific wind mill is still very much in its initial phase of development, but it is mainly envisioned as a kite like wind turbine. In some cases it is hovering in the air by means of helium (an example given in figure 4.3), in others the wind keeps the kite naturally in the air.

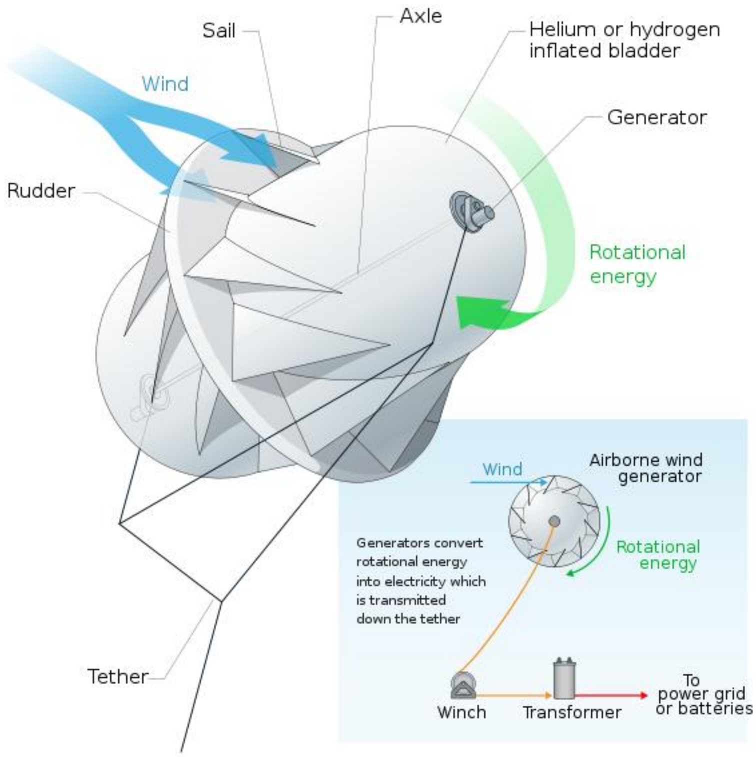

Figure 4.3: An example of an airborne wind turbine © 2008 James Provost.

O'Gairbhit (2009) states that a kite-based system is favoured compared to terrestrial wind-turbines because of lower production energy and lower cost per MWh. This is mainly due to a high capacity factor (more wind at higher altitudes) and thus more wind-energy to be gained.

4.1.3 The energy production of UGE-4K

In order to be able to make an estimate for how much wind energy can be produced per year, day and hour, some steps need to be taken. In the first place it needs to be decided which kind of turbine is used. As results from the last section the kite based turbine would not be relevant for making any calculations, such that for further purposes it will be neglected. Concerning the roof based turbine, the QR5 looks most preferable at an average annual wind speed of 7 m/s (table 4.1) and most probably also at 7.5 m/s. However, for computations the UGE-4K design will be used, which is fairly close, since the most technical data is available for this turbine, such that a realistic hourly estimate can be made.

Wind energy calculations start with the (electrical) wind power formula (such as in Manwell et al, 2002):

– [8]

Where C_p is the power coefficient (theoretically 16/27 ≈ 0.59 according to Betz' Law; practically 0.4-0.5), η_m and η_g are the mechanical and generator efficiency, ρ is assumed to be constant (1.225 kg/m^3 at 15°C and 1 atm), A is the wind turbine blade area (m^2) and v is the wind speed (m/s).

Urban Green Energy shows both the power curve (figure 4.4) and the annual production curve (figure 4.5) for the UGE-4K on their website. This allows for making instantaneous estimates of the wind power.

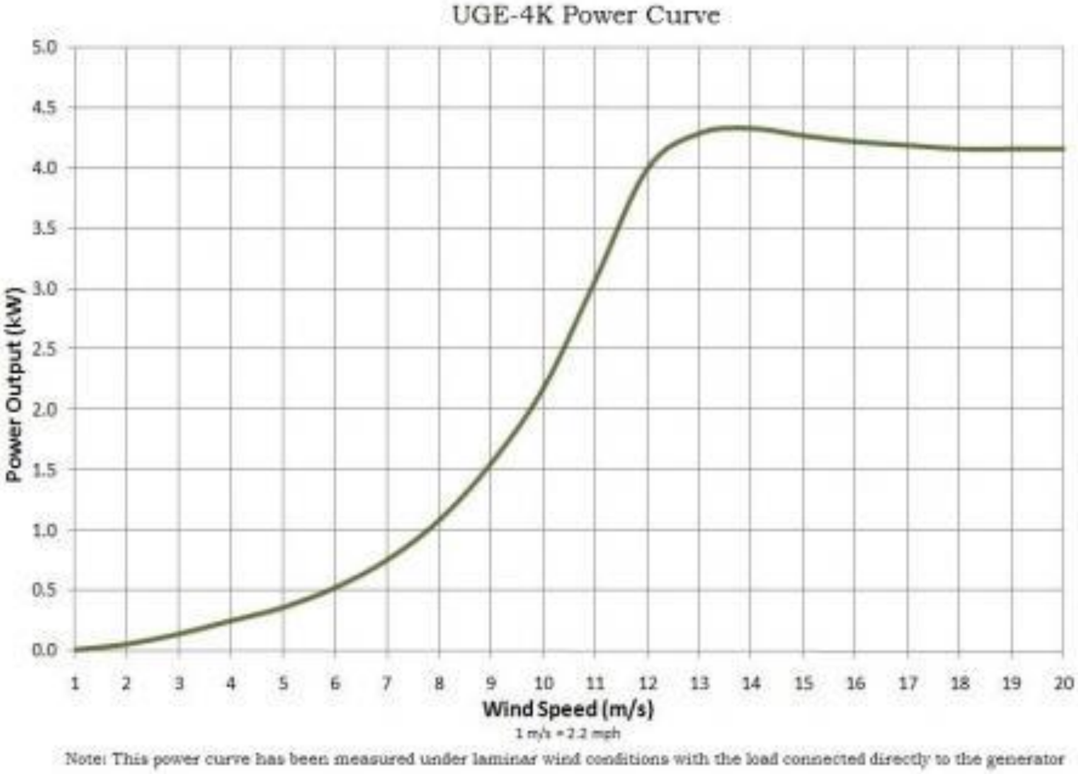

Figure 4.4: UGE-4K's power curve, net power output as a function of wind speed © 2011 Urban Green Energy.

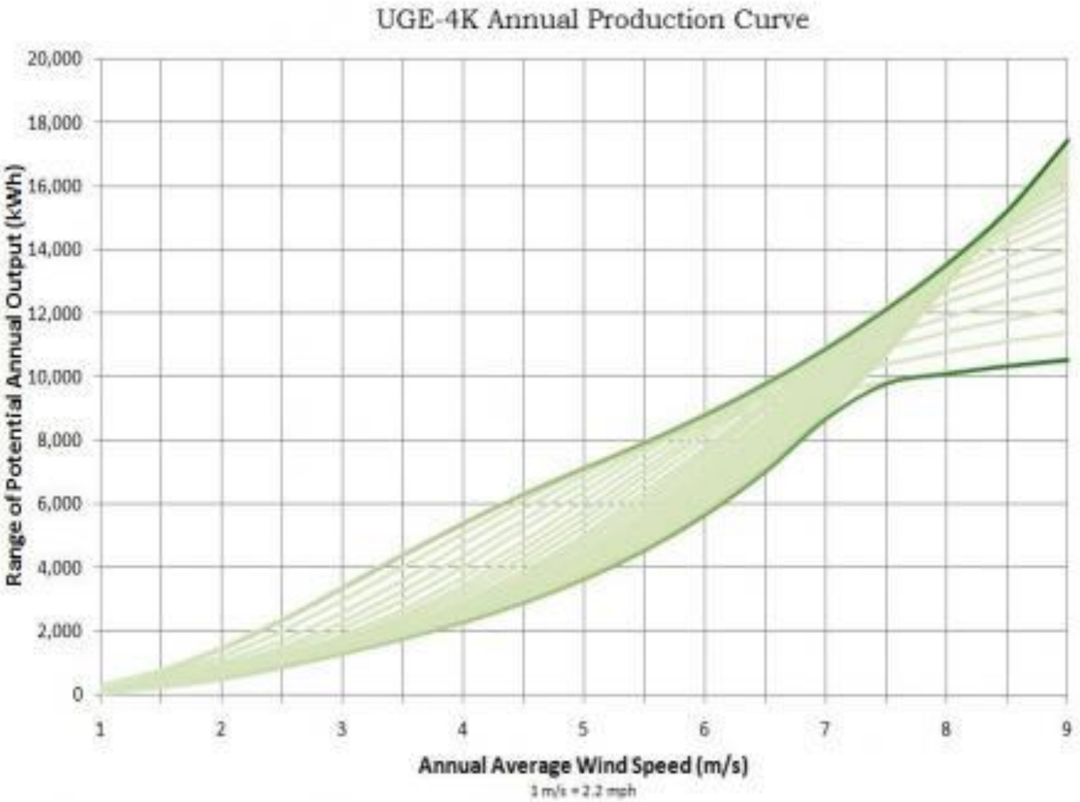

Figure 4.5: UGE-4K's annual production curve, potential annual energy output as a function of annual average wind speed © 2011 Urban Green Energy.

In equation [8] the values for C_p, η_m and η_g are unknown and for convenience will be gathered as the 'general' efficiency η_0. The constant ½, the values for ρ (constant) and A (13.8 m^2, see table 4.1) are known and the wind speed v is the variable: these will be gathered as the power in the wind P_w, such that the eloquent equation [9] arises:

[9]

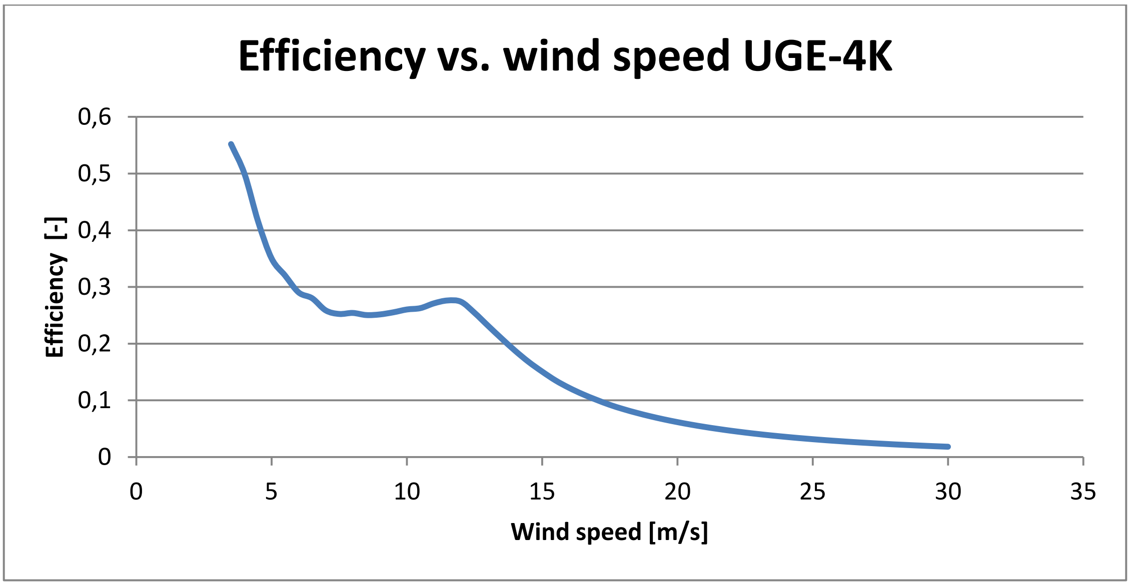

Figure 4.6: Efficiency as a function of wind speed for UGE-4K.

The efficiency η_0 is a difficult to determine value and is strongly wind speed dependent. However, with the (rated) power curve in figure 4.4 equal to P_e and being able to calculate P_w, it is possible to make a good estimate for the efficiency for a range of wind speeds. The wind speed data of the SC site runs approximately until 30 m/s, such that in figure 4.6 calculated efficiencies up to 30 m/s are given. It is assumed that the rated power of the turbine remains constant at 4.17 kW up to 30 m/s (a typical asset of wind turbines), which is also the cut-out wind speed for this turbine.

At this point one can compute the hourly production of wind energy. As mentioned before, a model in Matlab/Simulink has been made. The model part, where the wind energy is calculated looks like figure 4.7, which is essentially a representation of equations [8] and [9].

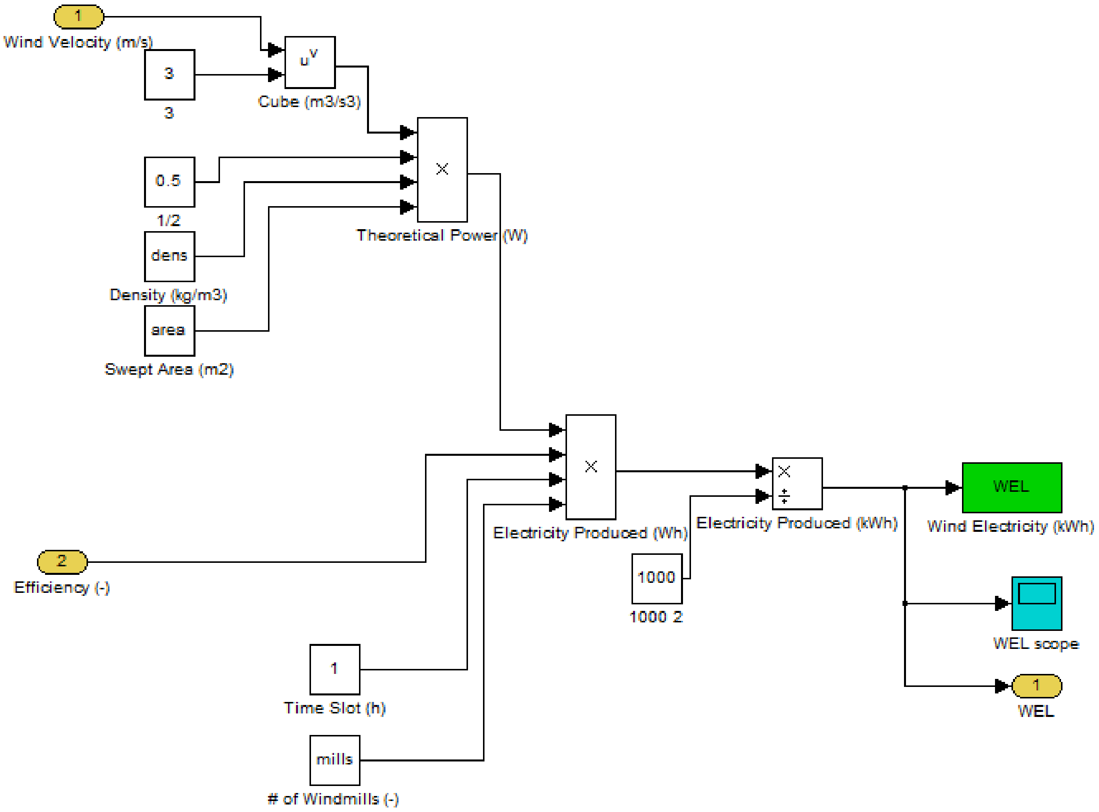

Figure 4.7: The wind energy model in Matlab/Simulink.

All the variables are known such that energy is simply calculated by:

[10]

Observe that in this case no capacity factor is needed, since the calculations are instantaneous and almost integral-like (steps of 1 hour). The hourly energy production of one windmill in one year is shown in figure 4.8.

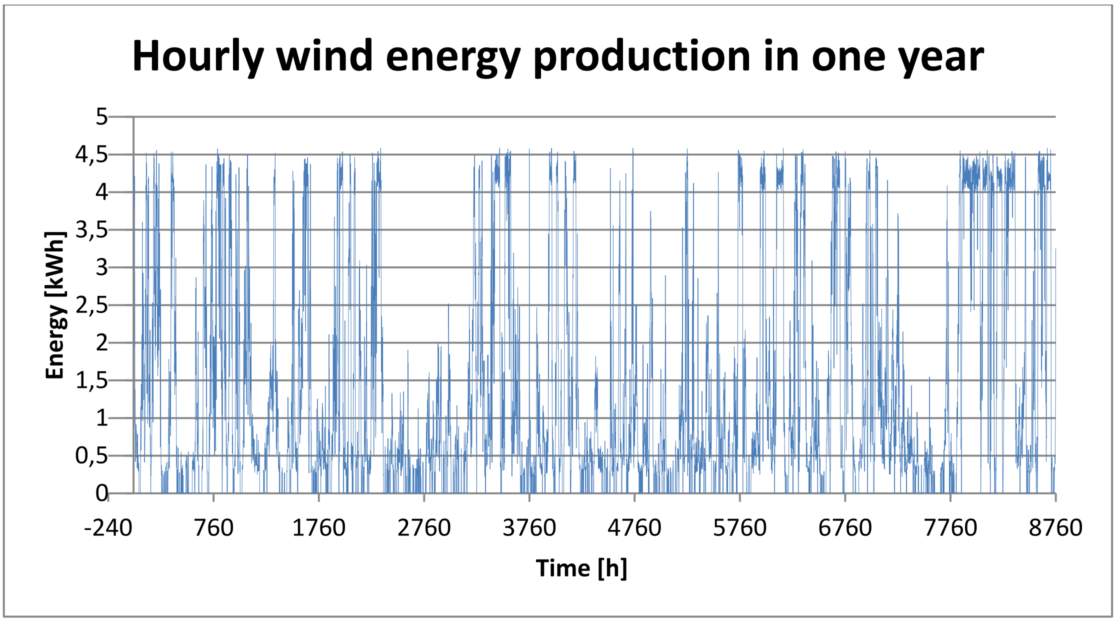

Figure 4.8: The hourly energy production in one year of the UGE-4K.

The summation of the energy (electricity) produced in one year for one UGE-4K wind turbine is 11,941 kWh (= 11.9 MWh). Comparing this with figure 4.5 it lies well in range of the manufacturer's estimation at 7.5 m/s.

4.1.4 Total wind energy production

The last step in the assessment of the wind energy supply for the multifunctional building is to define the number of windmills. The placing of the wind turbines on the building is an important aspect. According to the producer of the QR5 (Quiet Revolution, 2011) VAWT's cannot be located within 3 diameters (in this case 9.0 meters) of each other. Next to that the specified document of Turby (2006) tells us, that the turbines should stay above the top of the roofs for at least 2.5-3 meters.

Another fact is that for the H-Darrieus turbines to be mounted on the roof, a tripod mounting is used, since no deep excavation can be allowed. It implies that the maximum height of the mast can be 6 meters. With all these limitations it is clear from the close-ups in figure 4.9 and figure 4.10 that 6 windmills can be installed on the top of the multifunctional building.

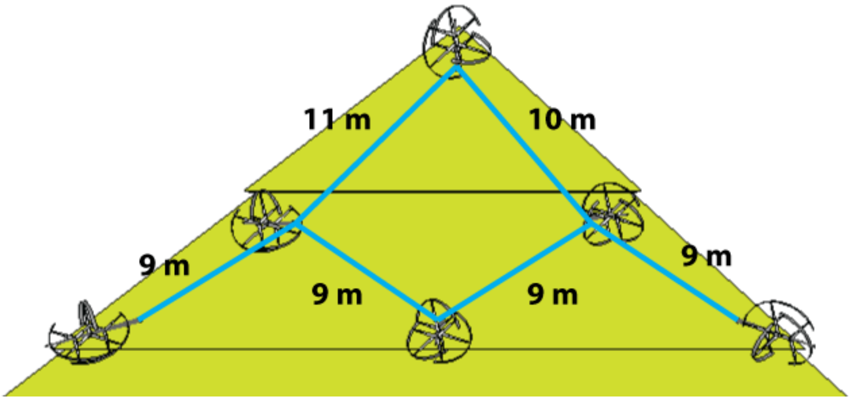

Figure 4.9: The distance between the 6 windmills on top of the multifunctional building.

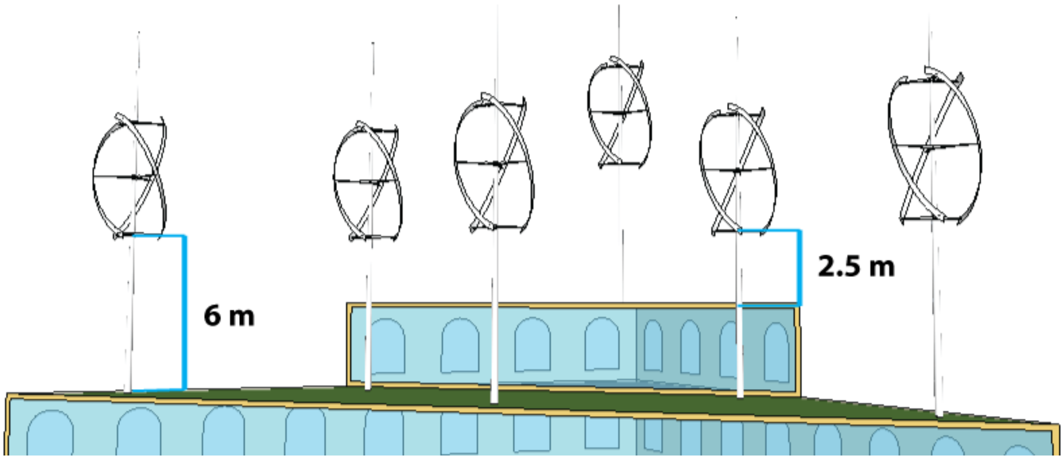

Figure 4.10: The distance in height between the roof of F7A or F8A and the windmills.

Although more wind mills could be placed on the roofs of the floors 1 through 6, these wind mills would not function as efficient as possible as the ones on the roofs of the floors 7 and 8. This is due to the fact that the building itself, but also the surrounding buildings will block the wind and thus disturb the flow. Although a wind model should prove if the lower positioned wind mills are indeed less effective, it will be based on Turby (2006) that 6 wind mills is the optimal solution. The total annual sum of wind based electricity, which the multifunctional building can produce, is thus computed to be $6 \cdot 11.9 = 71.6$ MWh.

4.2 Solar energy

In this section the solar power possibilities for the multifunctional building will be researched. As a start, the sun radiation in Göteborg will be analysed. In subsection 4.2.2 the used type of solar panel will be discussed, such that the output of the panel area can be estimated. Finally, the amount of solar energy produced on the roofs of the multifunctional building will be calculated.

4.2.1 Sun in Göteborg

According to Quaschning (2003) the global solar irradiance I_G that is falling on a horizontal surface on the earth is composed of a horizontal direct solar irradiance component I_{DIR} and a horizontal diffuse solar irradiance component I_{DIF} as seen in formula [11]:

[11]

If one would design for a horizontal solar panel the acquisition of the global solar irradiance data is sufficient to calculate the energy production. In Sweden this data can be easily accessed via the website of the Swedish Meteorological and Hydrological Institute (SMHI). The data is based on a model including statistical clouding and is available for locations within whole Scandinavia, such that it can be beneficially used within this thesis.

In order to be consistent with the wind data, the year 2011 is chosen for the coordinates of the Sustainable City site (57.70°N, 11.97°E). The values are instantaneous and hourly, such that 8760 data points in the year 2011 were acquired (see figure 4.11). The total energy per meter squared for 2011 then amounts to 907.80 kWh.

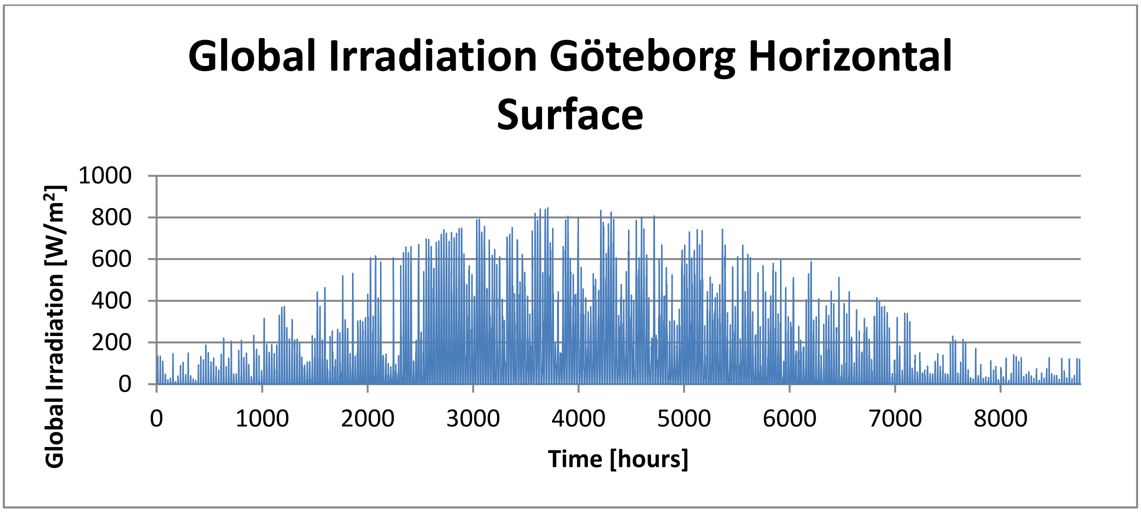

Figure 4.11: Global Irradiation at the SC for a horizontal surface.

Initially it was intended to use panels that move by solar tracking to increase the input from the sun. The calculation has been performed in Appendix A and it is indeed true that a 50.7% increase can be reached in Göteborg amounting to 1368.07 kWh/m^2 of global irradiation.

Nevertheless does this increase not make up for the loss of potential solar area on top of the multifunctional building. On the one hand, effective area is lost, because of the movement of the solar panels. The solar panel which is introduced in the next section (SunPower, 2011) has a typical size of 1.046 meters high and 1.559 meters wide. It would mean that at least a square of 1.559x1.559 should be kept free for the panel to manoeuvre in without any obstacles. The effective used roof area is therefore $(1.046 \cdot 1.559) / (1.559 \cdot 1.559) = 0.671$ times smaller. A simple calculation learns that $1.507 \cdot 0.671 \approx 1$, such that the solar tracking effect is already cancelled out.

The other contribution to the loss of effective solar area is caused by solar panels sun blocking other solar panels, because of series/parallel placement. This is especially the case for lower sun angles (in winter), such that either the designated area for a solar panel has to be increased, or it should be accepted that not all of the panels get their full amount of sun light. Obviously, this is also an unwanted drawback of having tilted surface, making the choice for horizontal fixed solar panels more justified.

4.2.2 Solar panel choice and its production

The most commonly produced material for PV panels is c-Si or crystalline silicon (Kalogirou, 2009). It is also the type of cell which has been researched the most in the academic world. This makes trustable and accurate estimations of the solar energy output possible.

A recent paper has been developed by Huld et al. (2011) where the performance of a generic crystalline silicon photovoltaic module is modelled. They claim that it is a model in which the average PV buyer is able to calculate the output with both the temperature and the irradiance.

Huld et al. (2011) put the following equation forward for solar power:

[12]

Where G' is the relative irradiance, which is the ratio G/G_{STC} of the actual global irradiance over the global irradiance at Standard Test Conditions (which is 1000 W/m^2) and where T' is the relative temperature, which is the temperature of the module T_{mod} subtracted by the temperature of a model at STC (which is 25°C). Furthermore are the coefficients k_1 through k_6 dependent on the PV module chosen, as is $P_{STC,m}$, which is the module power at the maximum power point (MPP).

Green et al. (2011) is listing the highest efficiencies confirmed for PV cells and modules every six months. In their latest report a crystalline silicon PV module of SunPower has the characteristics shown in table 4.2.

Table 4.2: Characteristics of the SunPower crystalline silicon PV module based on Green et al. (2011).

	SunPower
Efficiency [%]	21.4±0.6
Area of the aperture [m^2]	1.5780
V_{OC}, Open Circuit Voltage [V]	68.6
I_{SC}, Short Circuit Current [A]	6.293
Fill Factor [-]	0.784

The actual module power can be computed using Kalogirou (2009):

[13]

Using the values in table 4.2, P_{max} is computed to be 338.5 Watt. This is however for a module with the size of 1.5780 m^2 such that the Sun power PV module has a maximum power (MPP) of $P_{STC,m}$ = 214.5 W/m^2.

The values for the coefficients k_1 through k_6 are given in the paper of Huld et al., although they are presented in a relative form k_i'. This means that with the conversion $k_i = k_i' \cdot P_{STC,m}$ the module specific coefficients are formulated (since $P_{STC,m}'$ is set to 1). The values of k_1 through k_6 are given in table 4.3.

Table 4.3: The coefficients k_1 through k_6 for the SunPower crystalline silicon PV module based on Green et al. (2011).

Constant	k_1	k_2	k_3	k_4	k_5	k_6
Value	-3.70	-8.68	-1.01	0.0320	0.0315	0.00107

The last value which needs to be addressed before a Matlab/Simulink model can be set up is the module temperature T_{mod}. Because this data is not directly available, it has to be estimated. Huld et al. show that they do this with a simple linear relation:

[14]

The constant k_T is has a value of between 0.03 and 0.035 °Cm^{2}W^{-1}. Although Huld et al. chose for the upper limit, I will choose for the lower limit of the constant, which is 0.03. They explain that for windy conditions (and thus the lower value) a cooling effect of the module will occur, which is quite applicable on the site of the Sustainable City.

Obviously the ambient temperature is now a variable, which is unknown, but which can be retrieved. Again no data for the Sustainable City site itself is available, so compromises will have to be made. It is the American National Weather Service that has a measurement point at the airport of Säve, which is located some 12 kilometers out of the city centre. It is assumed this will represent the actual temperature in the city, although urban temperatures are mostly slightly higher than rural temperatures. This is however balanced by the open landscape of the river, where the wind can play around.

The NWS measured the temperature every half an hour, but there are some handicaps to the data. Some measurement points are not included, in few occasions the temperature is taken at irregular times and the data is in absolute values. The set has therefore been modified to an hourly average and is interpolated where necessary.

With the above a model has been created, which can be seen in figure 4.13. Using only the horizontal Global Radiation and the ambient temperature, the output is the hourly energy of the Sun Power PV module. This is done similar to equation [10], with a semi-integral:

[15]

The resulting hourly solar energy production per square meter in one year is shown in figure 4.12.

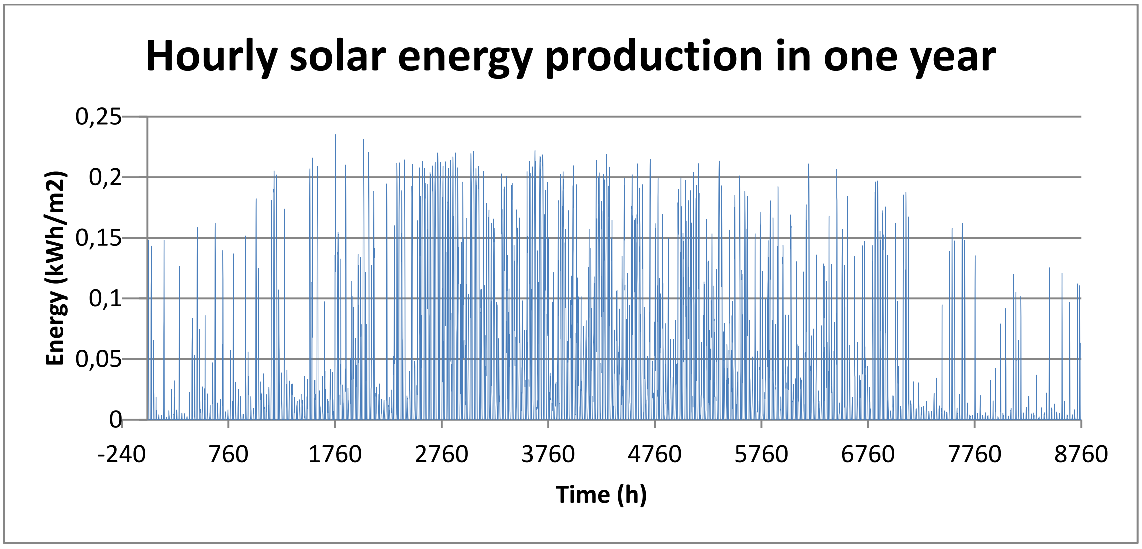

Figure 4.12: Hourly energy production in one year of the SunPower PV module.

The summation of the energy (electricity) produced in one year for a square meter Sunpower PV module is 182.47 kWh/m^2. Comparing this with the possible global irradiance on a horizontal surface (which is 907.80 kWh/m^2) it is a remarkable efficiency of 20.1%, but still lower than in table 4.2.

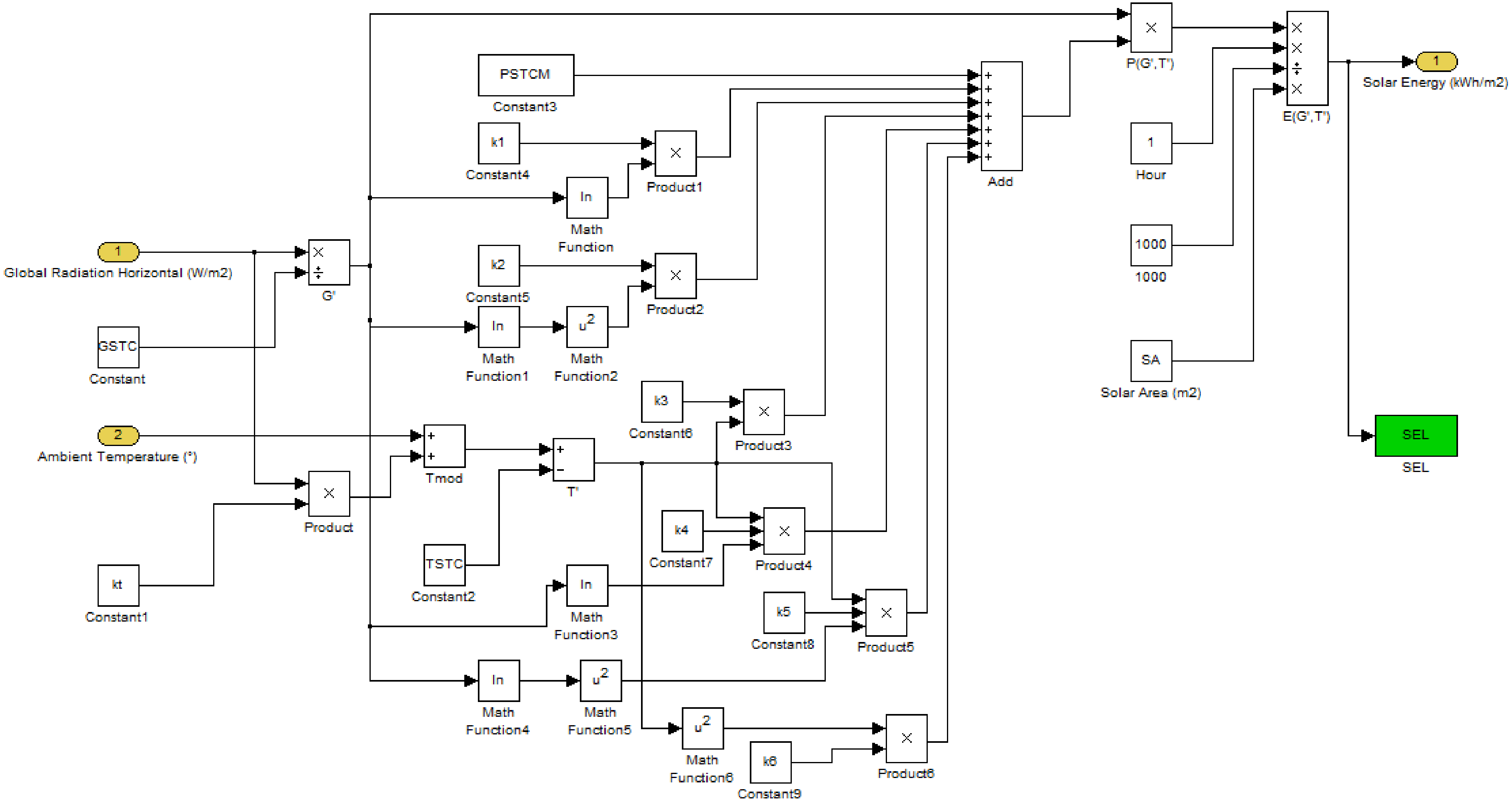

Figure 4.13: Solar energy calculation in Matlab/Simulink according to Huld et al. (2011) using Global Radiation and Ambient Temperature.

4.2.3 Total solar area energy production

The placement of the solar panels is the last step in determining the solar production capabilities of the multifunctional building. It is however a very important step, since it not only determines the roof lay-out, but also how much solar energy can actually be gained on the roof area. Theoretically the roof area has been computed to be 2,149 m^2. This refers to all the green area that is visible in figure 2.7. But practically, filling up this whole space is not desirable and economically unwise.

Firstly, it is not desirable from an inhabitant point of view. If the complete balcony is occupied by solar panels, there is no possible way to perform urban farming or to enjoy leisure time, as was in the original plan of Super Sustainable. Although no room will be kept free for this now, it is an important comment to keep in mind. Above all, the presence of 6 windmills will imply that 6 mounting areas will have to be kept free. According to the producer Quiet Revolution (2011) a rough 3 by 3 meters area should be kept free for placements on roofs. It means that 2,149 – 54 = 2,095 m^2 of effective area is left.

Secondly, it would be economically unwise to set up solar panels on the lower floors of the multifunctional building. As can be seen from figure 4.14 and figure 4.15 large parts of the building are overcast by the building(s) in front of it, taken that the situation in this particular case is at noon on the 21st of December. Moreover, at other times of the day the situation is even worse, since the sun is at a lower angle.

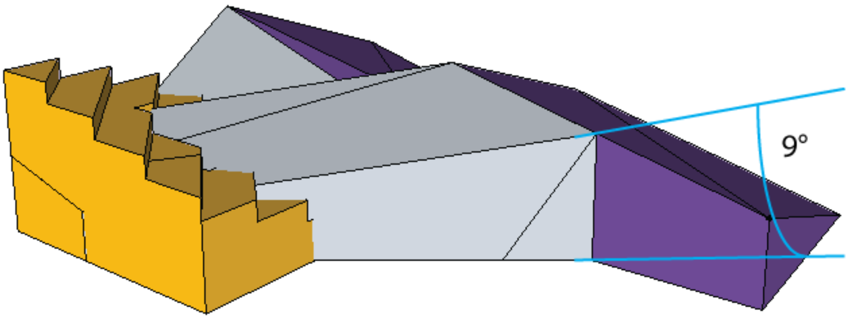

Figure 4.14: There is a 9 degree maximum sun angle at noon on the 21st of December causing partly shadows (grey parts) on the multifunctional building.

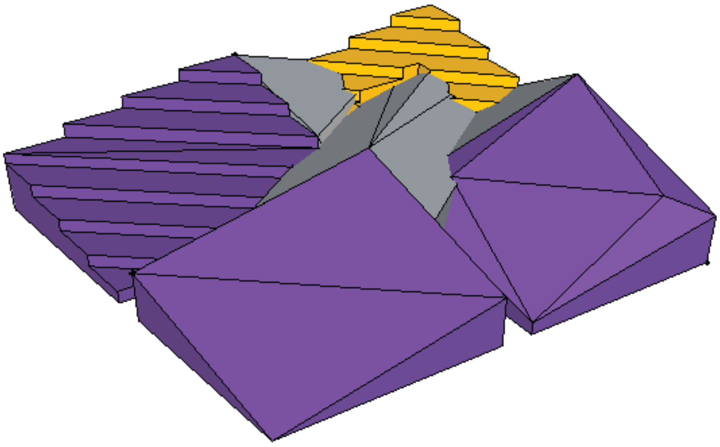

Figure 4.15: At noon on the 21st of December the multifunctional building is overcast by more than 50% by the three buildings in front (where grey resembles the shadows).

The last remark brings up two observations. Either the plan of Super Sustainable should be reconsidered in positioning the buildings further apart from each other, not blocking any useful sun. Or, there should be made an estimation of the area of the building being theoretically lit (that is, not overcast by shadow), in order to obtain a fair number for the solar energy being produced. Since the first option would mean severe adaptations, the second option will be investigated for now, although aware of a non-profitable energy per m^2 of solar panel ratio.

Since making an accurate calculation of where the sun would exactly shine is too time-consuming within this thesis, an educated guess is performed. It will be assumed that the area being lit at noon varies according to the daily maximum sun elevation angle (obtained in Appendix A) from 918.14 m^2 (21st of December) until 2,095 m^2 (21st of June, since it is practically the whole solar area available), which is visualised by figure 4.16. Furthermore, during the day, the area being lit varies from 0 m^2 at sunrise until 0 m^2 at sunset, reaching the maximum at noon, also following the hourly sun elevation angle, see figure 4.17.

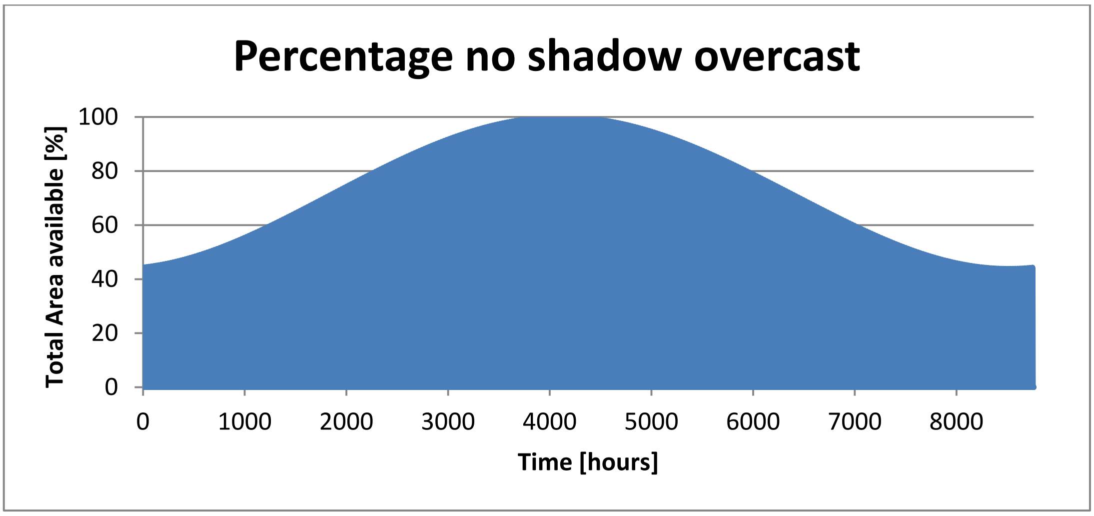

Figure 4.16: The total available solar area (in percentage) as a function of time (hours) due to the shadow overcast of other buildings – complete year.

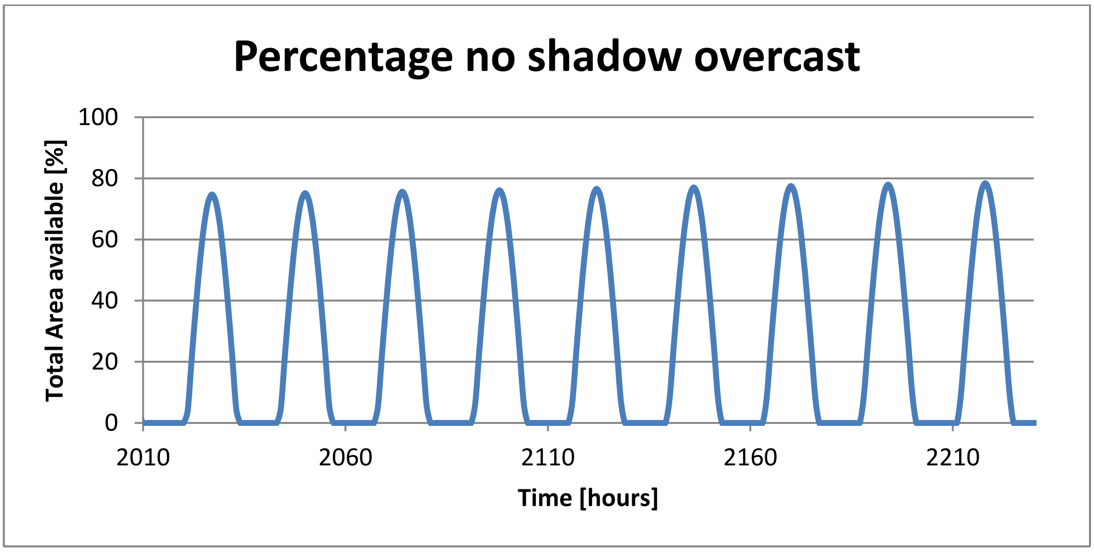

Figure 4.17: The total available solar area (in percentage) as a function of time (hours) due to the shadow overcast of other buildings – zoom-in to 26th of March until 3rd of April.

As a conclusion, it is assumed that 2,095 m^2 of solar panel area is installed on the multifunctional building. Not all of that area can be continuously used, due to shadow overcast according to the function in figure 4.16 and 4.17. Combined with the hourly solar energy production m^2/year an annual electricity production of 248.96 MWh can be obtained.

4.3 Municipal waste energy

At this point in time no waste from residences, offices and shops is fully recyclable, which means municipal waste still has to be either landfilled or incinerated. The Nordic countries have a good reputation of making use of the heat generated through incineration because of their district heating systems. At the same time Scandinavia tries to keep the amount of garbage put in the earth as low as possible. In this chapter the possible generation of both heat and electricity will be estimated, which is created by the waste coming from the windmill building. This is done by first making an overview of the waste situation in Sweden in subsection 4.3.1, such that the useful energy produced is estimated in subsection 4.3.2.

4.3.1 Sweden and waste

Sweden is one of the best performing countries in the world concerning waste treatment. Although according to Eurostat (2011) the amount of garbage produced is not low (485 kg/person in 2009) it treats almost all: 480 kg/person. It should be noted that within this value the waste produced in (amongst others) offices and shops is included, although industrial waste is excluded (Swedish Environmental Protection Agency, 2005). Above all has Sweden an impressive incineration and recycling rate, as seen in table 4.4.

Table 4.4: Municipal Waste Treatment Sweden in 2009 in weight and percentages.

	Landfilled	Incinerated	Recycled	Composted
Weight [kg/cap]	4.8	235.2	172.8	67.2
Weight [%]	1	49	36	14

In Sweden both electricity and heat are created when incinerating. According to Avfall Sverige (2007) of the 13.7 TWh of energy that was created in 2007 1.5 TWh (10.9%) became electricity and 12.2 TWh (89.1%) was used in the district heating systems. In that year 4.2 Mton of household waste was processed.

4.3.2 Waste energy output

Although the other energies in the sections before have been analysed per hour, it is quite difficult, almost impossible to determine the hourly energy output of municipal waste. On the one hand, the intake of waste is not instantaneous, nor is the incineration of the waste at the treatment plant, when the waste arrives. Nevertheless will the waste energy be considered as a base-load and thereby delivering a constant hourly production, in both electricity and heat.

Estimations will be made, using the values and fractions given in the last subsection as a guideline for future waste generation in the multifunctional building. Besides that, it will be assumed that 480 kg/person/year for 145 persons (see section 2.5) will create the total waste of the building, thereby also covering the waste produced in the offices and shops. It means that 480 kg/person/year · 145 persons = 69.6 ton of waste per year can be used. 4.2 Mton produces 13.7 TWh of energy, which is 3.26 MWh/ton, such that 69.6 ton/year produces 226.9 MWh of energy per year. This is equal to 202.2 MWh of heat (23 kWh/h) and 24.7 MWh of electricity (2.9 kWh/h) per year for the multifunctional building.

4.4 Wave energy

In the plan by Super Sustainable, the team of architects stated wave power could provide the Sustainable City with electricity at bad weather. Although such a production method does not coincide with the on-site energy production (Torcellini, et al., 2006) within this thesis, it will still be investigated, since it was in the original plan. To see if the assumption is valid, in this section the use of wave turbines will be researched. In the first place the river area will be analysed for wave behaviour (subsection 4.4.1), such that in subsection 4.4.2 wave energy production can be estimated.

4.4.1 The river behaviour

The Göta Älv is a water way with heavy transport. According to Göteborgs Hamn (2012) about 11,000 boats arrived into the harbour of Göteborg in 2011. Surprisingly or not, it is this coming and going of boats that dominates the wave pattern in the Göta Älv. Millet (2011) writes that on average wind can cause waves of maximum 0.3 meters for 90 hours per year. Next to that, the waves are mostly only seen at the long straight sections of the river.

It is Althage (2010) who discusses the wave production by ships entering the harbour. The ships create at maximum a wave of 0.6 meters, but on average for the 17 ships in his research this is 0.32 m (with 2.27 seconds wave period and 8.26 meter wave length) which last for about 20 seconds. The amount of hours of ship induced waves based on Göteborgs Hamn is thus 11,000 boats · 20 seconds / 60 seconds / 60 minutes = 61 hours.

4.4.2 Wave energy estimation

With the information in the last subsection a preliminary estimate can be made to investigate possible use of wave turbines in the Göta Älv. Herbich (2000) gives that the formula for regular waves looks like equation [16]:

[16]

Where J is the wave power per meter (W/m), ρ is the density of water (999.10 kg/m^3 at 15°C), H is the wave height and T is the wave period.

Looking at it in an optimistic way, which means that wind induced waves will be set equal to ship induced waves, gives the following result:

This would mean that per year 61+90 = 151 · 222.3 = 33.8 kWh/m could be produced. Many types of wave turbines are being developed (or have just been put on the market), but as an illustration of the calculation a wave turbine such as in figure 4.18 has been chosen. If this turbine would for example be 100 meter long (the river is circa 500 meter wide at the SC), it would then be able to create 3.4 MWh of energy.

Figure 4.18: Snake shaped wave turbine of Pelamis (2012) © 2012 Pelamis Wave Power.

Obviously efficiencies have not been taken into account (which are nowadays still difficult to know, seen the state of development of the technology). Capacity factors of wave turbines such as in figure 1 are said to be between 0.25-0.40, but this holds for water with continuous waves. According to the manufacturer Pelamis (2012) these capacity factors are also typically reached at sea depths of 50 meters and 2-10 kilometers from the coast.

Besides the uncertainties, the amount of energy produced with a hypothetical 100 meter wave turbine is already 3 times lower than a simple small wind turbine (as discussed in the wind energy chapter), which does not make it very cost-effective. It seems valid to say that various reasons add up to not include this technology in the energy balance of the Sustainable City.

5. Conclusion & discussion

In this final chapter the results so far will first be brought together. By doing this, an answer can be found to the question posed in the introduction of this Master thesis:

Is the multifunctional building within the plan of Super Sustainable for a Sustainable City in Göteborg an example of a zero net-energy building?

As has been noted from both chapter 3 and 4, two types of energy are relevant for the multifunctional building. On the demand side a certain amount of heat is requested for hot water and electricity is needed both for space heating/cooling and for lighting and electrical appliances. There has also been made a difference between two different operating temperatures (20°C and 22°C), however for further discussion in this chapter the results for 20°C will be used, since there is not much difference in the total analysis between the two temperatures, when compared with the energy supply.

On the supply side both the sun and the wind produce electricity, whereas municipal waste is able to deliver both heat (89.1%) and electricity (10.9%). This makes it legitimate to present the results in two ways: one part dedicated to heat, the other to electricity. An individual analysis of the two will in the end give a combined answer to the thesis' aim.

Besides the aim completion will a part of this chapter be dedicated to analysing the methodology applied within this thesis. It entails addressing the tools and calculations chosen and will propose improvements that can be made. Finally, recommendations will be given for further research.

5.1 Heat balance

The heat balance is a quite simple balance according to equation [17]:

[17]

Heat is not always needed in the multifunctional building, neither has it to be delivered in a maximum amount. The full amount of available waste heat is therefore only applied at peak loads of the energy demand for hot water. It results in the hourly heat balance for the multifunctional building in figure 5.1. In figure 5.2 a zoom-in of the first 500 hours of the year is shown as well (1st of January until 21st of January). Positive values stand for a deficit of heat, negative values stand for a surplus of heat.

It is clear from both figures that the multifunctional building will not be able to provide for its own energy demand for hot water. As a total, annually seen the deficit is 334.1 – 226.9 = 107.2 MWh. A number of reasons for why it is not able to be self-sufficient are applicable.

Firstly, the demand of the building might be too high. Literature has not been very explicit about the hot water demand and its schedules for both offices and shops. A more reasoned input by more researches for this demand

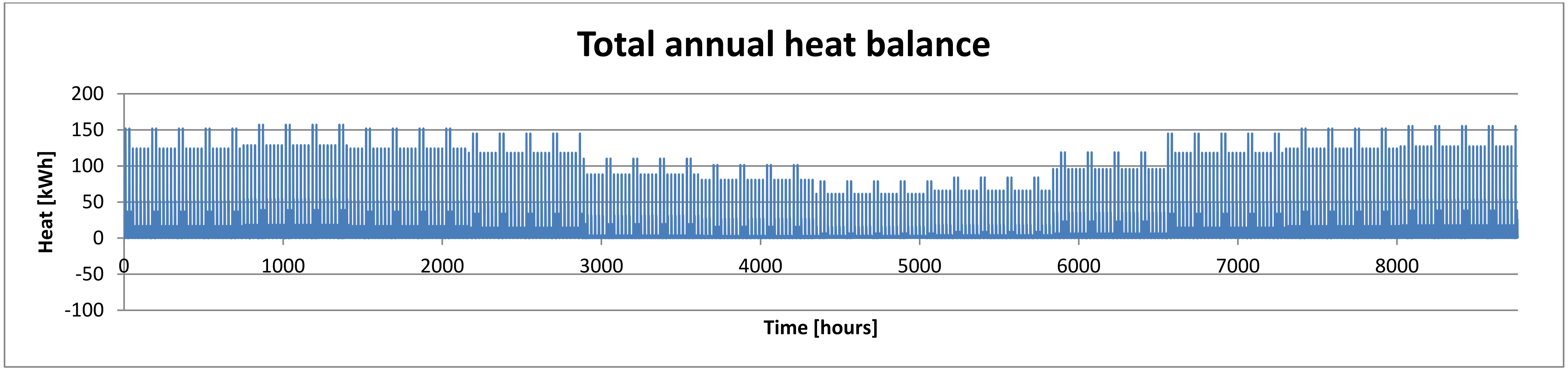

Figure 5.1: The total annual heat balance for the multifunctional building. Positive heat values stand for a deficit, negative heat values stand for a surplus.

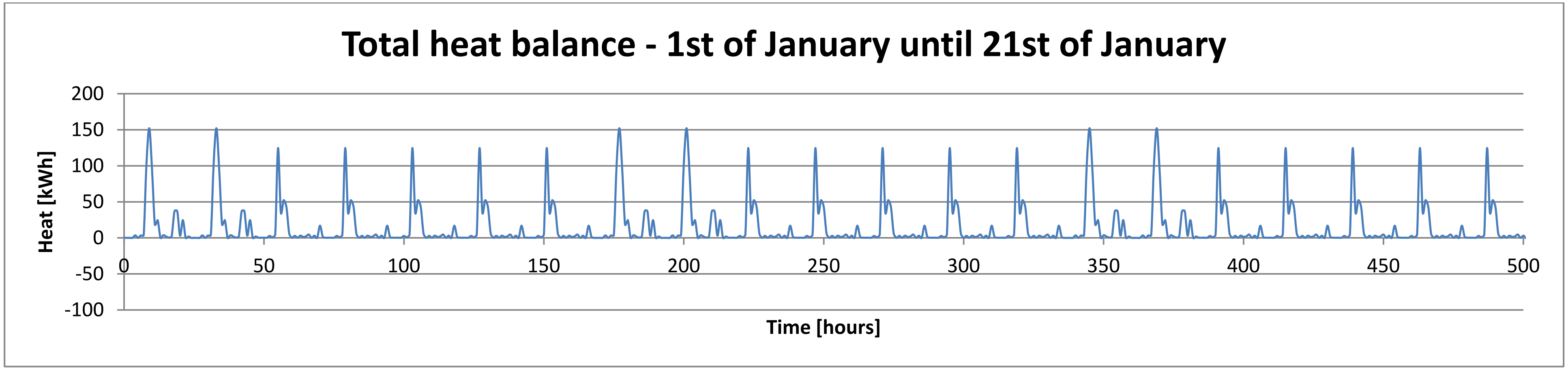

Figure 5.2: The total heat balance for the multifunctional building for the 1st of January until the 21st of January. Positive heat values stand for a deficit, negative heat values stand for a surplus.

would benefit the calculations. On the other hand, the value for apartments (25.5 kWh/m^2) is well within what is realistic (Wall, 2006). Marszal et al. (2011) claims however that a zero-energy building in Aalborg is able to diminish the hot water use to 14.4 kWh/m^2.

From the supply side not more energy from waste heat can be expected, since Swedish waste incineration is already at a high efficiency and the waste should only be coming from the people that live in the actual multifunctional building, to make it sustainable. One solution is to add solar thermal collectors to the building, which are able to warm up water, by putting flat plates on the roof. This technique could be very well researched within this thesis, however, installing thermal collectors would exchange place for PV panels, reducing the electricity production.

Another option would be to look more into the possibilities of geothermal energy. Cold water could be pumped into the ground, to be warmed up by the heat of the earth and arrive in the multifunctional building at the wanted temperature. Also this technique is viable and deserves further investigation.

5.2 Electricity balance

The electricity balance is slightly more advanced according to equation [18]:

[18]

In a similar way to figure 5.1 and 5.2, the total electricity balance is shown for the whole year in figure 5.3 and for the days 15th of April until 5sth of May in figure 5.4. Again, positive values stand for a deficit of electricity, negative values stand for a surplus of electricity. Waste electricity is only applied to reduce the peak loads of electricity.

Also figure 5.3 and 5.4 show that the multifunctional building is not able to take care of itself concerning energy. The annual deficit is 397.4 + 407.8 + 407.2 +156.1 + 128.1 – 249.0 – 71.6 – 24.7 = 1151.3 MWh, which is quite huge. Otherwise put, renewable energies are only able to cover 23.1% of the electricity demand. Also to understand this result, explanations can be given.

Firstly, the lighting demand is high, but this is mainly due to the lights in the shops. This statement is confirmed by Stensson et al. (2009) who analysed a shopping mall in Trollhättan, Sweden. They claim that 40-75% of the total energy use in Swedish and Norwegian shopping malls can be derived from lighting. Even more, in their model, Stensson et al. work with an annual mean of 37 W/m^2 of electricity determined for lighting, which is about three times as much as used within this thesis, therefore assuming an underestimation of the lighting use in the multifunctional building.

Concerning electric equipment the offices contribute the most to the high electricity demand. Poizaris et al. (2008) disproves this result however, since their research on an energy efficient office building in Göteborg itself only needs 21 kWh/m^2 compared to 41.90 kWh/m^2 (by applying energy efficient electric equipment). Space heating is considered the largest source for bought energy in this case: about 40% of the total energy use.

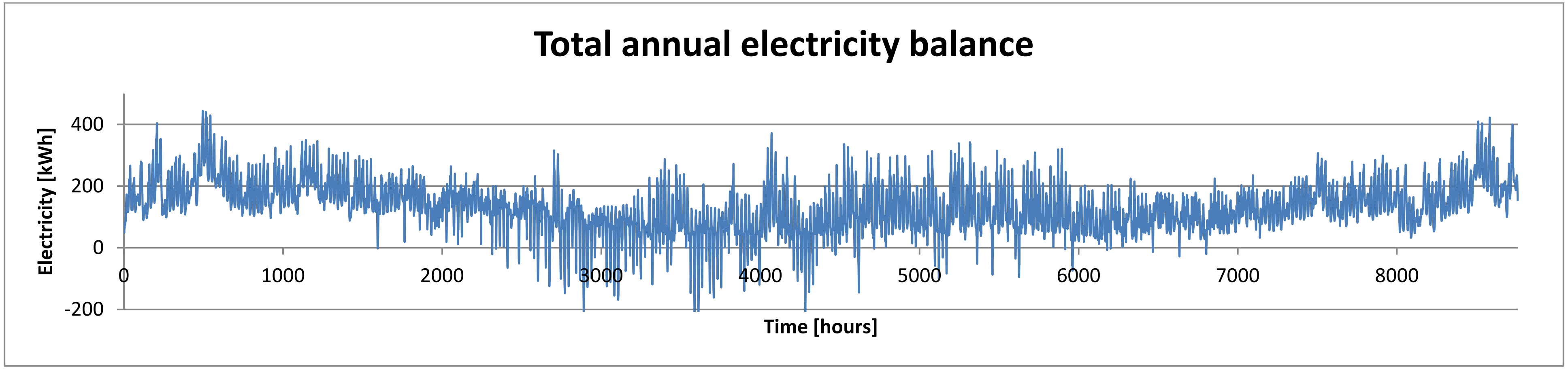

Figure 5.3: The total annual electricity balance for the multifunctional building. Positive heat values stand for a deficit, negative heat values stand for a surplus.

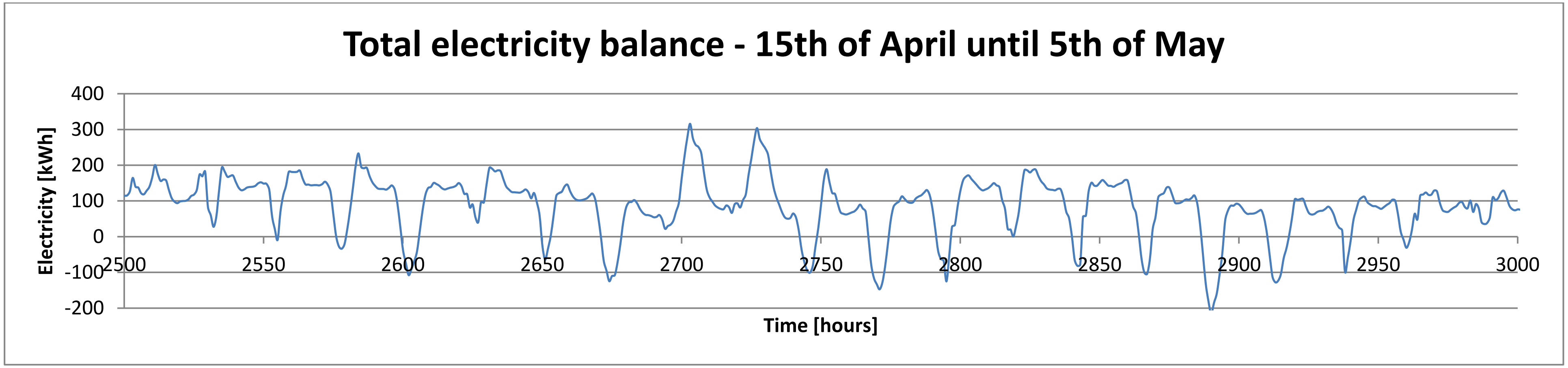

Figure 5.4: The total electricity balance for the multifunctional building for the 15th of April until the 5th of May. Positive heat values stand for a deficit, negative heat values stand for a surplus.

Finally the apartments have a combined lighting and electric appliance use of 31.2 kWh/m^2 which is similar to the findings of Wall (2006, i.e. 31.8 kWh/m^2). Marszal et al. (2011) claim to have found 15.0 kWh/m^2 for household electricity for the 60 apartments building, but Wall remarks that researchers tend to underestimate the household electricity use. All and all the overall lights and appliance electricity seems sound.

Concerning space heating the main electricity demand comes from the shops. That is to say, due to the high amount of people (13 times more than in an apartment) there is a high need for fresh air (new cold air has to be heated in winter) and there is a high infiltration rate because of people entering the shops. Stensson et al. (2009) uses however an about 3 times lower people occupancy (0.13 people/m^2 at the maximum) which brings down the combined space heating/cooling need to about 40-50 kWh/m^2.

The space cooling on the other hand is mostly a problem in the upper parts of the building, especially hitting the apartments. Due to the fact that the sun in summer time is always directed on these parts, it is a logical consequence. The energy model on the other hand did not take into account that sunlight is absorbed by PV panels on the roof, reducing the heat transfer into the building. Above all, shading of the windows was not included either, which according to Mlakar & Štrancar (2011) is one of the important solutions to limit overheating of a passive house. Improvements can certainly be made here, but compared to space heating, this is still of minor interest.

The use of fans finally is reasonable with its 7.5 kWh/m^2, in order to keep the heating/cooling and ventilation system going. Comparing this value with Wall (2006) no big difference is found (6.7 kWh/m^2).

As a main conclusion it can be said that it is difficult to get the demand side of the multifunctional building down, although more justification of the input used should be applied. But is it possible to get the renewable energy supply more up?

The solar energy is at its limit, seen the use of up-to-date solar panels. Although solar tracking (see Appendix A) would increase the output of the solar panel, shadow overcast and the manoeuvrability of the panel put the eventual output down. It would be an option too, to install solar panels on the upper west, south and east (vertical) sides of the building, but this is not as profitable as the ones on the roof. As said before, the only solution to increase the solar power output, is by locating the buildings within the plan of the Sustainable City further apart.

Concerning wind energy, no improvements can be done either. The maximum amount of wind mills is installed on the roof, which is limited by other buildings wind blocking wind mills on lower floors. Above all, the best wind mill technology available for buildings is used. Installing wind mills slightly more off-site, e.g. along the south-east water line of the Sustainable City would help improving the produced wind energy. The last renewable energy applied, waste energy, will not upgrade the electricity supply based on the same reasons mentioned in the heat section in this chapter.

To what extent could other techniques be used to produce electricity? Hydropower is an option which comes into mind, since the Sustainable City is built on a river. However, no height difference is overcome, which would highly increase the potential. Next to that, flooding becomes an unwanted risk, when the water flow is guided through a turbine.

The last two options are again earth related. The first does not create electricity: it lowers the space heating/cooling demand on the other hand. The multifunctional building would benefit from a seasonal thermal store, which is a storage of water underneath the ground. In wintertime hot water (replaced by cold water) is pumped from this storage room into the buildings, in order to lower the heating need by warming up the incoming air. In summertime the opposite is true: the cold water is pumped up from the storage room and cools the air of the buildings, at the same time by putting warm water (heated by solar collectors) away again.

The other geothermal option would be to use hot water further down from the ground (typically at a temperature of 150°C) to drive a steam engine, nowadays mostly performed by letting the high-pressured water separate in a low pressure tank into flash steam and (colder) water. In this way a flexible system of both production of electricity by the steam engine and the delivery of hot water for either the hot water demand or the aforementioned space heating need can be used.

5.3 Reflection

As a final statement, it can be concluded that the multifunctional building within the plan of Super Sustainable cannot function independently with the current renewable energy mix, when looking at both the electricity and heat balance of the building. Although sometimes the building creates a plus-energy situation concerning electricity, it is not able to cope with the high energy demand continuously, mostly caused by shops and offices. Net zero-energy buildings have however been proven to work (c.f. Wang et al, 2009), so has the applied methodology been correct?

Concerning the energy demand, the programs EnergyPlus and OpenStudio have been used. The first is not very easy to understand for a first-time user, seen the extensive manuals provided with it. The use of OpenStudio works as a relief however, by addressing the most important parts of EnergyPlus within an energy model for a building. The plug-in for Google Sketchup is certainly a plus, but probably also the only. OpenStudio (and thus its plug-in) is not able to cope with complicated buildings, making it a hurdle to get a building such as the multifunctional building modelled. This makes the process time-consuming and supports the choice for easier computer programs available on the (Swedish) market, like BV2 and DEROB-LTH and others.

Subsequently the input to the energy demand calculations has been both based on the Swedish Passive Housing regulations and academic data acquired. The first has been helpful, defining strict rules to be attained, however guide-lines for shops and offices are lacking. Also for the academic data the information has been extensive for apartments, but not so much for offices and shops. More reliable results could therefore be expected by input with more foundation for household electricity and hot water demand.

The calculations for the energy supply part have been fairly easy and have also led to reasonable results. The applied algorithm for wind energy is basic and uses up-to-date values for wind turbines. The wind input data might however not be as reliable, since it is based on wind speeds measured in the harbour of Göteborg. Moreover, the effect of the wind in the Sustainable City is an aspect which has not been highlighted in this thesis. Buildings are blocking other buildings, creating wind flows at the roofs highly influencing the wind energy output. Therefore the choice and placement for the amount of wind turbines could be more justified.

The solar energy algorithm has also proven to work well and supply the case study with useful output data per square meter. On the other hand, the estimation of the available solar area due to shadow overcast has been simple, questioning the validity of the end-result. It would be interesting to see what a more detailed calculation on shadowing would do to the assessment of effective solar area. But also changing the original plan by moving the buildings more apart deserves more attention.

Finally, the estimations for waste and wave energy have been straightforward, but do not require any advanced calculations. Waste energy has been shortly addressed, but follows the trend and efficiency of the current Swedish district heating. Wave energy on the other hand does not prove to be feasible and profitable in the sketched situation.

As has been mentioned before in this chapter, some technologies have not been highlighted in this thesis. This is partly because the up-front literature research did not give any reason for this; it is also partly because during the process it became apparent how the emphasis for the mix of the different renewable energies should lie. Wind energy did not turn out to be as effective in covering the demand (accounting for only nearly 5%), furthermore did solar energy lose a lot of potential due to the shadow blocking of other buildings. Waste energy however lived up to the expectations by covering two-third of the heat demand.

Geothermal energy, both as a source for heat and for electricity, has however been neglected, but shows itself to be promising and deserves a part in the energy assessment of the multifunctional building. Lund et al. (2004) already report that 60% of the heat load is covered by warmth from the earth, in houses in Sweden that have a heat pump installed. The trend at that point in time was set to reach a 80-90% heat pump fraction. Geothermally produced electricity has so far not been researched yet in Sweden (Antics & Banner, 2007) and would most certainly be recommended to include in future net zero-energy building studies.

As a final point, the conclusion of this thesis supports the vision of analysing the Sustainable City (or sustainable neighbourhood) by Super Sustainable not anymore as individual buildings, but as a whole. It would suggest the solution of off-site (thus not on/within the building; Torcellini et al., 2006) energy production methods, which are however still executed within the boundaries of the Sustainable City. The idea of one or several centralized energy production areas or buildings would for example support the attainment of a net zero-energy city, instead of a set of net zero-energy buildings.

Appendix A: Solar tracking calculations

Although flat horizontal solar panels have been preferred in the Master thesis, the technique of solar tracking has also been investigated. The calculation has been performed extensively, which is the reason why it is added as an Appendix. This is both for further use, but also as a proof of the justified choice for horizontal panels over solar tracked panels.

Solar tracking is a technique for which a solar collector will follow the sun throughout the entire day, which results into a changing tilt of the panel compared to the earth's surface. Quaschning (2003) tells us that therefore for tilted apertures another component is added to equation [11], which is the reflective solar irradiance I_{REF}:

[19]

It means as well, that the horizontal global irradiance value is not valid anymore for an energy calculation with a tilted surface, such that the global irradiance will have to be recalculated. For this we will need to know first where the sun is located (since the solar collector is normal to the position of the sun).

The sun elevation angle is dependent on the declination angle. Theoretically approaches such as discussed in Ehnberg & Bollen (2005) are correct, but practically *The European Solar Radiation Atlas* of Scharmer & Greif (2000) is more adequate. They give equation [20] for the declination angle δ:

[20]

Where j' is the Day angle, which is calculated by dividing the Julian day (1 through 365) by 365.25 days/year and multiplying by 360°.

In order to calculate the solar elevation angle Scharmer & Greif (2000) suggest formula [21]:

[21]

Where φ is the latitude (57.70°N), δ is the declination angle and ω is the solar hour angle, computed by $15 \cdot (t-12)$, where t is the local hour of the day (which is Coordinated Universal Time (UTC) +1).

Simple geometry to determine the tilted global irradiance from the horizontal global irradiance would be approximately correct, when the sun is high in the sky (for example 60° sun elevation angle). However at smaller sun elevation angle, the distance travelled of the sun beams plays a role (because of atmospheric disturbances) and the fact that the earth is round. That is why Klucher (1979) came up with a practical equation to determine the global irradiance on a tilted surface:

[22]

Where is the angle between the normal of the sun collector and the sun beam direction (in this case 0), ε is the tilt of the solar panel compared to the ground (which is for solar tracking 90 – α) and F is computed to be according to equation [23]:

[23]

Looking at equation [22] and [23] it is apparent that more data is needed in order to perform the calculations. Although the diffuse solar irradiance is not available through SMHI, the direct solar irradiance is, though in the direction of the sun elevation. It means the direct solar irradiance will have to be corrected geometrically by $I_{DIR,h} = \sin \alpha \cdot I_{DIR,t}$, such that $I_{DIF,h} = I_{G,h} - I_{DIR,h}$ (rewriting equation [11]). The data acquired from SMHI for direct solar irradiance in the solar elevation direction is based on the same conditions as the global solar irradiance earlier retrieved. With this information equations [22] and [23] can be rewritten to:

[24]

and

[25]

Making use of only the direct and global irradiance (for horizontal position) and the sun elevation angle, an hourly estimate of the global irradiance on a tilted surface can be computed. Again this is done using a Matlab/Simulink model where the mentioned conversions and the equations [20], [21], [24] and [25] have been implemented (see figure A.1).

A yearly estimation for the global irradiation for a solar tracking surface is then a summation of the hourly values: 1368.07 kWh/m^2 in 2011. Compared with the total horizontal global solar irradiance this is an increase of 1368.07/907.80 = 1.507, which is 50.7%. Looking at relevant literature, such as Abdallah & Nijmeh (2004), it looks like this value is reasonable. Their research showed an increase of 41.34% for a two-axis solar panel compared to a fixed. Neville (1978) calculated a 50% possible increase, such that 50.7% is in accordance to what other researchers have found.

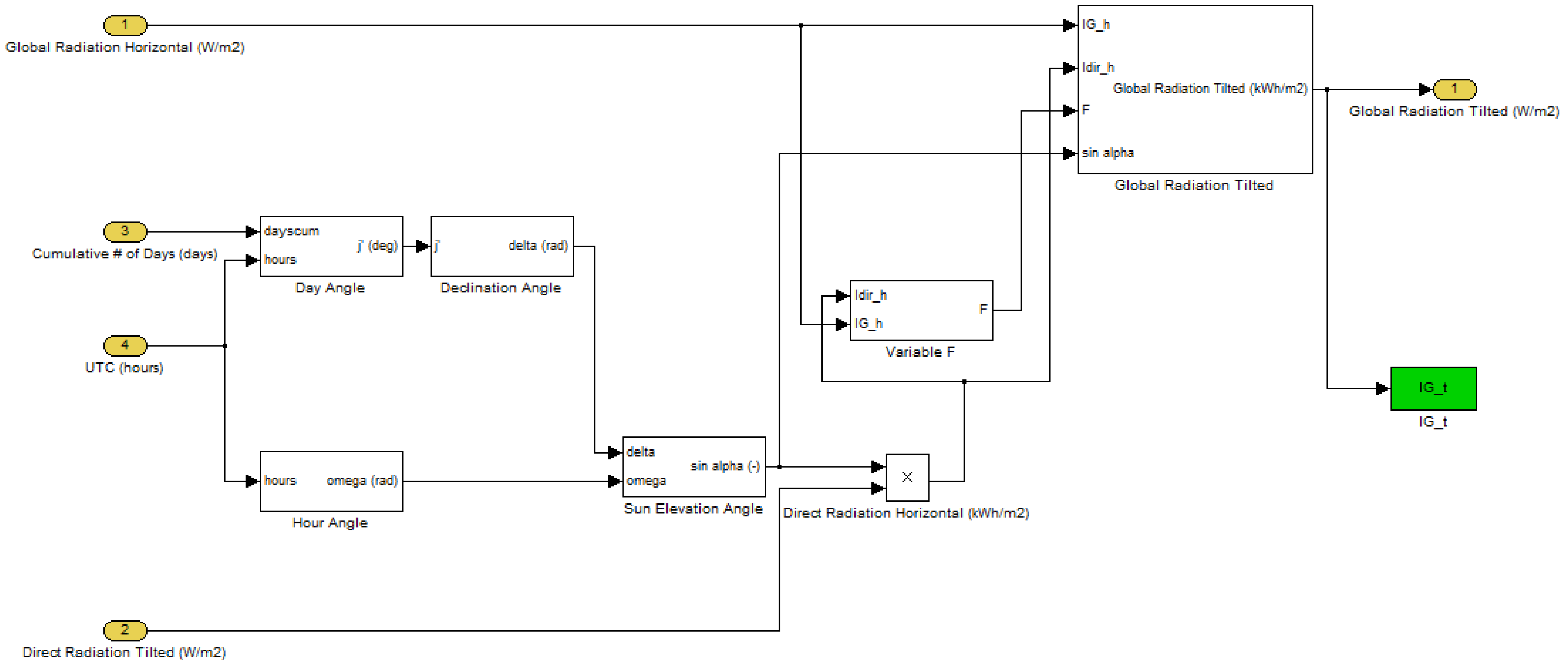

Figure A.1: Conversion from horizontal to tilted Global Irradiance in Matlab/Simulink.

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