THE POTENTIAL FOR HIGH-RISE ENVELOPES AS ENERGY PRODUCTION UNITS

Master thesis Anne Leeuw
THE POTENTIAL FOR HIGH RISE ENVENLOPES AS ENERGY PRODUCTION UNITS

Master of Science thesis by Anne Leeuw

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Abstract

By using Ladybug and Honeybee for Grasshopper, the energy production potential of high rise envelopes was investigated. Together with a technical design and the formulation of a flowchart strategy for energy production on high rise, an answer to the question 'How can high rise envelopes be utilized for energy production?' was sought after. The results showed that high rise envelopes can be used as energy production units by implementing energy production systems into existing façade systems. By doing so, modern buildings can produce over 30% of their total energy demand on-site. This will increase the global and national share of clean energy production, reduce negative environmental impacts of energy production and keep fossil fuels available for longer time periods. Changing policies and regulation along our own comfort standards can further increase the potential of energy production on high rise. However, high rise with a high window to wall ratio will have no future in the built environment, unless transparent energy production technology will see great efficiency improvement in the next few years.
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Summary

This thesis provides research on the future of high rise relating to net zero energy building and energy production on envelopes. The European Union (EU) has decided that by 2020 all new buildings must be nearly zero energy and that all members of the EU must increase their national share of clean energy production to 20%. High rise can only become net zero energy if the entire envelope is utilized for energy production. However, the building in itself must also be very energy efficient. The research question for this thesis was:

How can high rise envelopes be utilized as energy production units?

For this thesis a strategy was developed to choose which energy systems to use for a specific high rise design. The strategy is based on first assessing the renewable energy availability in terms of solar and wind energy. Which source is used depends on the climate system of the building and the minimum intensity of wind or solar energy required by different energy production systems. The researched systems are wind driven systems, photovoltaic systems, solar thermal systems and photobioreactors for algae production. A literature study led to the conclusion that vibrational wind systems are better suited for urban applications, although a new technology. Algae systems are difficult to integrate into a flat façade, but can be integrated with double facades, or placed on the roof in high density. Solar thermal, photovoltaic and vibrational wind systems can all be integrated into a curtain wall system as is shown in a design catalogue. The catalogue provides a basic set of solutions to integrate the energy systems in typical high rise buildings.

De Rotterdam, a high rise building by OMA, located in Rotterdam (NED), was used as a test case. The building is built to comply with modern energy codes and has a ‘typical’ façade, with a high window to wall ratio (53% - 75%). The façade was redesigned. A unitized curtain wall system integrating solar thermal and photovoltaic systems was designed, by first using the strategy and the design catalogue. Some design options are used for energy simulation, using Ladybug and Grasshopper plugins for Rhinoceros, to see how they affect heating and cooling loads.

In order to increase the energy production potential of a building, the window to wall ratio must be low to have more opaque space for energy systems integration. A window to wall ratio or 40% leads to lower cooling loads for De Rotterdam and it will do so for most office buildings in moderate to hot climates, where the cooling demand is much higher than the heating demand.

On the envelope of De Rotterdam, 31% of the energy demand could be produced. In reality it could be more, because water from the Maas is used for cooling and this was not accounted for. If the building did not have a cooling load, 42% of the energy demand could be met. The computations are based on averages relating to one office floor and governmental data on residential units. Therefore, these numbers are approximations of the actual energy potential.

The thesis led to the conclusion that high rise which does not use free sources of heat and cold for climate control purposes, could never become energy neutral. The equipment, lighting, fans & pumps already require a lot of energy. That means that energy production for net zero energy building, must be more context based. Buildings with different functions should provide energy for each other. Offices and residential units are a good example. Office energy demand peaks when residential demand is low. If residential units would produce energy in accordance to their peak demands, during the day the energy overflow could be allocated elsewhere.

Façade shape and envelope shape are also important to optimizing a façade for energy production. Orienting buildings to reduce solar gain is positive in terms of reducing cooling loads, but reducing the window to wall ratio has the same effect whilst providing more surface area to be used for energy systems integration.

A summarized answer to the research question is:

High rise envelopes can be used as energy production units by implementing energy production systems into existing façade systems. That way, modern buildings can produce over 30% of their total energy demand on-site. This will increase the global and national share of clean energy production, reduce negative environmental impacts of energy production and keep fossil fuels available for longer time periods. Changing policies and regulation along our own comfort standards can further increase the potential of energy production on high rise.
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1 INTRODUCTION

1.1 Background

1.1.1 High rise from the 16th century until the 21st.

As early as the 16th century the people of Shibab, Yemen, built tower blocks of 5 to 11 stories high with mud brick (Cizek, 2014). The dense layout of the blocks provided defensive advantages and growing tall protected inhabitants against flash floods (Jerome, Chiari, & Borelli, 1999). When the first elevators for industrial use were invented some 200 years ago and steel became a common construction material, high-rise became a more practical building typology. Although at first high-rise provided a poor living environment for the working class in ‘tenements’ (Riis, 2004), it started to become more popular when luxury apartment and office buildings erected in the late 19th century and early 20th century. The Home Insurance building in Chicago was the first skyscraper. With a height of 42 meters, completed about 20 years before the invention of reinforced concrete. The new building type asked for new façade structures. The main new invention on this part was the curtain wall. This is a thin façade structure which hangs from beams or floors, rather than carrying its own weight (Vigener & Brown, 2012). The high-rise building evoked innovation in construction and urban planning. The assumption that tall buildings leave more area available at street level for other purposes, led to the phenomenon of ‘utopian planning’. High rise leaves space for nature and leisure. A famous architect in this era was Le Corbusier, who made several plans such as the Plan Voisin shown in Figure 1.1 which incorporated the ideal way of living: within vertical cities that contain everything you need and provide space for the joys of nature on the ground where high rise blocks were connected by lush green parks. While these utopian ideas faded over the years, recently they have started to reappear.

High-rise was at first appreciated for providing affordable housing to the lower class and middle class citizens of large cities. The appreciation evaporated in the late sixties and seventies when the buildings became old and defects became apparent. Some high-rise buildings were built to such low standards that parts collapsed, as has happened in London. In the US these buildings were abandoned by the middle class and became homes to the lower classes and racialized poor. Eventually a lot of high-rise residential blocks were demolished. Office towers however, kept popping up through a combination of ego of investors, companies and architects (Appenzeller, 2012). Appenzeller has seen in his travels and research that a clear split in design typology existed between Europe and the United States, followed by popular styles formed by continental history. According to Appenzeller high-rises today can still be brought back to American high-rise built in a row, European free standing icons or the (utopian) inventions of Le Corbusier. In the US, high rise is often seen as a solution for high land values. Developers look to generate as much profit as possible from developing a plot of land. With more residential units or office space to rent after completion, the more feasible a project becomes. While this may be true for specific countries, in The Netherlands for example, this is not the case. The land prices depend on how much is built and its resulting value. A system which assures higher profits from low rise, which have to fund the construction of high-rise in larger projects (Zandbelt, 2012). Utopian buildings require heavy investments and thus require even heftier returns. Plans for utopian structures are nonetheless still made for places like New York City, or Dubai. For example: the Dubai City Tower shown in Figure 1.2 for which plans were created in 2008 (Diaz, 2008). These vertical cities provide all human needs, from work and leisure to food production. Most plans and designs for utopian architecture tend to remain in the conceptual phase.

The persistent interest in building tall requires adequate strategies and policies based on thorough research, but these strategies are not yet formulated by authorities (Nicolaou, 2012). Key terms in arguments for high-rise are: space-use intensification, global positioning, regeneration, diversification, promotion of development areas, (stakeholder) desire. Key arguments against high-rise are: it’s an inefficient building type with low energy performance, the actual impact for mixed space use is limited, drives vitality/liveliness away
from public space, negative impact in plinth, lack of development flexibility, narrow sector demand. Arguments such as low energy performance, negative impact in plinth and threat to liveliness on the street can be taken away by good design. For the latter, design strategies are already part of the high-rise vision, for example in Rotterdam in The Netherlands (Arends, 2012). Inefficiency within the building type might be compensated by space-use intensification and when integrated into a good network for public transport, the urban energy consumption for transport decreases (P.W.G. Newman & J.R. Kenworthy, 1987). The annual gasoline use is smallest in European and Asian cities with high densities, good public transportation and functions reachable by foot. Planning densification paired with space-use intensification proves however to be more difficult than expected and has turned out differently in a number of cases.

Examples are the Canary Warf in London, a district filled with high-rise blocks, which has a plot ratio of 4:1 while the city centre has a plot ratio of 5:6:1. In the city centre of Paris, where building height is limited to 32 meters, the plot ratio is 6:1. Rotterdam's city centre has a plot ratio of 5:1 with 450,000 inhabitants, compared to 2,300,000 inhabitants within approximately the same area in Paris. The numbers prove that high-rise is not the (only) solution to densification and intensification. But if high rise remains on the city-planners and developers agenda’s, they need to be utilized to their maximum potential.
1.1.2 Urban energy consumption

It is estimated that by 2050 almost 70% of people worldwide will live in cities (United Nations, 2014), a 20% increase from today. Areas where the largest growth in urbanization will take place are found in Asia and Africa, since European countries are already housing 73% of their inhabitants in urban areas. Within European cities energy consumption in buildings accounts for 41% of the total energy consumption (Steemers, 2003). The energy consumption per capita is growing as we expect our living and working environments to meet high comfort standards and use of electronic equipment is still rising. In urban areas, where half of the world population lives, around two thirds of the total primary energy supply is consumed (OECD/IEA, 2008). The energy consumption of cities is based on factors such as population density and the wealth of inhabitants, therefore energy consumption per capita (within cities) differs around the world, but overall urban energy consumption is expected to increase. The increased energy consumption needs a growing energy production to meet the demand. Energy is now mostly provided by burning of fossil fuels (oil, coal and gas). In The Netherlands renewable energy sources only accounted for 5.3% of the total energy supply in 2014 (International Energy Agency, 2014) and the goal is set to achieve 14% by 2020, still 6% below the target of the European Union. The global share of renewable energy is much higher at 17%. With the depletion of fossil fuels approaching quickly – within 40 to 70 years for oil and coal and 100 to 200 years for gas (Shaﬁee & Topal, 2009); (BCC, 2015) it is important that a shift in dependence from fossil fuels to renewable energy sources takes place. Furthermore our dependency on fossil fuels leads to high CO2-emissions. Cleaner energy production is necessary to mitigate negative effects such as climate change. With buildings consuming 37% of the energy supply in The Netherlands in 2012 (compared to 44% by Industry and 19% for transport), it makes sense to try to make a difference in this sector. Buildings take up a vast amount of land and push back the borders of nature, resulting in effects as the Urban Heat Island, where the mass of materials in urban areas accumulates heat and keeps the temperatures at higher levels than those in rural areas. This effect will lead to greater need for cooling installations and an increase in energy consumption because cooling relatively requires more energy than heating. However, a key element and advantage about dense cities are their short transport lines for goods and people that lead to lower energy consumption per capita.

New challenges have also emerged for urban areas concerning energy. The European parliament requires all member states to construct only nearly zero energy buildings by December 31st 2020 (European Parliament and Council, 2010). In the years afterwards, member states should see to induce an increase in the amount of nearly zero energy buildings, meaning not just new buildings should be nearly zero energy, but the existing stock needs to be improved. The demand for nearly zero energy buildings stems from the Kyoto protocol. The countries participating in the Kyoto protocol strive to decrease greenhouse gas emissions by 20% below the level of 1990. Reducing the energy demand of the built environment is a big part of that, because the built environment consumes about 40% of the primary energy supply. Within buildings, the embodied energy accounts for about 10% - 20% of its lifecycle energy consumption, while operating energy accounts for 80% - 90%.

1.1.2.1 The availability of finite energy resources

Fossil fuels and ﬁssile materials are the main recourses for heat and electricity generation. The world relies on finite recourses for 80 – 85% of the total energy supply. It is clear that we will run out of these resources, but the question is when. The remaining volume of these resources is subject to speculation and many different calculation methods. Combining different sources the BBC (2015) predicts gas to remain available for just over 110 years and oil and coal for just over 50 years. The remainder of conventional oil is estimated in a range of 4,900kJ (current reserve) and 13,700kJ (reserves plus resources) (GEA, 2012) and we are nearing the point at which the cumulative oil production is almost equal to the remaining resources. However, there is no deﬁnitive answer to when the fossil resources will be gone. The problem in estimating the reserves and resources is that estimates are based on limited geological data gained from excavations and explorations, which are easily interpreted in different ways. That’s why there are different predictions on whether the peak-oil is already reached. **Graph 1.1** shows an undulating
plateau when the peak of oil production is reached. An undulating plateau represents a wave motion. The graph shows that CERA expects the oil production to be somewhat stable (wave motion) for a few decades before it will start to decline (Jackson, 2007). Oil production graphs are based on oil extraction expectations, thus they give insight into the oil availability.

Power plants worldwide that use coal as fuel provide 41% of the world’s electricity supply. This is an average and countries dependency on coal-fuelled electricity production varies from below 41% to around 93% for South Africa as shown in Table 1.1 (World Coal Association).

The proven reserves for coal are abundant and the resources are estimated to be even greater. The GEA and Shafiee & Topal agree that coal resources will be sufficient for at least a hundred years. GEA supports the statement with a 2% annual increase in coal production.

<table>
<thead>
<tr>
<th>Country</th>
<th>Share of Coal as Resource for Electricity Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Africa</td>
<td>93%</td>
</tr>
<tr>
<td>Poland</td>
<td>87%</td>
</tr>
<tr>
<td>PR China</td>
<td>79%</td>
</tr>
<tr>
<td>Australia</td>
<td>78%</td>
</tr>
<tr>
<td>Kazakhstan</td>
<td>75%</td>
</tr>
<tr>
<td>India</td>
<td>68%</td>
</tr>
<tr>
<td>Israel</td>
<td>58%</td>
</tr>
<tr>
<td>Czech Rep.</td>
<td>51%</td>
</tr>
<tr>
<td>Morocco</td>
<td>51%</td>
</tr>
<tr>
<td>Greece</td>
<td>54%</td>
</tr>
<tr>
<td>USA</td>
<td>45%</td>
</tr>
<tr>
<td>Germany</td>
<td>41%</td>
</tr>
</tbody>
</table>

Table 1.1: Share of Coal as Resource for Electricity Generation. Source: IEA 2012

The demand for gas used for heating, on average, seen a worldwide decrease from 2009. The drop is stimulated by energy saving regulations that require buildings to have sufficient insulation. According to the International Energy Agency the demand for natural gas will keep increasing in other sectors and it will peak around 2030 in their reference scenario (IEA, 2009), based on the ‘real world’. In a best case scenario where governments apprehend stricter regulations, gas demand could be 17% percent lower in 2030.

Uranium, Thorium and Lithium are resources found in rocks, soils and waters. The materials are all abundant, but scarce nonetheless. The exploration and mining technology need to be lifted to a higher level, otherwise the supply cannot meet the demand in the future.

1.1.2.2 The new stepped strategy

Strategies on how the built environment should react and adapt to the uncertain circumstances relating to energy availability and pollution are already being explored. Trias Energetica is such a strategy and it consists of three simple steps:

1. Reduce energy demand;
2. Use renewable sources;
3. Use fossil fuels wisely and sparsely.

This strategy from the 1990s gives guidance for sustainable design. Now, 20 years later, with the depletion of fossil fuels approaching, this strategy is outdated. The New Stepped Strategy adapts the Trias Energetica line to a more sufficient strategy, excluding the use of fossil fuels and introducing the use of waste streams (Tillie et al., 2009). The new stepped strategy is presented in Figure 1.3.
1.2 Problem statement

Energy consumption is on the rise and cities are growing. Energy consumption is correlated with economic activity, transport costs, geographic factors and also by urban form. Cities provide a dense living environment that offers certain advantages over wide spread town structures, but overall urban areas account for two thirds of the global energy consumption. 40% of energy consumption is used within buildings, of which 80% - 90% during its years of operation. Energy consumption, especially when met by fossil fuel burning is now a problem because of pollution and the depletion of resources. The Kyoto protocol, drafted in 1997, requires all participants to reduce their greenhouse gas emissions to 20% below the emission of greenhouse gasses in 1990. Reducing energy consumption all around is a large part of that. The European Union requires all new buildings to be nearly zero energy by December 31st of 2020 and member states must increase their share of clean energy production to 20%. Zero energy buildings and positive energy buildings will be the standard requirement in a few decades. This means that the buildings need to produce energy to compensate for their consumption. In the year 2015 we still rely mostly on fossil fuels for heat and electricity generation. That needs to change, sooner rather than later, because the earth is running out of fossil fuels. Buildings provide surface area usable for renewables-based energy production, e.g. photovoltaic panels, wind and bio-fuel. Solar powered electricity has the fastest growing share in the total energy production, although it only accounts for 2% of the total energy production right now, it also has the most potential of all types of (renewable) energy resource. We see solar energy (electricity and thermal) used more and more on low rise buildings. In our ever growing cities, high rise lags behind on energy performance and getting towards a zero energy status. But, its potential is found in the height of the structure: high rise often pops out of its surroundings, and has a large surface area. The surface area could be used as a farm for bio-crops and oils with an algae-plant, solar thermal collectors might be integrated to provide heat and hot tap water to the buildings itself and the surrounding buildings. Photovoltaic cells can provide electricity, especially further away from the equator where the sun's angle is closer to vertical than horizontal. One advantage of dense cities is its short transport structures of goods and people, but energy is still produced far away. So why is energy production not being integrated on high rise? Especially when considering that high-rise buildings tend to consume more energy per square meter of floor area than low rise buildings. It needs pumps and vents to distribute air and water around the building. High-rise has a relatively small roof area compared to low rise buildings. Where low-rise buildings (of up to 6 stories) can cover the roof with photovoltaic panels and thermal collectors to compensate its energy usage, high-rise cannot. According to a study conducted by Engineering firm Arup(2012) a 12 story office building, built with passive strategies cannot become zero net energy. What the study doesn’t take into account is that high-rise buildings have large facade areas which are underutilized.

1.2.1.1 Problem definition

High rise faades are not being utilized for energy production, while international targets are set to increase renewables-based energy production and to make all new buildings nearly zero energy.
1.3 Relevance

1.3.1 Scientific Relevance
By researching the ways in which tall structures can contribute to the urban energy system, designers and policymakers are given an incentive to incorporate energy production in their designs. Developing energy facades is only useful when the high rise is energy efficient by itself. Otherwise, the impact could never be compensated. It is thus important to catalogue the status quo of low energy high rise. When the European Union and the Kyoto protocol ask for a zero energy built environment, it must be feasible to build zero-energy high rise. Otherwise, high rise cannot be a part of the future built environment, although it offers advantages over solely low-rise urban areas. Since it’s seems obvious that covering the roofs of high rise doesn’t generate enough energy, the potential of façade integration needs to be addressed.

1.3.2 Social relevance
Fossil fuels are running out fast. Without the discovery of new oil and gas bubbles these resources will run out in between one to two human lifetimes. The lifespan of high rise tends to be longer than that of humans (71 years) (The World Bank, 2013), although it does depend on the type of high rise. Some of the oldest high rise buildings, such as the Wainwright building in Chicago (completed in 1889) and the Witte Huis in Rotterdam (completed in 1898) are still standing today. A lot of high rise residential towers, built after the Second World War in the United States or England or elsewhere, were of poor quality and lasted only a few decades. If the oldest high rise buildings are now around 100 – 120 years old, we cannot simply design high rise that consumes vast amounts of fossil fuels. Buildings now are built to a much higher standard than the Witte Huis or the Wainwright building, so it is plausible that they will last longer too. Buildings consume 80-90% of their total energy use during its operating phase. That means, if the systems for indoor climate regulation and other functions still rely on fossil fuels, they will need to undergo renovation to work with renewable sources.

Since most people will live in urban areas in the future, the implementation of renewable energy generation in these areas makes sense. With development of smart grids, which look to share and transport energy more efficiently (and thus over shorter distances) it makes even more sense to generate energy on the sites where we live or work.

1.3.3 Ecological relevance
High rise puts pressure on the environment in a number of ways. It affects the climate conditions around the building. Its shape affects wind flows and creates shadows. All construction materials have a specific embodied energy. The production and transportation to the building site add to the environmental impact of the building. During construction, waste is produced. Waste materials, but also waste energy. When a construction is finished, it keeps using energy. It is already proven that low rise buildings can be energy positive, so they can compensate for the energy used in construction and use phase. While high rise office towers have been found impossible to become zero-net energy, that doesn’t mean its surfaces shouldn’t be designed to mitigate its energy use. Especially when the building is not in use 24/7. The surrounding buildings can benefit from energy high rise energy production. With local production of clean energy, air quality will improve and CO₂-production will decrease.
1.4 Objective & research questions

1.3.4 Objectives
The objective of this thesis is to:

Show the potential of energy production on envelopes of high rise.

Sub objectives are:
1. Finding out which renewables-based energy systems are already used and what their potential is for high rise applications.
2. Taking an existing high rise buildings that has already dealt with spatial limitations and exploring the possibilities for energy production on its envelope.
3. To figure out an effective balance in direct use of energy, storing the energy for later use and redistributing energy.

1.3.5 Research question
The vertical surfaces of high rise are underutilized. Many articles about energy consumption of high rise can be found and about low energy building strategies, but research seems to focus less on energy production on facades. The research question is formulated to ensure the research and design will provide useful information on the possibilities of producing energy in urban areas. The research question is stated here:

How can high rise envelopes be utilized as energy production units?

1.3.6 Sub research questions
The research focuses on three main topics: High rise, façade systems and energy, from production to distribution and storage.

1.3.6.1 Energy demand & consumption
a. What does the energy consumption distribution in high rise look like?
b. What factors influence energy consumption in high rise?
c. Which climate installations can use renewables-based systems as energy input?
d. What is the energy supply and demand balance for a building and its context?

1.3.6.2 Energy production
a. Which renewables-based energy production systems are suitable for façade-integration?

b. What is the efficiency of different renewables-based energy production systems?
c. How can you assess the availability of renewable resources around high rise?

1.3.6.3 Façade & envelope design
a. How does façade design influence the indoor climate and energy consumption?
b. What are the different façade systems used in high rise?
c. Which façade systems lend themselves for implementation of energy producing elements?
1.5 Scope

The problem that this thesis deals with stems from conventions on climate change, the rise in energy consumption and the need for a better energy balance in the built environment. A logical approach to deal with the energy challenge is the New stepped strategy. The steps, with number 1 – 3 are shown in Figure 1.4. In finding the potential for energy production on high rise, the goal is to try to find how the energy balance (the sum of energy consumption and energy production) can be as near to zero as possible. Research is therefore needed into façade optimization and energy generation technology which is adaptable to the building scale. The main focus thus lies with the green boxes in Figure 1.4, but the relation between a building's interior and the envelope cannot be ignored. The scope includes everything within the red dotted lines and the relation between the building's interior and envelope in terms of energy consumption.

![Figure 1.4: Scope, own ill](image-url)
2 APPROACH

The research question: 'How can high rise envelopes be utilized as energy production units?' needs to be answered to find out if high rise can become zero energy buildings with today’s technology. The objective is to show the potential of energy production on high rise. For this goal, it is useful to design a strategy which enables a planner or designer to quickly assess the potential of an envelope. This strategy is step one in answering the research question, because the integration of energy systems into a building envelope is different for every case. Every building has a unique context, thus also a different energy production potential, because the context influences the availability of wind and solar energy. The aim of the strategy is to assess the energy production potential of an envelope. If the energy resources (sun and wind) are not present, or sufficient, the potential is 0. To see if such a strategy is useful, it is tested on an existing building: De Rotterdam. A design catalogue provides a set of solutions for high rise facades that includes energy production systems. This catalogue is used to redesign the façade of De Rotterdam.
3 METHODOLOGY

3.1 Phases
To formulate a strategy for assessing the energy production potential of an envelope it is first important to know how the design of an envelope relates to energy consumption. A literature study will answer this question and will provide the base for developing the strategy. A study into renewables-based energy production will provide the necessary information on efficiency of several systems and their applicability in terms of façade design. The end product of this thesis is a redesign for fragments of De Rotterdam, see Figure 3.6 and a strategy for assessing the energy potential of high rise envelopes. The redesign will show how energy production can be integrated into a façade of an existing high rise building. The building and its context

3.1.1.1 Literature review
- The literature review is phase 1 of the research project and answers most of the sub-research questions first. The literature review provides all necessary input for the design phase and the climate analysis. The study will lead to design restrictions for the energy producing envelope.
- A summary of the renewables-based technology explains the potential of solar thermal, solar electric, wind driven power and the potential for biomass production.
- Case studies provide information on current projects integrating energy production within the façade or new technology in energy production systems which could be applied to building envelopes.

3.1.1.2 Strategy development
During the literature study the outlines of the strategy become apparent. After the literature study, a preliminary strategy is established which will be used for the redesign of De Rotterdam’s envelope. After the climate & context analysis, the strategy can be adjusted to new finds, as well as after the redesign phase.

3.1.1.3 Climate & Context analysis model
Effective façade design leads to lower energy demands and high indoor comfort on aspects of thermal comfort, indoor air quality and daylight. In order to find boundary conditions relating to outdoor climate conditions an analysis model will be created using Rhinoceros 5.0, Grasshopper, Ladybug and Honeybee. A volume model of De Rotterdam and its context will be made in Rhinoceros. Grasshopper will allow for algorithmic modelling inside Rhino. The plugins Ladybug and Honeybee provide climate analysis components. These plugins provide a graphic interface for EnergyPlus (energy modelling) and Radiance (daylight modelling) and have several components that allow users to model, run and visualize sun paths, solar irradiation, daylight simulations and more. Wind flows are simulated with Autodesk Flow Design. A very basic computational fluid dynamics program that creates a wind tunnel around a 3D model.

Figure 3.1: Modelling and data analysis, software relation (own ill.)
3.1.1.4 Redesign of De Rotterdam

To show the potential of energy production on high rise envelopes a design for façade integrated energy production will be made. By choosing an existing building as under layer, a dose of realism is added to the research project. De Rotterdam has been chosen because it is located in a medium sized European city within the moderate climate zone. Rotterdam is sometimes considered the most modern Dutch metropolis. De Rotterdam was completed in 2013 and thus meets modern standards in terms of indoor climate comfort and energy design. Although the building has some energy efficient climate systems, which will be explained later in this thesis, its envelope is an almost homogenous curtain wall system that does not seem to incorporate climate adapted measures. The final design will be tested for heat gain through the façade and daylighting, to see if the new design still provides enough indoor comfort and has no negative but rather positive effects on energy consumption.

3.2 Building & Location

Rotterdam is a Dutch city with over 615,000 inhabitants ("Geschiedenis van Rotterdam," n.d.). The city has the largest port of Europe and is split into two parts by the river Maas. During the Second World War, the city centre was heavily bombed and had to be rebuilt. The new city centre got its shape between 1945 and 1975. The port moved away from the centre, wide roads and construction of the metro made Rotterdam a ‘modern’ city ready for growth. The speed of expansion came to a halt and the focus shifted towards increasing the quality of the built environment (“Een vernieuwde stad.”). The area on the South banks of the Maas (Kop van Zuid) becomes the canvas for a city of the 21st century where all functions of life are combined. Part of Kop van Zuid is the Wilhelminapier, where ships used to depart to all corners of the world. On this pier, that had to become the Manhattan on the Maas, De Rotterdam started to rise in 2009 and was completed in 2013 (“De rotterdam opgeleverd,” 2013). The 44 floors reach up to 144 meters high.

3.2.1 Interior layout of De Rotterdam

The building is just over a 100 meters wide and contains 60,000m² of office space, 1500m² of food services, a hotel with 2000m² of event space, 280 rooms and numerous guest services. The building further contains 240 apartments and 670 parking spaces. The ground on which the building stands is now the most densely populated area of the Netherlands. With approximately 5000 people
walking in and out of the building every day, the number of people on the Wilhelminapier has been doubled. In Figure 3.7 the layout of De Rotterdam is shown in a section of a 3D model. In the South West tower the apartments are placed around a service core that separates the living tower from the office block in the middle. In the middle part the offices are also draped around a service core. The office tower is separated from the hotel in the North East tower by an open void. The ‘gap’ in the building provides extra daylight for both towers. Further upwards the gap jumps towards the South West. The top blocks contain more open plan office spaces and apartments.

The building has an energy monitoring system, to maximize efficiency.

<table>
<thead>
<tr>
<th></th>
<th>apartments</th>
<th>hotel</th>
<th>offices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor height</td>
<td>3020</td>
<td>2600</td>
<td>3400</td>
</tr>
<tr>
<td>Sandwich panel height</td>
<td>500</td>
<td>500</td>
<td>900</td>
</tr>
<tr>
<td>Window-to-wall ratio</td>
<td>75%</td>
<td>60%</td>
<td>53%</td>
</tr>
<tr>
<td>G-value</td>
<td>0.34</td>
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</tr>
<tr>
<td>LTA</td>
<td>0.61</td>
<td>0.51</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Table 3.1: De Rotterdam Envelope Design, source: Ellen van Loon (2014)
3.2.2 Envelope design of De Rotterdam

De Rotterdam envelope can be seen as a solid rectangular base with 3 towers on top. The gaps provide extra daylight. The façade looks slightly different from some sides. Figure 3.4 shows a floor plan of a corner apartment on the South corner of the building. The apartments facing South West have balconies which are 1.7m wide. The apartments thus have slightly different facades than the office and hotel spaces and feature sliding doors and windows. Figure 3.10 shows an interior view of the façade that covers the offices. The aluminium curtain wall spans from floor to floor and sometimes features a sandwich panel between elements, located at or just below the concrete floors. The mullions have a centre-to-centre distance of approximately 850mm-900mm and a width of 15 in the apartments and hotel and 30mm in the offices (CTBUH, 2014). The glass panels differ in height from 3 meters to 6 meters ("Project gallery - the rotterdam," n.d.). Seen from the inside, this results in an approximate window-to-wall ratio of 79% for low panels and 70%, see Table 8 for the outside ratio. The sandwich panels are not seen at most levels, because it ends at the height of the suspended ceilings.

3.2.3 Climate system of De Rotterdam

De Rotterdam is attached to city-heating and has a cooling system with three machines, that have a combined power of 6000kW (Noorlander, 2013), which uses water from the Maas to reduce energy consumption. It also features a co-generation system which runs on bio-fuel and outputs electricity and 300kW of heat. The building uses low-temperature heating ("About de rotterdam," 2013). The mullions contain 800 ventilation panels in the hotel and offices. The ventilation system's fan rotation can be adjusted and the system also incorporates heat recovery. The apartments can be naturally ventilated through sliding doors and windows.

The high window-to-wall ratio lets a lot of daylight in and when or where this is not sufficient, high-efficiency reflector armatures which supplement the natural lighting. The lighting features motion control in office areas. The offices and hotel have both a lower g-value (solar gain) and lower TL (daylight transmission) than the apartments as shown in Table 8, because in general they need more cooling.
3.3 Computational energy modelling

Hand calculations require vast amounts of time and knowledge. Computational modelling bridges the gap between the designer and the physicist. There are numerous software packages available for energy modelling such as DesignBuilder, TRNSYS, Capsol, Ladybug & Honeybee for Rhinocerous. For this research Ladybug & Honeybee were used. The program runs on the foundations of EnergyPlus. EnergyPlus is an open source simulation program developed by the U.S. Department of Energy. The program enables users to model energy consumption for heating, cooling and ventilation, lighting and equipment. EnergyPlus is energy modelling software and was first released in 1998 (Crawley et al., 2001), thus considerable time elapsed for testing and improving it. By using weather data as input and by giving the user control over the time steps (up to seconds), the simulation provides elaborate results. The user or designer can give all kinds of characteristics to the geometry relating to energy demand and consumption, such as the climate systems which are used, air flow rates between spaces or between outdoors and indoors. Other software provides a more graphical interface for EnergyPlus, such as DesignBuilder or the Grasshoppper plugins Ladybug and Honeybee. More information can be found on: https://energyplus.net/

Ladybug & Honeybee are used, because together with 3D modelling software Rhinocerous they provide greater flexibility in simulations because it incorporates daylight simulation to a greater extent than DesignBuilder and if no input is provided, it uses its own defaults, which are provided by the developers.

3.3.1 Rhinocerous 5.0

Where DesignBuilder combines the 3D-model with the energy modelling, Grasshoppper is a plugin for 3D modelling software Rhinocerous. The 3D model is built in Rhinocerous and its characteristics can be interpreted and used through the Grasshoppper plugins. The Grasshoppper models are described in APPENDIX D: GRASSHOPPER MODELS. The boundary conditions for the models are also mentioned here.

3.3.1.1 Energy simulation geometry

The energy demand analysis requires a much more detailed model, but because energy calculations are complex and can take extensive amounts of time to run, only one floor of one of the office towers was modelled. This is floor near the top of the building. The roof and floor are adiabatic, considering the same conditioning will be applied on the lower and the upper floors. The service core has gypsum internal walls and is a conditioned space, so that heat transfer between the core and the office zone will be accounted for. The surface next to the office block represents the neighbouring tower of De Rotterdam, which shades part of the office. The office block is square with sides of 32 meters. The office zone has a floor area of 860m² and the core has sides of 9.35m and 17.60 meters and is placed 5.8 meters from the façade in the y-direction and 9.15 meters from the façade in the x-direction.

3.3.1.2 Environmental analysis model

For the environmental a model of the entire building including the surrounding buildings is made. The context models (red) are based on dimensions measured with Google Earth and models made available through the Sketch up Warehouse. The models are placed on a scaled image extracted from Google Earth, which was loaded into the Rhinocerous 5.0 model. In the model the North direction is set at 225 degrees.
Figure 3.16: Rotterdam from above with reference names used later on. Own ill.

Figure 3.14: Rotterdam model used for analysis. Own ill.

Figure 3.15: 3D model of De Rotterdam with context seen from the south

Figure 3.13: 3D model of De Rotterdam with context seen from the north. Own ill.
THE POTENTIAL FOR HIGH RISE ENVELOPES AS ENERGY PRODUCTION UNITS

ANNE LEEUW
PART 1
LITERATURE REVIEW
4 ENERGY DEMAND & CONSUMPTION

4.1 Introduction
Building construction is influenced by governing bodies around the world from early in the 20th century, but demands relating to energy consumption set in when energy prices started to rise and when climate change and pollution were seen as a threat to human life far into the second half of the 20th century. European Union members now have to apply labels to old and new buildings. In The Netherlands the Building Decree sets requirements for the energy performance coefficient (EPC) of buildings. The lower the EPC, the more energy efficient the building is. An energy label contains information on the Energy Use Intensity (EUI) of a building. The EUI is expressed in kWh/m² and represents the annual energy consumption of a building. New buildings can only be built with an A label. However, the EUI is not used to give the label, but the label relates to a building’s function and façade to floor ratio. A benchmark for low energy buildings is not easily set at a specific value for kWh/m², however, the lower the EUI the better the energy performance. There are three basic building forms that adapt to the climate (Dahl & Albjerg, 2010):

1. A **passive building** consisting of static elements in which space use varies depending on the outdoor climate conditions.
   For example, when outside temperatures are high, rooms away from solar radiation are used.

2. An **actively conditioned building** that has dynamic elements by which it can adapt to outdoor climate conditions.
   For example, when outside temperatures are high, shutters or blinds are closed to reduce solar gain.

3. A combination of the aforementioned: a **hybrid building**.
   This type finds the optimal combination of active and passive measures to maximize indoor comfort.

High rise buildings thus fall in one of these categories, but passive high rise buildings are seldom found. Oldfield, Trabuccoo & Wood (2009) describe five energy generations of high rise, from the very first built towers in the late 19th century to the beginning of the 21st century. Throughout history energy consumption of buildings changed because of the invention of heating, ventilation and cooling systems and new developments in artificial lighting. It made staying in high rise more comfortable by creating an isolated climate zone, but also more energy intensive, because there is a lack of relation between outdoor and indoor climate conditions. Government policy started to influence the design of high rise. Zoning laws requiring buildings to be set back from its alignment to the roads as their height increases Figure 4.1 were set to improve the daylight availability in buildings and on the streets.

Later governmental requirements were set for luminance levels, but deep office buildings did not allow daylight to penetrate to workplaces far away from the facades, thus electricity consumption for artificial lighting increased. The invention of the glass curtain wall helped to maximize daylight availability, but the single glazed surfaces had very high U-values. Furthermore, the black skyscraper became a trend all over the world, independent from climate zones. The dark facades absorbed a lot of the solar irradiance. The buildings heated up quickly and new electronic equipment (such as computers) increased internal heat gains even further. The invention of air-conditioning brought a solution at first, but when the energy crisis hit the U.S. in the second half of the 20th century, things
needed to change. In the 1990s the sustainable skyscraper made its introduction. A new structure that takes into account orientation, geographical location, social and economic context and new technology aimed at energy intensity reduction and a healthy indoor climate. The next paragraphs will explain how energy consumption in buildings is influenced and how energy consumption is related to sustainability.

This chapter answers the following sub-questions:

a. What does the energy consumption distribution in high rise look like?
b. What factors influence energy consumption in high rise?
c. Which climate installations can use renewables-based systems as energy input?
d. What is the energy supply and demand balance for a building and its context?

4.2 Factors that influence the energy consumption of buildings

Energy consumption in buildings is dependent on the building’s design and the presence and type of climate systems. It is the responsibility of architects and engineers to adapt the building and system design to minimize energy loads and maximize comfort. However, the influence of the engineers and architects only goes so far. The building occupants will determine when systems are put to use and how efficiently they are used. The designers and engineers should try to provide an indoor climate that needs little input by occupants, because of the complexity of energy systems. In order to understand energy consumption in buildings, it is useful to categorise the influencing factors. In short, there are 7 factors that influence energy consumption in buildings (Yu, Fung, Haghighat, Yoshino, & Morofsky, 2011):

1. Climate (e.g., outdoor air temperature, solar radiation, wind velocity, etc.),
2. Building-related characteristics (e.g., type, area, orientation, etc.)
3. User-related characteristics, except for social and economic factors (e.g., user presence, etc.),
4. Building services systems and operation (e.g., space cooling/heating, hot water supplying, etc.),
5. Building occupants’ behaviour and activities,
6. Social and economic factors (e.g., degree of education, energy cost, etc.), and
7. Indoor environmental quality required.

4.2.1 Climate

The climate zone affects the buildings contained in it by outdoor temperature, humidity and precipitation, wind direction and velocity, solar radiance and the sun path. Each of those climate characteristics differs for different location on the planet. This thesis focuses on a building (De Rotterdam) within the temperate climate zone. The temperate climate zone consists of areas that lay on the eastern side of the US and China and the west of Europe and the central-eastern part of South America (Met Office, 2012). However, local climates may vary strongly from the averages of the climate zone a building is located in. For example, an urban environment already has a different local climate than a rural environment within the same climate zone. Urban areas are generally warmer than rural areas. This can have positive effects on a buildings heat load in cold climates (less heating required), or negative effects in already hot climates (more cooling needed) (Stewart & Oke, 2012). The urban zones become exceptions to the rules, possibly tainting average climate data for larger zones. On an even smaller scale, high rise is affected by the microclimate. The microclimate is influenced by other structures. They can form wind tunnels or cast shadows. Water bodies, high trees, open fields all have different effects on the microclimate within an area. When designing a building or a building element, it is therefore of importance to not only include the climate zone statistics into the design, but also the local context.

To summarize this, the climate can affect energy consumption (and comfort) through these elements:

1. Dry-bulb air temperature
2. Relative humidity
3. Precipitation
4. Solar radiation and daylight
5. Wind direction and velocity

4.2.2 Building-related characteristics

High rise generally consumes more energy than low rise. This is because high rise needs infrastructure that moves people and goods
(ventilation air, water, products) vertically. The function(s) contained inside a building have different EUIs. Office buildings use more electronic equipment per square meter than a residential building of the same shape and size and they have a higher occupancy level (more people per square meter). The equipment results in a higher energy demand directly, but it also releases a lot of energy into the offices as heat, just like people do. A desktop and monitor provide about 130W of heat (University, 2015). So the buildings function, which could also be dubbed a user-related characteristic, already determines some influential factors. The orientation and percentage of glazed surface area (window-to-wall ratio) influence internal gains by solar radiation. Glazed areas orientated south, acquire more solar irradiation than glazed areas orientated north. Blinds, reflective glazing or smaller window sizes can reduce the solar gains. But they also reduce light transmittance. High daylight availability means electric lighting can stay switched off during most of the day, depending on the location inside the building. While solar gain reduction in summer is desirable to reduce heating loads and cooling demand, in winter solar gains reduce the need for space heating. The heating and cooling load are further influenced by the heat transfer characteristics of the façade, but also by a building's mass. Buildings with high thermal mass, can absorb more of the heat into its materials. It takes more time for these materials to absorb the heat before it starts to radiate back into the room. Exposed mass can have a stronger effect than mass hidden behind false floors or ceilings that is not in contact with the circulating air (Gratia & De Herde, 2003).

4.2.3 User-related characteristics
A factor that influences the energy demand for cooling and for ventilation is the occupant density. A factor strongly related to the type and function of a building. Figure 4.2 shows the average office space per worker for countries within the temperate climate zone in Europe. An office worker has a metabolic rate of 135W. In a dense office in London, office workers produce 14W/m² of heat. In Dusseldorf, this would on average be 5,6W/m². Rotterdam has an average of 18m² of floor space per office worker.

By breathing and transpiring humans also increase the relative humidity of rooms. This affects the perception of indoor air quality. The higher the indoor temperature gets, the more relative humidity influences the perception of air quality (Fang, Clausen, & Fanger, 1998).

4.2.4 Building services systems and operation
A building has a lot of installations that ensure proper usability and a comfortable indoor climate.

Office space per office workstation

![Figure 4.2: Office space per office workstation](image)

Building service systems include all operations and installations concerning people's movement, health and safety, communication networks, lighting and more.

4.2.5 Building occupants' behaviour and activities
Occupants produce heat. The amount of heat is based on their activity. People in a gym or children in school will have a higher metabolic rates than an office worker. People's activities therefore influence internal gains. People's activities also affect the buildings indoor climate based on the equipment they use. Electronic devices produce heat, but in some cases they also release particulate matter. The activities can thus influence indoor air quality not in terms of temperature and humidity but by releasing polluting particles. Occupants can often adjust the indoor climate to their needs, but the degree to which they can influence the indoor climate depends on the function of the building, the façade design and the integrated (control) systems. For example, in an office building the temperature and ventilation rate

Figure 4.2: Office space per office workstation, source: (DTZ Research, 2008)
are often automated and regulated centrally for the entire building, but occupants can sometimes open windows or operate blinds manually, thus influencing indoor climate conditions. Depending on the function of the building, occupants will have different options and restrictions for manually trying to influence climate comfort. In residential buildings, occupants have more possibilities than visitors of a public library or gym for example.

4.2.6 Social and economic factors
Social norms have influence on human behaviour (Goldstein, Cialdini, & Griskevicius, 2008). A study by Goldstein et al., into towel reuse in hotels compared the effect of two signs. The first sign appealed to the eco-mindedness of people and the second sign said that the majority of people reused their towels. The latter proved to be more effective. A different study showed similar results. Finding office workers to switch the light off after a meeting more often when prompted by a normative prompt (that showed how much people switched the light off) than a regular prompt (Tetlow, Beaman, Elmualim, & Couling, 2012). Energy consumption is also influenced by who pays for the energy directly (Graham, Burnett, & Knowles, 2010). A study into mid- and high rise residential towers in British Columbia, Canada, showed that when someone other than the occupant pays the electricity bill the energy intensity increased by more than 100%.

Economic factors are factors such as energy prices, but also the investment capital available to construct a building, or the wealth of occupants and companies.

4.2.7 Indoor environmental quality required
Building regulations are in place to ensure the health and safety of occupants and guarantee fitness and technical quality of a building. Building regulations set the minimum requirements (or standards) for buildings and structures.
4.3 Energy consumption breakdown

There are different statistics available on energy consumption in buildings. Although high rise can contain almost all sectors, two sectors are clarified in this chapter, because they reflect the mass of high rise: the residential and office sector.

4.3.1 Residential sector

Table 4.2 shows a breakdown of energy consumption in households. It shows the energy end use distribution of the entire US and the state of New York, because the whole of the US does not lay within the temperate climate zone. The energy end use of the state of New York (US (NY)), The UK, The Netherlands (NL) and the lower mainland of British Columbia (BC), Canada are also displayed. There is a clear difference between the energy used for lighting and appliances and space heating and cooling between the two European countries and the US. Energy use for DHW is similar for all, except BC. This might be due to the fact that some of the buildings examined in the study used hot water for space heating. The difference in electricity consumption for lighting and appliances can stem from many factors. These include among others: social and economic factors (behaviour due to culture, price of energy) and energy efficiency of appliances.

Electricity consumption in US households appears to be much higher than in the UK or The Netherlands. However, if electricity consumption is divided by the average floor space of a household, the differences are smaller. The average floor space of a house in the US (222m²), is more than twice that of a house in the UK (88m²) and almost twice that of a Dutch house (120m²). Figure 4.3 shows the total energy consumption of households in The Netherlands between 1975 and 2012. There have been some peaks in gas consumption around 1980, 1996 and 2010, but overall it shows a decline. In the last 35 years, gas consumption has declined by 40%. The same cannot be said for electricity consumption. Electricity consumption per household is almost constant. It increases and declines little, even though people use more appliances now than they did 30 years ago. The appliances that are used have to meet higher energy standards than 30 years ago and lighting technology has led to fixtures that consume a fifth of the energy of the incandescent light bulb.

Residential units in high rise can have certain advantages over low rise units. The biggest chunk of the total energy consumption is used for cooling and heating. High rise units have less transmission losses compared to low rise houses. For example, apartments in the Netherlands have an average gas consumption of 1100m³ annually, compared to 1500m³ for single family row-houses (Milieu Centraal). Table 4.3 shows a comparison of the yearly heat and electricity demand based on different sources and regulations. It shows how stricter regulations of the Dutch building decree influence the yearly heat demand. The Passive House standard maximum is shown because it reflects on a trend of using less and less heating energy, but more electricity. Lastly, these numbers are compared to actual national averages for Dutch rowhouses and Dutch flats. Flats and rowhouses have the same electricity consumption based on household consumption. However, electricity consumption in high rise will be influenced by common that need lighting and ventilation and elevators. The heating demand is lower, probably due to much smaller energy losses through surfaces. A study into multi-unit residential buildings (MURBs) in the Lower Mainland of Canada showed an average annual energy consumption per household in British Columbia of 212kWh/m² (with a range of 144kWh – 299kWh/m²). Electricity consumption has a 49% share (102kWh/m²). Of the total electricity consumption, 57% was consumed by households and 43% was needed for equipment and lighting in common areas. The large share of electricity consumption in BC compared to NL is because a large part of the energy consumption for heating is electric, as opposed to gas in NL. Lastly it is interesting to look at the diurnal pattern of energy consumption for households. Although the peak loads shown in Figure 4.4 are predictable (they show after office hours), the loads between 6:30h and 17:00h are high. These graphs show the average electricity loads for working days and holidays for 250 households across England.
Energy consumption households 1975 - 2012

Figure 4.3: Energy consumption in households, source: CBS, The Netherlands

Table 4.3: The R-values from the 2003 and 2012 Dutch building decrees are used for the walls (2.5 m²K/W and 4.5 m²K/W) and windows (0.24 m²K/W and 0.61 m²K/W). The closed façade is 30 m² and the windows have an area of 20 m². The data for average electricity and gas consumption are CBS data (source).

<table>
<thead>
<tr>
<th>Annual electricity consumption</th>
<th>US (average)</th>
<th>US (NY)</th>
<th>UK</th>
<th>NL</th>
<th>BC (HR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumption per household [kWh]</td>
<td>10.908</td>
<td>7.224</td>
<td>4.192</td>
<td>3.150</td>
<td>-</td>
</tr>
<tr>
<td>Average floor space per house [m²]</td>
<td>222</td>
<td>222</td>
<td>88</td>
<td>120</td>
<td>-</td>
</tr>
<tr>
<td>Consumption per m²</td>
<td>49</td>
<td>33</td>
<td>48</td>
<td>26</td>
<td>21</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Energy end use</th>
<th>US (average)</th>
<th>US (NY)</th>
<th>UK</th>
<th>NL</th>
<th>BC (HR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating and cooling</td>
<td>48</td>
<td>57</td>
<td>66</td>
<td>68</td>
<td>46</td>
</tr>
<tr>
<td>Domestic hot water (DHW)</td>
<td>18</td>
<td>17</td>
<td>17</td>
<td>18</td>
<td>32</td>
</tr>
<tr>
<td>Lighting and appliances</td>
<td>35</td>
<td>26</td>
<td>17</td>
<td>13</td>
<td>21</td>
</tr>
</tbody>
</table>


Figure 4.4: Diurnal electricity loads for households, source: Godoy-Shimizu, Palmer, and Terry (2014).
4.3.2 Office buildings

Office buildings tend to vary more in climate installations, but they have strict occupancy hours. Figure 4.6 and Figure 4.5 both show energy consumption breakdowns for office buildings in the UK. The first breakdown is for a naturally ventilated office and the second for an air-conditioned office. Steemers (2003) explains that space heating is not the most energy demanding factor in office buildings, but lighting and air-conditioning are. It thus makes sense to reduce the need for space cooling and artificial lighting. This has implications for the maximum building depth, which is set at between 12 and 15m. Buildings with this depth, which are naturally ventilated use up to 40% less primary energy than their air-conditioned counterparts. For deep office floor plans however, the energy consumption increase for air-conditioning is only around 20%, because deep buildings with natural ventilation will need to be supplemented more with fresh air through a mechanical ventilation system.

Air-conditioning logically follows a mirrored path compared to heating, and thus reaches its peak demands in the summer months. Figure 4.7 shows a diurnal energy end use graph for the IBR building in Shenzhen, China. 21% of its annual energy end use is accounted for by the air-conditioning and the mechanical systems only account for 8% of the annual energy consumption (Diamond et al., 2013). The energy consumption for cooling at 29% is thus lower than for the office buildings in the UK (34%) even though Shenzhen has higher average temperatures than the UK, because of its subtropical climate. Figure 4.7 and Figure 4.8 also shows that the share of air-conditioning in the summer months is much higher than the yearly average. This building has a relatively low energy use intensity (EUI) at 63kWh/m².

Figure 4.5: energy consumption breakdown for air-conditioned offices in the UK, source: K. Steemers, C. Ratti, informing bioclimatic design (1999)

Figure 4.6: energy consumption breakdown for naturally ventilated offices in the UK, source: K. Steemers, C. Ratti, informing bioclimatic design (1999)

Figure 4.7: hourly end use of IBR building Shenzhen, source: Diamond et al. (2013)

Figure 4.8: monthly IBR energy end use, source: Li, C., Hong, T., & Yan, D. (2014)
4.3.3 Combined consumption curves

A consumption curve is the curve that describes the energy consumption over a specific time period. Such as shown in Figure 4.4 and Figure 4.7. These curves are however in different units, so it is difficult to see the direct relation between the two. In this paragraph both graphs are translated into energy consumption over the total floor areas of both offices and residential units and energy consumption per square meter of floor area. To create the curves shown in Figure 4.9, Figure 4.10 and Figure 4.11, which are based on estimated data, some assumptions have to be made:

- The Dutch housing stock contains 7.4 million houses with an average floor area of 120m², which brings the total floor area to 888 million square meters. To project the graphs of UK households onto the Dutch housing stock, the consumption is averaged over a floor area of 120m² and multiplied by 888 million to achieve the total consumption pattern for the entire building stock.

- The office building stock contains approximately 50 million square meters of floor area. The IBR building used as example in the previous paragraph has a floor area of 18,000m² and is used as a reference for office energy consumption, because of its low EUI of 63kWh/m² and the presence of a cooling system that shows a clear seasonal pattern (Figure 4.8) which relates to the seasonal pattern of The Netherlands. The EUI and diurnal pattern are multiplied by 50 million to find the consumption curve for the total office stock.

From the resulting energy curves it can be concluded that:

- The EUI of offices is larger than that of housing, but because the total housing stock is much larger, the total energy demand tops the office demand.

- The peak in total energy consumption is found between 18:00 hours and 20:00 hours, a time at which energy production based on solar energy will not be available year round.

- If the housing stock could produce approximately 30% more energy than their own demand, starting from 8:00 hours and ending at 18:00 hours, the office demand could be met.
The potential for high rise envelopes as energy production units | Anne Leeuw

Figure 4.11: Diurnal energy consumption in kWh/m² based on the graphs of Diamond et al. (2013) and Godoy-Shimizu et al. (2014)

Figure 4.10: Diurnal energy consumption for the building stock in kWh based on the graphs of Diamond et al. (2013) and Godoy-Shimizu et al. (2014)

Figure 4.9: Diurnal energy consumption of de Rotterdam in kWh/m² based on the graphs of Diamond et al. (2013) and Godoy-Shimizu et al. (2014)
4.4 Heating, cooling and ventilation systems

The systems for heating, cooling and ventilation are combined under the term HVAC. The HVAC system of a building has 3 functions (Designing Buildings, 2015c):

1. Maintain indoor air quality
2. Regulate indoor temperatures
3. Regulate humidity

HVAC systems can be placed centrally in a building and they require ducts (air) and piping (water) to reach and influence the climate in different zones or rooms of the building. HVAC systems can be designed for zones, entire buildings or single rooms, so the scale of a system can vary. From chapter 4.2: FACTORS THAT INFLUENCE ENERGY CONSUMPTION, it has become clear that HVAC systems consume a lot of energy. However, there are also passive HVAC systems. These systems are not based on installations, but on natural processes of variable air pressure and solar gain to regulate fresh air inflow, temperature and humidity. These passive systems generally require no energy, but they are often insufficient by themselves to create an acceptable level of comfort. Passive systems can be mixed with active systems. This creates a hybrid system which goal should be to lower the energy demand. However, some passive strategies can be counter effective to active systems and actually increase energy consumption. An example is a conditioned space where air quality, temperature and humidity are regulated through a central system, but there are operable windows to control the indoor climate during warmer months. In the heating season, people could open the windows which would lead to higher heating loads. Some examples of different HVAC systems, both active, passive and how they could mix, are described in the next paragraphs. They do not provide information on all possible systems and combinations, but on a selection of frequently used systems and combinations.

### 4.4.1 Heat generation

<table>
<thead>
<tr>
<th>Generators</th>
<th>Fuel/source</th>
<th>Bio fuel?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boilers</td>
<td>Gas</td>
<td>Yes</td>
</tr>
<tr>
<td>Solid fuel burners</td>
<td>Solid fuels</td>
<td>Yes</td>
</tr>
<tr>
<td>Combined heat and power (CHP) plants</td>
<td>Gas, oil, mass</td>
<td>Yes</td>
</tr>
<tr>
<td>Electrical heaters</td>
<td>Electricity</td>
<td>-</td>
</tr>
<tr>
<td>Gas heaters</td>
<td>Gas</td>
<td>Yes</td>
</tr>
<tr>
<td>Heat pumps</td>
<td>Electricity</td>
<td>-</td>
</tr>
</tbody>
</table>

- Heat recovery
- Solar gain
- Internal heat loads
- Solar thermal
- Geothermal
- Ground source
- Water source

Table 4.4: Heat generators and their fuel or energy source. Source: Designingbuildings.co.uk/wiki/Building_heating_systems (2015)

### 4.4.2 Heat distribution

Heat is generated and then distributed through ducts or pipes by air or water. The generated heat can be delivered to a space at low temperatures (20°C – 35°C) that are slightly higher than the required temperature or at high temperatures (50°C - 80°C). A system that spreads the heat across the space evenly is more often a low temperature system, such as underfloor heating or radiant ceilings. A high temperature system uses less surface to distribute heat, for example by separate radiators, and thus requires higher temperatures to adequately heat a room.

### 4.4.3 Heating system examples

Geothermal combined with a heat pump. A heat pump has (depending on the input temperature of the source) an efficiency (COP) of up to 500% and is powered by electricity. A heat pump can work with an air and water side in which it uses outdoor air as a source and the heat is exchanged onto water or it can work with water on the input side and on the output side. When the temperature difference between the source and output rises, the efficiency drops quickly. Combining a heat pump with a geothermal source ensures a high COP throughout the year. While the outdoor temperature fluctuates, the ground temperature stays more constant. The output temperature of the heat pump is low (to keep the efficiency high) and it therefore requires a low
temperature distribution system. The distribution system could be a radiant ceiling or underfloor heating for example. This system will then only require electricity to run the pumps and compressors. The system is shown for a dwelling in Figure 4.13.

**Combined heat and power (CHP)** is the generation of electricity and heat in one system. The engine or turbine which produces electricity is also producing heat. This heat is captured and redistributed so it becomes useful energy. This increases the efficiency of CHP to over 80% (Rosen, Le, & Dincer, 2005). The heat that is recovered can also be used in an absorption chiller to provide cooling (Dynamic Energy, n.d.). This type of system is sometimes referred to tri-generation. A schematic representation is shown in Figure 4.12. The engine or turbine has a fuel to electricity efficiency of up to 35%.

A conventional system would be using a condensing (gas) or electric boiler to heat water up to 60°C - 80°C and distribute the hot water through pipes and radiators. The radiators cause convection (it heats the air around the radiator which starts an air flow because the warmer air moves up and away from the radiator) and objects close to the radiator are heated through radiation. This system uses electricity or gas as a source. Both boilers have an efficiency of approximately 100%, but heating water with electricity is economically much less interesting. In the Netherlands 1m³ of gas costs €0,62 which is equivalent to 9,78kWh and a kWh of electricity costs €0,22 (Milieu Centraal, n.d.).

A passive heating system can be a trombe wall, where a glass surface is used to capture heat between the wall and the glazing. The high mass wall accumulates this heat and radiates it into the adjacent space. The space between the glass surface and the trombe wall can contain openings towards the inner space to heat the air.

Another passive heating strategy is using a large glazed surface to capture solar gain in a buffer zone. The buffer can be a cavity of a double wall in a cold climate. Energy loss through the inner wall is then reduced, because the temperature in the cavity is high than the outdoor temperature. Or the buffer zone can be a larger zone that would need a lot of heating otherwise.
4.4.1.4 Cooling system examples

Conventional air conditioners are perhaps the most well-known cooling systems. However the term can be misleading. An air conditioner unit functions like a heat pump, but instead of using the outdoor heat source and further increasing the heat, it uses the indoor heat as the heat source and blows the heated air out the other side while the cooled air is blown back inside. This system warms up the outdoor air and is a contributor to the urban heat island effect (it creates waste heat). Especially because the warmer it gets, the higher the demand and more waste heat will be blown into the environment. A new system uses ice to reduce the energy demand and the amount of waste heat that's generated. When the temperature is low a heat pump is used to produce ice. The ice is stored in a tank and used during the day to dampen the energy consumption during peak hours (Ice Energy, n.d.).

Heat exchange with ground or water can provide cooling by putting ducts in the ground or pipes in water bodies. The water and ground have a temperature below the desired indoor temperature. Air or water is cooled through the ducts or pipes and used to cool the ventilation air that is blown into the building or the chilled water which is run through radiant ceilings or floors.

Active evaporative cooling makes use of the phase change of water from a liquid to a gaseous state. When water condenses, heat is released (Designing Buildings, 2015a). Evaporative cooling can be direct or indirect. With direct evaporative cooling water is sprayed onto fresh air, which cools down and flows into the space. The humidity of the air in the space will also rise, which is not always desirable. Indirect evaporative cooling uses a heat exchanger to separate the humid air stream from the air stream that is blown into the space (Wescor, n.d.). A disadvantage of the direct system is that in a badly maintained direct system, bacteria that accumulate and grow in the system can get into the airstream. A diagram of the systems is shown in Figure 4.15.

Absorption cooling functions similarly to compression refrigeration, but instead of using electricity for the compressor (used for compression cooling) it uses heat as input for compression. Figure 4.16 Shows how an absorption chiller works.

Passive evaporative cooling can be achieved by introducing ponds in a building or spraying water onto a façade or roof. The water will slowly evaporate, subtracting heat from the surface and cooling the surroundings.

Natural ventilation is another form of passive cooling where the outdoor air streams in through windows or ducts and cools a space. Natural ventilation can introduce problems when the outdoor air quality is poor, when the building very deep or when there is lots of noise. Buildings that have a high demand for fresh air, often have a supplementary mechanical ventilation system.
4.4.1.5 Mixed system examples

Some buildings will require both cooling and heating. Some of the systems described earlier lend themselves for combinations.

**Geothermal systems with a reversible heat pump** use the stable ground temperature in winter and summer to feed the heat pump. In winter the heat pump uses ground water which has a higher temperature than outside air as input and in summer the ground temperature is lower than the outdoor temperature so it can be used for cooling.

**Geothermal systems without a heat pump** use the ground temperature to cool water that runs through the building in summer through a heat exchanger. When passing through the heat exchanger the outlet stream is warmed up. This warmer water can be stored and used in winter to heat the building. In winter, the warm water passes through a heat exchanger and the cool water then flows back to storage, which is used in summer.

**Reversible heat pumps combined with heat exchangers** provide cooling in summer and heating in winter. Without connecting them to a source with a stable temperature, the efficiency is compromised. The system will require a lot of energy during relatively hot periods and relatively cold periods, because the difference between input and output temperature is large.

**Tri-generation** functions like a CHP system, but an absorption chiller is added. The absorption chiller uses heat to produce chilled water (it is described in the previous paragraph).

**Combining passive with active** systems are an option if for example the cooling demand is little and the heating demand is large. During cold periods an active heating system generates and distributes heat and during the hot periods cooling is acquired by natural ventilation. A system that only requires little heating but cooling for most periods can have an active cooling system combined with dynamic shading. When heating is required, the shades let the sun in and during the cooling period the shading is down to keep the sun out. The chapter on façade design explains more about these kind of design choices.
4.5 Estimating energy demands

4.5.1 Heat balance

The heat balance ($Q_{\text{tot}}$) of a building consist of heat losses and heat gains. Within the characteristics described in paragraph 4.3.3 lay the criteria for the heat balance estimation. In a basic steady-state heat balance calculation, the climate data provides daily, hourly and average temperatures. The building characteristics provide information on fabric properties and ventilation and the user-related and occupant characteristics determine further internal gains. The heat balance ($Q_{\text{tot}}$) is the sum of internal gains by people ($Q_p$), equipment ($Q_e$) and lighting ($Q_l$) and climate related gains or losses: solar gains ($Q_s$) through transparent surfaces, ventilation losses ($Q_v$), fabric losses ($Q_f$) and infiltration losses ($Q_i$).

$$Q_{\text{tot}} [W] = Q_p + Q_e + Q_l + Q_v + Q_f$$

$Q_p$ = number of people · metabolic rate

$Q_e [W] = $ total equipment heat output

$Q_l [W] = $ total lighting heat output

$Q_v [W] = I \cdot A \cdot g$

$Q_v [W] = \Delta T \cdot \text{air flow} \left[ \frac{m^3}{s} \right] \cdot c \cdot \rho$

$Q_l [W] = \Delta T \cdot \text{air flow} \left[ \frac{m^3}{s} \right] \cdot c \left[ \frac{J}{kgK} \right] \cdot \rho \left[ \frac{kg}{m^3} \right]$

$Q_f [W] = \Delta T \cdot A \cdot U$

For which:

$I$ = Insolation $\left[ \frac{W}{m^2} \right]$

$A$ = surface area $[m^2]$

$c$ = specific heat of air = 1000 $\frac{J}{kgK}$

$\rho$ = density of air = 1.2 $\frac{kg}{m^3}$

$U$ = U value of fabric $\left[ \frac{W}{m^2K} \right]$

$\Delta T = T_{\text{desired}} - T_{\text{initial}}$

$g = g$ value of the glass (solar transmittance)

4.5.2 Energy for space conditioning

Now that the heat balance is estimated, the energy needed for space conditioning can be calculated. This is the energy required for creating a comfortable space. The system includes ventilation and temperature control for either heating, cooling or both. The formula from the previous paragraphs is a static heat balance equation. It can be used to calculate a worst case scenario for the coldest day of the year or the hottest day of the year, depending on whether heating or cooling is applied. The worst case scenario is the scenario on which the capacity of the energy system is designed. In order to find the annual energy consumption, the formula can be applied to calculate a heat balance for every day or hour of the year to approximate the total energy consumption:

$$Q_{\text{tot hourly}} [W] = \sum_{i=1}^{8670} Q_{p,i} + Q_{e,i} + Q_{l,i} + Q_{v,i} + Q_{f,i} + Q_{i,i}$$

When $Q_{\text{tot hourly}}$ or $Q_{\text{tot}}$ is zero, the room temperature is at balance, because the energy flows are in balance. Watt is the SI-unit for Power. Power is energy [E] divided by a time period [t] in seconds. A year contains 31,536,000 seconds.

The amount of power needed to reach this balance is dependent on the type of installation and the energy content of the medium which is used to produce the energy:

$$E_{\text{input}} [W] = \frac{Q_{\text{period}} \cdot t_{\text{period}}}{E_{\text{inst}}}$$

$Q_{\text{period}} [W] = $ heat balance over a time period

$t_{\text{period}} [s] = $ time period in seconds

Energy density

$E_{\text{inst}} = \text{efficiency of the installation}$

4.5.3 Hot water demand

Real time data on hot water demand is difficult to find. Usually hot water is produced by the same system that provides hot water for a buildings heating system. Vitens provides some data on residential water consumption as shown in Figure 4.17. Water consumption worldwide varies from 85L per day per capita in Portugal to 119 for The Netherlands, 198 for the USA and 375 for Argentina (Vitens, 2013). The amount of hot water which is provided by the central heating system is used for showering and bathing (51,17L and 2,38L), cooking (1,19L), doing the dishes or washing clothes by hand (3,57L and 1,19L). Dishwashers and washing machines generally contain a heating element. Hot water consumption for a dwelling in The Netherlands thus amounts to 59.5 litres of hot water per person per day. The energy required to heat 59.5 litres of water from 14°C to 5014°C can be computed as follows:

$$Q [kJ] = c \cdot m \cdot \Delta T$$

$$Q = 4.19 \cdot 59.5 \cdot 36 = 8974.98kJ \text{ or } 2.5kWh$$
For which:
\[ c \left[ \frac{kJ}{kg} \right] = \text{specific heat of water} = 4.19 \]
\[ m [kg] = \text{mass of heated body} \]
\[ \Delta T = T \text{ input}[^\circ K] - T \text{ output}[^\circ K] \]

For hot water consumption in buildings the Engineering Toolbox provides an estimate of 22 litres per person per day (The Engineering ToolBox, n.d.).

**Figure 4.17:** Water consumption in liters per day per activity for The Netherlands. Source: Vitens (2013)
4.6 Conclusions on energy consumption

This chapter answers the following sub-questions:

a. What does the energy consumption distribution in high rise look like?
b. What factors influence energy consumption in high rise?
c. Which climate installations can use renewables-based systems as energy input?
d. What is the energy supply and demand balance for a building and its context?

Factors that influence energy consumption were explained. They can be separated in categories:

- **Factors that cannot be altered by human behaviour/interaction:**
  1. Climate (e.g., outdoor air temperature, solar radiation, wind velocity, etc.),
  2. Factors which are established in the design phase of a building
  3. Building-related characteristics (e.g., type, area, orientation, etc.)
  4. Building services systems and operation (e.g., space cooling/heating, hot water supplying, etc.),
  5. Factors that can be influenced when a building is in operation:
  6. User-related characteristics, except for social and economic factors (e.g., user presence, etc.),
  7. Building occupants' behaviour and activities,
  8. Social and economic factors (e.g., degree of education, energy cost, etc.), and
  9. Indoor environmental quality required.

The first category we cannot influence directly. The second category represents how a building is designed to work within the outdoor climate. In this category measures should be taken to adapt a building to its local climate (2), meaning that as little energy as possible is required to maintain comfortable living and/or working environments (3). The last category represents the 'human factor'. The factors (4, 5, 6 and 7) in this category decides how factor 2 and 3 are given shape during design and construction and how they are being put to use during operation. The last factors are thus the deciding factors for the energy demand and consumption of a building.

Low rise energy consumption differs from high rise energy consumption most clearly in terms of heating. The heat loss surface is much smaller for apartments than for row houses. The difference in electricity consumption is less clear, but function dependent. Office buildings have a higher energy use intensity than residential units because they require more climate installations, due to occupancy levels and equipment.

The difference in energy demand for hot water, electricity, heating and cooling and the daily energy demand (curve) shows how energy demand and supply could be balanced between buildings with different functions and operating hours, see Figure 4.18. The energy demand for residential buildings is lowest between office hours, so overproduction and redistribution could close the gap for the high energy demand for office buildings during office hours. Balancing energy streams is in line with the new stepped strategy, because balancing energy streams is about managing waste streams (excess energy).

Heating and cooling can be provided by different systems that require one or a combination of these (re)sources:

- **Free (re)sources:**
  1. A ground source
  2. A nearby water body
  3. Solar thermal energy
- **Costly resources:**
  1. Fuel or biomass
  2. Electricity

In order to reduce the energy demand of a building, it is important to look at the climate system to decide which energy form or resource needs to be produced or incorporated into the design. This way, transport losses or transport energy (for fuel or biomass) are minimized.
Design guidelines/boundary conditions for energy demand and consumption

<table>
<thead>
<tr>
<th>Occupancy</th>
<th>Dwelling: 2pax/dwelling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Office: 1pax/18m²</td>
</tr>
<tr>
<td>Electricity</td>
<td>Adapt production to demand curves of a buildings context or to an even larger scale</td>
</tr>
<tr>
<td>Hot water</td>
<td>0.9kWh/person/day for offices</td>
</tr>
<tr>
<td></td>
<td>2.5kWh/person/day for dwellings</td>
</tr>
</tbody>
</table>

Table 4.5: Design guidelines and boundary conditions that are used for energy modelling and energy demand and production potential calculations.

**Figure 4.18:** Comparison of energy patterns for residential units and offices, own ill.

**Figure 4.19:** Energy source demand by different systems. Dark grey = high demand, medium dark grey = medium demand, light grey = low demand. Own ill.
5 ENERGY PRODUCTION

5.1 Introduction

Whenever we are inside a building, we require the indoor temperature to be in a specific range, we require enough fresh air and sufficient lighting. All of these requirements need energy. The previous chapter explained that heating and cooling can be provided by different systems that require thermal energy, electricity or both. The energy (re)sources can either be harvested, produced or taken from the grid. To be able to create zero energy high rise, energy must be produced on-site. If fuel is required, this must also be produced on-site. This chapter provides information on the availability of renewable resources and the status quo of renewables-based energy production related to the built environment. In this context, three categories are discussed:

- The sun as a source for thermal energy and electricity production.
- Wind as a source for electricity production.
- Biomass as a source of biofuel for thermal energy production and electricity production.

In this chapter, the following questions are answered:

a. Which renewables-based energy production systems are suitable for façade-integration?

b. What is the efficiency of different renewables-based energy production systems?

c. How can you assess the availability of renewable resources around high rise?
5.2 Low grade versus high grade energy

Renewable energy sources have to be transformed to usable energy. Energy can either be high grade or low grade. The division depends on how easy the energy can be transformed into other forms of energy. Exergy is a term which describes the usefulness of energy.

*The maximum fraction of an energy form which (in a reversible process) can be transformed into work is called exergy. The remaining part is called anergy, and this corresponds to the waste heat.* (Honerkamp, 2002, p. 298)

Solar energy (radiant) is transformed into thermal energy or electrical energy. Wind energy (kinetic), is transformed into electric energy (Wind energy development, n.d.). Biomass is modified to create biofuel (potential energy). Through combustion the potential energy is released as mechanical energy and then transformed into electrical energy. In this process heat is released which can be recovered in the form of thermal energy. Electric energy is easily converted into thermal energy and qualifies as high grade energy. Thermal energy to electrical energy conversion has a much lower efficiency (NPTEL, n.d.). Thermal energy is thus rated as low grade energy. Fuel is different, because it stores potential energy. The potential energy can be released as thermal energy or mechanical and then electrical energy. By creating mechanical energy, heat is a waste product. Fuel is thus somewhere in between the two.
5.3 Renewable resources

5.3.1 Sun

In theory, the surfaces of the Earth receives enough solar irradiation to power the world, as shown in Figure 5.2. The solar irradiance is not the same everywhere on Earth. Figure 5.3 shows that irradiance is highest, not on the equator, but just above and below. The northern hemisphere receives the least solar irradiance, but still around 1000kWh/m² annually. Low energy office buildings have an annual total energy demand of 40 to 100 kWh/m². An average Dutch household has an annual electricity demand of 30kWh/m². Solar irradiance thus has high potential for growth. The actual potential is defined by technical feasibility. Estimates for the technical potential reach from 50,000EJ to 280,000EJ a year (United Nations Development Programme, United Nations Department of Economic and Social Affairs, & World Energy Council, 2000); (GEA, 2012). Still plenty for the worlds demand.

5.3.1.1 Solar irradiance in the built environment

Solar irradiance differs according to the location on earth, the season and the time of day, because the intensity of solar radiation has both a diurnal and seasonal cycle. During a year the earth rotates around its polar axis, which stands at angle of approximately 23.5° in summer and -23.5° in winter (Iqbal, 2012). Figure 5.1 shows that the solar paths for winter and summer at 60 degrees latitude on the Northern hemisphere vary quite a bit. In winter the solar altitude is lower and the sun rises later and sets sooner. The changing intensity and position of the sun determines the solar irradiance on certain surfaces. Solar radiation that reaches a surfaces consists of three different types of radiation: direct (or beam) radiation, diffuse radiation and reflected radiation. The total radiation, thus diffuse, reflected and direct is called the global radiation.

The direct radiation is available for numerous locations on earth. With this number, the insolation on a surface can be calculated quickly. Below, this calculation is done for 12:00 hours on June 21st in Rotterdam for a horizontal surface (β = 0°) and a vertical surface (β = 90°) facing south.

\[
\Phi = \text{Latitude of location} = 55° \\
n = \text{day number} = 172 \\
S = \text{maximum direct radiation} = 1000 \text{[W/m}^2\text{]} \\
HA = \text{hour angle} \\
\delta = \text{declination angle} \\
= sin^{-1}(\sin(23.45°) \sin\left(\frac{360}{365}(284 + n)\right)) = 23.45° \\
Z = \text{Zenith angle} \\
= \cos^{-1}(\sin\Phi \sin\delta + \cos\Phi \cos \delta \cos HA) \\
= 31.55° \\
\]

\[
l_x = \text{Insolation on horizontal surface} \\
= S \times \cos(Z) = 1000\cos31.55° \\
= 852.18\text{W/m}^2
\]

For a tilted surface, instead of the Zenith angle, the elevation angle is used.

\[
\beta = \text{tilt angle} = 90° \\
\alpha = \text{elevation angle} = 90° - Z = 90° - 31.55° = 58.45° \\
l_\text{vertical} = \text{Insolation on vertical surface} \\
= l_x \times \sin(\alpha + \beta) = 852.18 \times \sin(58.45° + 90°) \\
= 523.25\text{W/m}^2
\]
THE POTENTIAL FOR HIGH RISE ENVELOPES AS ENERGY PRODUCTION UNITS | ANNE LEEUW

**Figure 5.1:** Angels and tilt of the sun, source: xxx

**Figure 5.2:** Solar irradiation, source: GEA, Global Energy Assessment (2012)

**Figure 5.3:** Global solar irradiation per square meter, source: solargis.info (2015)
5.3.2 Wind

Wind, like the sun, is available everywhere but not in the same intensity. For wind, the desire is to have a continuous speed throughout time. Currently, wind energy provides more primary energy than solar power, 1.1EJ as opposed to 0.39EJ (GEA, 2012). GEA sets the technological potential of wind energy at 1250EJ - 2250EJ a year, thus much lower than that of solar power, but a lot higher than hydro power which is estimated to be 50EJ - 60EJ a year. The interesting thing about wind is that wind speeds tend to increase with height (MacKay, 2009). Doubling the height increases wind speed by 10% and wind power by 30%.

In the built environment, wind speeds and directions are affected by the urban texture and general laws for wind speed need to be altered to be accurate (Mertens, 2002). Figure 5.4 is an illustration in which Mertens shows that the roughness of urban texture changes the wind profile. The vector arrows on the left show a regular wind profile, with a low roughness, the right shows how this pattern would change. Figure 5.6 shows that wind flows more ‘fluently’ around an aerodynamic body than around a flat body. Figure 5.5 shows the wind velocity on top of a flat building. This image shows that directly above the roof the wind velocity is relatively low and the vectors point opposite to the wind direction. This indicates that the potential for wind energy in urban areas is not straightforward and placement of wind energy harvesting systems requires careful modelling.

The Dutch KNMI have created a wind map for The Netherlands at a height of 100 meters. The map is shown in Figure 5.7. The average wind speed in Rotterdam is approximately 7 – 7.5m/s, but at a lower height the annual mean wind speed was reported to be 5.71m/s, measured at Rotterdam Geulhaven and 4.42m/s at the Rotterdam Noord Police station (Yemer, 2010).

**Figure 5.4**: Sketch of a boundary layer profile change due to a step in roughness height. Source: Mertens (2012)

**Figure 5.5**: CFD calculation of the velocity vectors around a 2D building, source: Mertens (2012)

**Figure 5.6**: CFD calculation of the streamlines around an aerodynamic and flat body. Source: Mertens (2012)
Figure 5.8: Global wind resource Source: 3 Tier, 2011

Figure 5.7: Wind speed in the Netherlands at 100m altitude, source: KNMI (2014)
5.3.3 Biomass

Algae use carbon dioxide, sunlight and water to grow through photosynthesis. When they grow they become rich with oils and other nutrients and can be harvested and processed in different ways to provide different biofuels, such as biodiesel, methane and bio-hydrogen. Algal species have varying lipid content relative to the weight of the complete mass. The cultivation can produce more than 30% of the dry weight in oil (Chisti, 2007; Demirbas & Fatih Demirbas, 2011). Table 5.1 shows how much land area is needed for replacing 50% of the US fuel needs for transport by renewable sources. The land area needed for oil production from algal mass is one tenth of that of palm oil, considering only 30% of the algal mass consists of oil. Pfromm, Amanor-Boadu, and Nelson (2011) also conclude that algae cultivation for bio-fuel purposes can provide a sustainable alternative for diesel. Pfromm et al. and Demirbas & Demirbas Fatih both state sources that claim a heating value of 41MJ/kg for oil derived from algal mass, which is almost as high as the heating value for petroleum diesel at 42.7MJ/kg, but lower than that of natural gas at 54MJ/kg. An important note, is that not all types of algae are suitable for biodiesel production and algae cultivation requires controlled conditions. They will be discussed in paragraph 5.8

**Table 5.1:** Comparison of some sources of biodiesel (Chisti, 2007)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Oil yield (L/ha)</th>
<th>Land area needed (Mha)a</th>
<th>Percent of existing US cropping area²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>172</td>
<td>1540</td>
<td>846</td>
</tr>
<tr>
<td>Soybean</td>
<td>446</td>
<td>594</td>
<td>326</td>
</tr>
<tr>
<td>Coconut</td>
<td>2689</td>
<td>99</td>
<td>54</td>
</tr>
<tr>
<td>Oil palm</td>
<td>5950</td>
<td>45</td>
<td>24</td>
</tr>
<tr>
<td>Microalgaeb</td>
<td>136,900</td>
<td>2</td>
<td>1.1</td>
</tr>
<tr>
<td>Microalgaec</td>
<td>58,700</td>
<td>4.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

a. For meeting 50% of all transport fuel needs of the United States.
b. 70% oil (by weight) in biomass.
c. 30% oil (by weight) in biomass.
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5.4 Photovoltaic systems

5.4.1.1 Introduction
Photovoltaics use sunlight to generate electricity. Certain materials absorb photons (from sunlight) and release electrons. The electrons can be captured, which results in an electric current. The principle, already discovered by Becquerel in 1839, was put to use and made viable by space industry in the 1960s (Knier, 2002). It is now the fastest growing supply of renewable energy on earth.

5.4.1.2 Technology overview
Solar modules are applied in three general configurations:
1. Flat (-plate) modules. Flat collectors, where cells are spread across the surface in clear order.
2. Thin film. The cells are arranged on a flexible thin surface that can be transparent.
3. Concentrator-modules. Sunlight is collected on a large surface area and concentrated (with a lens and/or mirrors) onto a smaller area that contains the actual solar cells.

The most commonly used cell structures are described below (Wenham, 2007):

- **Monocrystalline silicon solar cells (MSC)**
  MSC panels contain wafers with crystalline silicon atoms. The atoms are arranged in a very regular pattern. The ideal structure allows for higher solar cell efficiency, but MSC are harder to manufacture and thus more expensive.

- **Polycrystalline silicon solar cells (PSC)**
  PSC panels have groups of crystalline silicon which are not bounded together regularly. They are divided by so called ‘grain boundaries’. This makes the flow of energy less efficient, because it needs to pass the irregular bonds between groups of the crystalline silicon.

- **Thin film solar cells (TFSC)**
  TFSC contains amorphous silicon. That means all bonds are irregular and thus efficiency is lower, but manufacturing costs are also lower than for PSC.
5.4.1.3 System output for PV modules
The power of PV systems is indicated in watt [W] or Watt-peak [Wp]. Modern standardized modules often measure 992mm by 1442mm and produce up to 300Wp. To convert watt-peak to kilowatt-hours the factor 0.85 is used in The Netherlands. An installation with a capacity of 1000Wp delivers approximately 850kWh annually. This factor is an estimate.
The efficiency of consumer available pv-modules ranges between 15% and 21.5%. For multi-junction cells, efficiencies are higher. These type of cells respond to more ranges of the light spectrum and efficiencies increase to 46% (Shahan, 2014), but are for non-specialized applications costs are high.

5.4.1.4 Efficiency limit for solar cells
The limit for efficiency for solar cells using one material (single junction), in this case silicon, as semiconductor is about 30%. In practice, solar cell efficiency is slowly but steadily reaching this limit. The record efficiencies for MSC, PSC and TFSC are 25.6% ±0.5, 20.8% ±0.6 and 10.5% ±0.3 respectively (Green, Emery, Hishikawa, Warta, & Dunlop, 2015). When more materials are used as semiconductors, sunlight is concentrated and cells are stacked, the theoretical limit rises to 75%. The exploration of different atoms than silicon have led to thin film cells with a cell efficiency of 28.8% ±0.9. These cells, made by Alta Devices use gallium and arsenide atoms.

5.4.1.5 Solar tracking and optimal angles
Solar modules are often mounted on a fixed frame. The frame tilt or angle can be optimized according to the sun path for different locations in order to achieve maximum output. The optimal angles are shown in Figure 5.14. Different studies have shown that the energy production can increase by making the frame moveable. This is because the power generation of PV systems is highly dependent on orientation and inclination angle of the system. The optimal orientation and inclination angle to maintain the highest insolation depends on the location of the system, the time of day and the season (Mondol et al., 2007). Figure 5.17 shows the in-plane insolation for different inclinations (tilt angle) and surface Azimuth angles, with 0 being south. The hourly insolation data used by Mondol et al is obtained by a meteorological station located at Aldergrove, Northern Ireland, latitude 54°.

Rizk & Chaiko found that when adding a sun tracker that keeps the solar cells as perpendicular to the sun’s rays as possible, the energy production would be 30% higher on average Figure 5.16 (2008). Another study compares modules moving on two axis to modules with inclining angles, but a fixed orientation. The two-axis tracking system proves to be most effective in increasing the power output (Huld, Suri, & Dunlop, 2008). The results of the study show that for a two axis tracking system, the power output potential rises with 25% - 70% within Europe.

5.4.1.6 Increasing output with static design
Making solar panels dynamic means more moving parts and a bigger construction and a dynamic system requires a (expensive) solar tracking system. By creating a more complex, yet simple structure, that changes the flat PV module into a 3D PV module, system output in kWh/m² can also be increased by a factor 1.3 – 1.8 compared to dual axis tracking and 1.5-4 for static flat panels (Bernardi, Ferralis, Wan, Villalon, & Grossman, 2012). The system also shows less variation in output through seasonal and diurnal climate changes. The results and shapes used in this study are shown in Figure 5.13. Number 1 is the cube, 2 the tall cube and 3 the tower.
5.4.1.7 Transparency

Thin film can be combined with glazing to form transparent solar panels. The efficiency is highly dependent on transparency, meaning, the higher the transparency the lower the efficiency. Regular glazing has a visible light transmittance in the range of 50% - 90% and a g-value in the range of 0.2 – 0.7 (Designing Buildings, 2015b). Transparent cells added onto glazing could provide similar characteristics. Lunt and Bulovic (2011) studied an organic solar cell which had a power conversion efficiency of 1.7 ±0.1% and a visible light transmittance of > 55±2%. A relatively new technology is being explored and developed by Oxford PV, founded by scientists of the Photovoltaic and Optoelectronic Device group of the University of Oxford. They claim that the technology can reach an efficiency of 20.1% (Oxford PV, n.d.), which is comparable to conventional non-transparent solar cell modules.
Figure 5.14: Standard tilting possibilities for PV modules. Source: Solargris.info

Figure 5.15: Integration of glass and solar cells. From left to right; clear glazing, mono-crystalline cells 30% transparency, thin film 50% transparency, thin film 20% transparency. Own ill.

Figure 5.16: Tracking panel versus fixed panel power output. Source: Rizk & Chako (2008)

Figure 5.17: In plane insolation at different tilt angles (Mondol, Yohannis, & Norton, 2007)
5.5 Solar thermal systems

Solar thermal energy systems are a type of heat exchangers. The solar irradiation is caught and transformed into heat. The heat is transferred onto a medium, such as water. These heat exchange systems are called solar thermal collectors.

5.5.1.1 Technology overview

Solar thermal collectors consist of several parts: The solar collector that catches and converts the solar irradiation, a transport medium (e.g. water or air) where the heat is transferred onto and a storage tank to store the heated medium. Like photovoltaic systems, solar thermal collectors come in two forms: non-concentrating and concentrating modules (Kalogirou, 2004). Table 5.2 summarizes the collector types, not by concentrating systems and non-concentrating systems but by stationary and non-stationary systems. Non-concentrating collectors have a concentration ratio of 1 and are stationary. The concentrating collectors have a large area where the irradiation is concentrated towards an absorber with a smaller area, thus the concentration ratio is larger than 1. On average these collectors have a higher output temperature. The thermal efficiency is computed with both the aperture area and the total area used by the system. The aperture area is smaller thus resulting in higher thermal efficiency of 68.7% (Apricus, n.d.) versus 43.7%. Figure 5.18 shows the efficiency of evacuated tube, flat plate and unglazed collectors set off against the difference between output temperature of the collector and the ambient temperature.

- **Flat plate collectors**
  This system is shown in Figure 5.21. Small pipes are placed behind a glass panel in an absorber plate. The back of the panel is insulated to keep the heat in the system.

- **Evacuated tube collectors**
  A schematic view of this system is shown in Figure 5.20. This system is more expensive than the flat panel system, but it can produce higher output temperatures. A vacuum provides insulation and heat pipes containing a fluid such as anti-freeze are used as transport medium.

- **Concentrator systems**
  A number of concentrator systems are shown in Figure 5.19. These systems are more complex and expensive but can produce the highest temperatures. The systems use mirrored surfaces and solar tracking systems to optimize solar gain in the collector.

<table>
<thead>
<tr>
<th>Motion</th>
<th>Collector type</th>
<th>Absorber type</th>
<th>Concentration ratio</th>
<th>Indicative temperature range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stationary</strong></td>
<td>Flat plate collector (FPC)</td>
<td>Flat</td>
<td>1</td>
<td>30–80</td>
</tr>
<tr>
<td></td>
<td>Evacuated tube collector (ETC)</td>
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</tr>
<tr>
<td></td>
<td>Compound parabolic collector (CPC)</td>
<td>Tubular</td>
<td>1–5</td>
<td>60–240</td>
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<tr>
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<td>Linear Fresnel reflector (LFR)</td>
<td>Tubular</td>
<td>10–40</td>
<td>60–250</td>
</tr>
<tr>
<td></td>
<td>(PTC)</td>
<td>Tubular</td>
<td>15–45</td>
<td>60–300</td>
</tr>
<tr>
<td></td>
<td>Cylindrical trough collector (CTC)</td>
<td>Tubular</td>
<td>10–50</td>
<td>60–300</td>
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<td><strong>Two-axes tracking</strong></td>
<td>Parabolic dish reflector (PDR)</td>
<td>Point</td>
<td>100–1000</td>
<td>100–500</td>
</tr>
<tr>
<td></td>
<td>Heliostat field collector (HFC)</td>
<td>Point</td>
<td>100–1500</td>
<td>150–2000</td>
</tr>
</tbody>
</table>

**Table 5.2 Note:** Concentration ratio is defined as the aperture area divided by the receiver/absorber area of the collector.
Figure 5.21: Flat plate solar collector. Source: Kalogirou (2004)

Figure 5.20: Schematic view of an evacuated tube collector. Source: Alternative-Energy-Tutorials.com (n.d.)

Figure 5.19: Schematic view of concentrator systems. Source: Solar-Tower.org.uk (n.d.)
5.6 Solar thermal & photovoltaic systems combined

Considering that photovoltaic (PV) systems can be made partly transparent, and that PV systems accumulate heat, which at some point decreases its efficiency, there might be potential for combining a PV system with a solar thermal (ST) system. These systems have been studied and are often referred to as PV/T systems. While their combined efficiency tends to be higher than singular systems, the cost of PV/T systems is higher. The heat can be transported by either water or air.

5.6.1.1 Technology overview

Prakash (1994) studied a PV/T system as shown in Figure 5.23 where the solar cells are the first layer of the system and either fluid or air flows underneath the cells and an absorbing plate to transfer the heat away from the panel. This study concludes that cell efficiency is increased marginally, but thermal efficiency ranges between 50% - 70% for water heating in duct depths ranging from 1cm to 3cm. A more efficient absorber plate is used by Huang, Lin, Hung, and Sun (2001), as shown in Figure 5.22. They use a constant electric power generation efficiency of 0.09. This study also reviews the primary energy savings efficiency, which is found to be around 0.6. That is higher than for singular PV or ST systems. The thermal efficiency of the system is on average 76% of the thermal efficiency of a regular ST system. Zondag, De Vries, Van Helden, Van Zolingen, and Van Steenhoven (2002) found lower efficiencies for both thermal and electrical energy production, but the area needed to produce 540W for the combined system is only half of the area needed to produce 760W for the separate systems.

Both Prakash and Tripanagnostopoulos, Nousia, Souliotis, and Yianoulis (2002) found that using water as heat transfer medium is more efficient than air. The latter study also showed that increasing thermal efficiency by adding a glass plate causes the electric efficiency to drop.
Figure 5.23: Design of a theoretical PV/T system. Source: Prakash (1994)

Figure 5.22: Design diagram of integrated PV/T system. Source: Huang et al. (2001)
5.7 Wind driven systems

5.7.1.1 Introduction

Wind is available everywhere, but wind velocities vary geographically. Wind driven systems are designed to capture wind flow with moving elements, such as rotors and they transform the mechanical energy into electrical energy. When researching wind energy in urban environments and integrated with buildings it proves to be difficult to find performance data of built systems.

5.7.1.2 Technology potential

This paragraph will go into two types of wind energy systems:

1. Rotational systems:
   Turbines with rotor blades which rotate in a specific direction.

2. Vibrational systems:
   Systems with elements that can move in whatever direction, depending on the direction of wind streams.

Rotational systems


"the typical windmill of today has a rotor diameter of around 54 metres centred at a height of 80 metres; such a machine has a "capacity" of 1MW. The "capacity" or "peak power" is the maximum power the windmill can generate in optimal conditions. Usually, wind turbines are designed to start running at wind speeds somewhere around 3 to 5m/s and to stop if the wind speed reaches gale speeds of 25m/s. The actual average power delivered is the "capacity" multiplied by a factor that describes the fraction of the time that wind conditions are near optimal. This factor, sometimes called the "load factor" or "capacity factor," depends on the site; a typical load factor for a good site in the UK is 30%. In the Netherlands, the typical load factor is 22%; in Germany, it is 19%.

While the size of a high rise building might be comparable to the size of a wind turbine, combining the two provides numerous challenges. In urban environments and around high rise wind flow is turbulent, turbines create noise and vibration and there are safety concerns (Wilson, 2009). Wilson also quotes Randy Swisher of the American Wind Energy Association: "that stress can be transmitted to the building structure, creating substantial problems." Wilson also addresses the economical side and finds that while large scale wind turbines provide relatively low cost energy compared to PV, building integration quickly increases the cost of the installation (the buildings structure needs to be adjusted to the introduced loads and stresses and the efficiency of the turbine reduces quickly and the turbines need more maintenance than PV).

There are projects that incorporate micro-turbines. The smallest ones have a diameter of about 1 meter. Encraft, a British company, has monitored energy production of 26 building mounted micro-turbines. The results of the study show an average annual production of 78kWh and a capacity factor of 0.85% (Encraft, 2009). The capacity factor rises to 4.15% when the number are adapted to exclude downtime.

Mertens (2002) provides us with a theoretical study into wind turbines in the urban environment on high buildings. The study uses start wind speeds of 4m/s and the turbines stop at speeds above 25m/s. Mertens describes several drag-driven, lift-driven (conventional, most cheap system) and hybrid wind turbines. Examples of drag- and lift-driven systems are shown in Figure 5.26. Mertens' models show an energy yield on top of a roof, in an open field, of 3717kWh/year (for a lift-driven turbine), but this figure drops to 1046kWh/year for that same turbine in a city-like environment. If the turbine would be placed around the side of a cylindrical building, the potential power output rises to 1608kWh/year. The turbine used for this study has a rotor area of 6m².

Vibration systems

Another way of harnessing wind energy is to through oscillation. The set-up is shown in Figure 5.25 and Figure 5.24. The system requires wind speeds of at least 2m/s and can produce approximately 54W/m² (Kluger, n.d.) at wind speeds of 10 m/s, but this reduces to approximately 22W/m² for wind speeds around 7m/s and to 1W/m² for speeds below 5m/s. Combining the data from Kluger with the wind speed and frequency data from Yemer (2010) gives an approximation of 6.9W/m² power output for a system at Rotterdam Geulhaven.
**Figure 5.26:** Drag and lift-driven wind turbines, source: Mertens (2012)

**Figure 5.25:** Vibro-wind oscillators. Source: J. Kluger (2010)

**Figure 5.24:** Vibro-wind test setup. Source: Kluger, J., Moon, F., & Rand, R. (2013)
5.8 Algae cultivation

Where wind driven systems and PV-systems provide electricity and solar thermal systems provide heat which can be used directly at the building site, algae can be used as a fuel, but they are not a direct form of energy. However, algae cultivation in a closed system does provide hot water. This paragraph will go into different cultivation systems and cultivation criteria.

5.8.1 Algae production systems

On a horizontal surface, algae can be produced in a raceway pond. This is an open system, placed outdoors mostly. Therefore temperature fluctuations can be large and water is lost through evaporation. Carbon dioxide is used less effectively, because some is lost to the atmosphere. These raceway ponds have lower operating and construction costs, but they also produce less biomass than photobioreactors. Tubular photobioreactors are closed systems that only contain a single species of algae. The conditions inside the systems are controlled more than in the open system. The diameter of the glass or plastic tubes depend on the possibility for sunlight to penetrate the biomass. Because the density of the biomass is high, the diameter of a tube is mostly less than 10cm. On a production plant, the tubes are stacked vertically and the pane of the tubes is orientated North-South. These systems need cooling during daylight hours. Cooling can be provided by spraying water on the tubes (evaporation) or heat exchange through a heat pump.

In High Density Vertical Growth (HDVG)-systems, the algae are packed in polyethylene sleeves that form a closed loop (Ryan, 2009). This system is similar to the tubular photobioreactor. Flat panel reactors are narrow vertical basins. On the bottom of the basin air is blown into the tank through a perforated tube, consequently causing the water to flow and the algae to move around the basin (Posten, 2012).

5.8.1.2 Cultivation

Algae are living mass. The mass needs light to survive and grow. In order to maximize daylight penetration tubular systems are orientated North-South and the surface beneath the system can be covered with a high reflecting coating (Chisti, 2007). Kim et al. (2012) have studied 3 algae species (Chlorella sp., Dunaliella salina and Dunaliella sp.) and their growth rate for different nutrional ions, CO₂ content, pH-values, temperature ranges and illumination. The results show the highest growth rate and biomass production for Dunaliella salina at a temperature of 27°C, a pH-value of 8 and an illuminance of approximately 6000lux. The study also notices the importance of the concentrations of nitrate and phosphate, ions that are found in high concentrations in wastewater.

Rodolfi et al. (2009) tested several marine and freshwater strings (among them Chlorella sp.-strings) under controlled circumstances as well as outdoors. The outdoor system of tubular photobioreactors started to cool down when the water temperature exceeded 30 °C. CO₂ was injected during daylight hours and the pH-value kept between 7.5 and 8.1. They found that the marine strings with the highest growth rates did not necessarily had the highest lipid-content (which is important for bio-diesel production), but the freshwater strings did show higher lipid content for strings with high biomass productivity. Nannochloropsis, a marine string, showed the best characteristics for algal oil production with a growth rate of around 0.21g/L/day and a lipid growth rate ranging between 0.55 - 0.61mg/L/day. This same culture was tested by Sforza, Simionato, Giacometti, Bertucco, and Morosinotto (2012) under different light conditions. They found that culture growth peaked at a light intensity of 150 µE/m²/s, with a duplication time of 0.44 days and showed ‘good growth rates’ between 100 µE/m²/s and 250 µE/m²/s, both showing duplication times of 0.24 days. With a conversion factor of 54 for sunlight (Apogee Instruments, n.d.), these values range between 5400lux and 13500lux.

For a horizontally assembled air-lift system, submerged in a pool to control the temperature, which contains a Phaeodactylum tricornutum culture, much higher growth rates, 1.9g/L/day, were measured (Molina, Fernández, Acién, & Chisti, 2001).
THE POTENTIAL FOR HIGH RISE ENVELOPES AS ENERGY PRODUCTION UNITS | ANNE LEEUW

Figure 5.27: Tubular photobioreactor. Source: IGV Biotech (2013)

Figure 5.28: High density vertical growth. Source: Valcent Products Inc. (n.d.)

Figure 5.29: Photobioreactor system. Source: bott2013studio.wordpress.com (2013)

Figure 5.30: Raceway pond. Source: AlgaeIndustryMagazine (2012)
5.9 Case studies

5.9.1 Photovoltaic systems

Battery Park buildings, New York City, NY, USA
The Battery Park is located on the South side of Manhattan and contains a number of buildings with PV systems. The buildings have PV-systems on the roofs, walls or integrated in windows (Medio, 2013). The architects themselves did not choose to apply PV to the facades, it was a requirement. At least 5% of the building related electricity demand should be met with PV systems. The envelopes, massing and orientation were also largely fixed. That meant the architects did not have much influence on how and where to place the PV modules, because there was a limited space available to them (also due to overshadowing by neighbouring buildings).

The Solaire
The Solaire is a 27-story high building located on the South bank of Manhattan, New York. It is a residential building with 293 units. On the west façade 120.7m² of solar panels are placed as façade cladding (Epstein, 2008) which provide 11kW of power. Above the main entrance, BIPV within the canopy provides another 662W. At the top part of the building, the envelope sets back. The south and west part of this part of the building are covered in 185.8m² of PV that provide 21kW. In the canopy the PV modules replace regular glass and on the facades it replaces cladding. The PV modules are custom shapes and sizes and use recycled silicon. Between 2005 and 2006 the 120.7m² of PV provided 6000kWh of electricity.

The Visionaire
This building, also located in the Battery Park incorporates PV-modules into the façade so that it looks like a continuation of the glass curtain wall. The PV-modules are located on the top part of the West and East façade. The 35-story building has over 420m² of photovoltaic modules, which should provide 48kW of electricity.
5.9.2 Thin film photovoltaic systems

Polysolar curtain walling system
The system integrates a curtain wall system with double glazing and photovoltaic cells. The system has a U-value of 1.2W/m²K and a G-value of 0.42 (Polysolar Ltd., 2013).

5.9.3 Solar thermal systems

Façade elements with integrated evacuated-tube collectors
On the outside of a façade, evacuated tubes are mounted onto mullions. Behind the tubes, perforated rounded mirrors reflect light back onto the tubes. The mirrors thus function like blinds and spread light more diffuse into the room behind. The cooling loads are reduced by 70% - 90% (Bine Information Service, 2013). Within the tubes, temperatures can rise above 80 degrees Celsius throughout the year. In summer, temperatures are the highest and the hot water can even be used for solar thermal cooling. With a perforation of 19% for the reflectors, a g-value of 0.15 is obtained. The collectors can be placed with or without a cover plate. A cover plate of protective glass reduces the solar yield by 2%.

Through simulation the yields of the collectors placed at a 90 degree angle were compared to collectors placed on a roof on an optimal tilt angle. The vertically placed collectors yielded up to 70% of the optimally placed collectors.

The collectors are, in this set-up only reachable from the outside.
Located in a hot region, this office building requires adequate cooling. Cooling is provided through a tri-generation system with an absorption-chiller ("Latest sustainable addition to Sydney’s skyline features absorption cooling," 2012). This office building has a rooftop filled with 315 m² of solar thermal evacuated-tubes which produce approximately 113,400 kW of heat at a thermal efficiency of 36%. This heat is fed into the absorption-chiller and reduces the energy demand from the grid by 13%.

5.9.4 Combined solar thermal and photovoltaic systems

The solar window

This system was introduced in 2003 (Davidsson, Perers, & Karlsson, 2010) and the prototype is tested on a building in Lund, Sweden. An absorber contains PV-cells and reflectors concentrate the irradiation on the absorbers surface. The absorber plate is cooled with water and the heated water is captured and available for domestic use. Test results show that the system provides 35% more electricity than a vertically placed PV-module, but just under 20% less than a PV-module on a 20 degrees tilt. The thermal efficiency was much lower than either a roof or a wall mounted system. Respectively, it required three or two times the surface area.

Figure 5.37: 1 Bligh Street rooftop. Source: ARUP (2012)

Figure 5.38: Schematic view of the solar window. Source: Davidsson, Perers, & Karlsson (2010)

Figure 5.39: Prototype of the solar window. Source: Davidsson, Perers, & Karlsson (2010)
5.9.5 Wind

The Museum of Science, Boston, US

Atop the roof of the Museum of Science in Boston, US, wind turbines with a combined capacity of 15.6kW were installed in 2009 (D. Rabkin & M. Tomusiak, 2012). The total system consisted of 5 different types of turbines (all lift-driven). On average the actual annual power output of the turbines has been 4.229kWh. After a three year monitoring period a team has concluded that the installation was not cost effective because the installation costs were too high and average wind speeds too low. The average wind speed was approximately 3m/s, where it should have at least been 5m/s.

Figure 5.40: Wind turbines on the Museum of Science. Source: Museum of Science wind lab (2012)

Figure 5.41: AVX100s on the Museum of Science, source: J. Hilton (2009)
San Francisco Public Utilities Commission Headquarters
This building, designed by KMD architects, is located in San Francisco, US. 7% of the buildings energy demand is generated on-site, through a combination of PV panels and wind turbines (227,000 kWh/year) ("San francisco public utilities commission headquarters," n.d.). The building has a gross floor area of 25784m² and 13 stories. With no performance data available, it is estimated that the solar panels could deliver up to 120kWh/m² annually. By measuring the buildings perimeters in Google Earth, the area of PV-cells are estimated at 1500m². Assuming the panels could produce 180,000kWh annually, which means the wind turbines are designed to produce some 50,000kWh/year.
Ammophila system for facades by Murtada Alkaabi

A TU Delft student has designed a system which uses wind movement to create pressure differences at two sides of a fixed object. The force is used as mechanical energy which had to be translated to electrical energy. Peters (2014) quotes Alkaabi on the power output:

"If we want to produce seven megawatts of energy, we only need to use 1.3 square miles of surface area," he explains. "That’s less than half what’s needed for 11 big, expensive, and ugly wind turbines."

Figure 5.44: Working principle of ammophila system. Source: M. Alkaabi (n.d.)

Figure 5.45: Facade of beach pavilion. Source: M. Alkaabi (n.d.)
5.9.6 Algae

**Bio Intelligent Quotient (BIQ) building, Hamburg, Germany**

On March 23rd 2013, Arup presented the world’s first building that implements photobioreactors for energy production. 129 flat panel PBR’s are placed on the façade of a residential building, with 15 residential units.

Each panel is 2.5m high, 0.7m wide and 0.2m thick. The PET-panels are mounted on the sun-facing facades and produce heat of up to 40ºC. The heat is used to heat water which is then used for space heating or domestic hot water. Excess heat is stored in tanks. Together the algae panels provide a third of the heat demand. The carbon that’s required to make the algae grow may be supplied from neighbouring sources (Arup, n.d.). The mass that is extracted from the panels can be sold and used for methane or oil production. The efficiency of light to biomass is around 10% and the efficiency of light to heat is around 38%. The expectation is that the system will produce 15 grams of dry biomass per square meter each day (Wurm, 2012). Algae cultivation is thus possible on a façade, but it comes at a cost of €2.500/m².

![Figure 5.46: BIQ Building Hamburg, Flat plate reactor, source: Arup (2013)](image)

![Figure 5.47: BIQ Building in Hamburg, source: Arup (2013)](image)
5.10 Conclusions on energy production

a. Which renewables-based energy production systems are suitable for façade-integration?

b. What is the efficiency of different renewables-based energy production systems?

c. How can you assess the availability of renewable resources around high rise?

As shown by the case studies, all energy production systems show the potential to be integrated within envelopes of buildings. The efficiency and cost of systems varies. Photovoltaics in the form of thin film, introduce lots of possibilities for integration in façades, but their efficiency is low at around 10%. The efficiency of mono-crystalline panels are higher at 25%, but module efficiency is lower at 21.5%. Thermal collectors can return temperatures in a great range, depending on the system, but systems already used on buildings deliver temperatures in a range of 30°C – >90°C at an efficiency of >60%, computed with the aperture area and >40% computed with the actual used surface area (for glazed collectors). Solar tracking can improve output for photovoltaic systems as well as thermal systems.

While algae cultivation on façades is in its early stages, algae provide a fuel that could potentially replace fuels such as diesel. Arup has proven that algae cultivation is possible, but investment costs are high. The efficiency in terms of heat in this case is estimated at 38% and the efficiency of algae production is estimated to be 10%.

Wind powered energy production is unpredictable and actual production does not always meet simulated or estimated production. However, a prototype of a vibrational system has shown an output of 54W/m² at wind speeds of 10m/s. The average wind speed in Rotterdam at 100m height is 7m/s, which reduces the output to 22W/m² and an annual production of 192kWh/m². Combining the data of Yemer (2010) and Kluger (n.d.) gives a mean annual output of 6.9W/m² (see Appendix A: wind data) which could result in an annual production of 60.44kWh/m², but this might be higher at greater height (or lower at a different location). Photovoltaic systems with an efficiency of 20% would require an insolation of 938kWh/m² or 300kWh/m² per year to meet that production. However, given that wind behaviour is very unpredictable at building envelopes, it is hard to tell how much time the wind system will generate power (and how much), while a solar panel in direct sunlight can produce more than 100W/m² and the sun hours and intensity are fairly predictable.

Some forms of energy can be used for different purposes: with heat or electricity hot water can be produced and water with high temperatures (T>90°C) can be used in absorption chilling processes for cooling purposes. Algae cultivation requires cooling to keep temperatures below 40°C. The water which is used to cool the algae tanks can be used elsewhere, in the form of thermal energy. All systems discussed in the chapter are in some ways suitable for façade integration in that they can all be adapted to be mounted on a façade. The options for façade integration are discussed further in chapter 9: Façade design options.
<table>
<thead>
<tr>
<th><strong>Design requirements</strong></th>
<th><strong>Design guidelines</strong></th>
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<td><strong>Solar electric</strong></td>
<td>Maximize</td>
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<td>Minimum insolation 400kWh/m²</td>
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<tr>
<td></td>
<td>Solar tracking significantly improves output</td>
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<tr>
<td><strong>Solar thermal</strong></td>
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<tr>
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<td>Minimum insolation 400kWh/m²</td>
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<tr>
<td></td>
<td>Solar tracking significantly improves output</td>
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<td>When designed to support building heating, design to minimal needs, otherwise the</td>
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<tr>
<td></td>
<td>system will be oversized (heat going to waste).</td>
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<tr>
<td><strong>Wind</strong></td>
<td>Only applicable if PV or Algae are not feasible</td>
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<tr>
<td></td>
<td>Turbines should be high above the roof require a wind speed &gt;5m/s.</td>
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<td></td>
<td>Turbines introduce vibration loads on the structure.</td>
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<td></td>
<td>Vibration systems require a wind velocity of at least 2m/s.</td>
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<td></td>
<td>Could be placed on low insolation areas, where potential of solar energy &lt; 400kWh/m²</td>
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<td></td>
<td>or the mean wind speed is &gt;7m/s</td>
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<td><strong>Algae</strong></td>
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<td></td>
<td>pH range of 7 − 8</td>
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<tr>
<td></td>
<td>Illuminance range 5400lux − 13500lux</td>
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<tr>
<td></td>
<td>Nutrition supply</td>
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<td></td>
<td>Harvesting</td>
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<td>Algae can use wastewater as nutrition</td>
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*Table 5.3: Design requirements and guidelines used for energy modelling and computing the energy demand and production potential.*
6 ENVELOPE & FACADE DESIGN

6.1 Introduction
The façade of a building is the exterior surface. A few centuries back, the term façade was often used to describe the front side of the building, but nowadays, the façade consists of all exterior walls. The roof is often viewed as a separate element as is the lowest floor and foundation of a building, but in this case the roof is also considered to be part of the facade. All together these elements form the buildings envelope. The envelope can be described as all parts of the buildings that separate the interior climate from the outdoor climate, that protect a building and its inhabitants against temperature fluctuations, water and air (wind).

This chapter answers the following questions:
   a. How does façade design influence the indoor climate and energy consumption?
   b. What are the different façade systems used in high rise?
   c. Which façade systems lend themselves for implementation of energy producing elements?
6.2 Functional requirements
A façade is a protective layer against the outdoor comfort, so to protect is its main function. But what criteria does a façade design need to comply with in order to realise its function? Hutcheon (1963) has made a list of criteria which incorporates all essential functions of the façade:

1. Control heat flow;
2. Control air flow;
3. Control water vapour flow;
4. Control rain penetration;
5. Control light, solar and other radiation;
6. Control noise;
7. Control fire;
8. Provide strength and rigidity;
9. Be durable;
10. Be aesthetically pleasing;
11. Be economical.

Criteria 1 – 8 can be tested in controlled circumstances and often have to comply with national or international regulations. By completing criteria 1 – 8 a façade system has proven itself to be durable for a variety of circumstances except for the test of time. Criteria 10 is in great part subjective and criteria 11 depends on factors such as building budget or potentially payback times, but economical can be interpreted as suited for and fitting within the budget.

6.3 Façade types
There are two basic façade systems: the single skin façade and the double skin façade, which is sometimes called a multi-layered façade. Both systems are usually a curtain wall system (a non-structural façade system).

The double skin can be used in different ways concerning climate regulation. Boake (2003) distinguishes three types: The buffer system, which acts as a thermal buffer to increase the thermal performance of old façades with single glazing. The extract air system is a design for which the cavity becomes part of the HVAC system. The outermost layer is often double glazing and the inner layer single glazing. Air is extracted from spaces through the cavity and can be used to preheat ventilation air. Natural ventilation does not occur. The twin-face system contains openings in both facades so
natural ventilation is possible. The outer layer can either be single or double glazing and the inner layer is double glazed, because this forms the actual thermal buffer. Note that these can be seen as main categories, but hybrids are used as well.

6.4 Façade optimization

The envelope has influence on the indoor climate and the local climate around a building and therefore also on the energy consumption of high rise. It provides the first layer of protection against outdoor climate conditions. It functionality is acquired by meeting the criteria stated in paragraph 0, but these only the boundary conditions. These boundary conditions can be summarized in a few goals. An optimal façade design tries to maximize these goals:

1. Thermal comfort;
2. Visual comfort;
3. Lowest energy demand for cooling;
4. Lowest energy demand for heating;

In the case of this thesis one criterion is added:
5. Integration of energy production;

These goals however, are in conflict with each other. Maximizing visual comfort, could result in a very high window-to-wall ratio, which results in high solar heat gain. The energy demand for cooling will thus grow. Conflicts also occur based on the seasons. In winter, passive solar gain can lower the energy demand for heating, but in summer, the heat gain will result in high indoor temperatures. Giving occupants means to control or influence their comfort, means they will probably be more comfortable (Raja, Nicol, McCartney, & Humphreys, 2001), but they are directly interfering with a buildings energy system.

6.4.1.1 Thermal comfort & control

Thermal comfort is correlated to outside temperature. Meaning that in winter, the indoor comfort temperature is lower than in summer. In unconditioned buildings the comfort temperature has an almost linear relation with the outdoor temperature, while in conditioned buildings the comfort temperature seems to vary between 18 degrees Celsius and 24 degrees Celsius.

While the results of such studies seem straightforward, they tend to be oversimplified according to Nicol and Humphreys (2002). Important factors to consider are humidity and air-

movement, climate controls, clothing and activity are not necessarily taken into account, while they play a very important role in thermal comfort. Environmental factors thus are temperature, air-velocity and humidity and human factors are e.g. clothing and activity.

6.4.1.2 Visual comfort & control

Visual comfort is about luminance levels, contrast and glare. Solar control in the façade can increase visual comfort by reducing glare or extreme contrast between opaque and transparent surfaces, but it can also reduce luminance levels.

6.4.2 Temperature, wind and water

In colder climate regions, the envelope needs to keep the heat in. In hot climates the envelope needs to keep the cold in. It does so, by having a high thermal resistance, or R-value. The total façade area, and each material used, have a specific heat transfer coefficient. The overall heat transfer coefficient is the U-value with SI units [W/m²K]. The R-value is the inverse U-value (U = 1/R). The higher the R-value, the slower heat will transfer from the warmer side of the structure to the colder side. The thermal barrier works best if it is also airtight (and thus watertight). Otherwise, air leakage will speed up the process of heat transfer. The warm indoor air will find its way outside through cracks and gaps. The places where different building elements are joined together, logically form the highest risk for air and water leakage and these places need special attention. Air- and water tightness are often solved.
with rubber or glue-like sealants. Façade types like curtain walls or façade elements are tested under controlled conditions to guarantee water and air permeability at specific pressure levels.

6.4.3 Natural ventilation
Natural ventilation occurs through infiltration. This can either be intentional, by opening doors, windows or other façade elements, or it can be due to holes or cracks in the building shell. Natural ventilation is found to have a positive effect on energy consumption in multiple forms:
- Night ventilation can reduce energy consumption for cooling during the day, especially for buildings with high thermal mass (Kolokotroni & Aronis, 1999).
- Daytime ventilation combined with solar control can, according to simulations, result in savings between 13kWh/m² – 22kWh/m² for an office building in Stuttgart and 38kWh/m² – 44kWh/m² in Istanbul (Schulze & Eicker, 2013).

6.4.4 Window size, orientation and position
Daylight availability and solar gains are influenced by the visible light and radiation transmittance of the windows and the size and position of the windows (Gratia & De Herde, 2003). Optimizing the daylight availability and thus the size and position of windows will reduce internal heat gain and electricity consumption by artificial lighting and it allows a designer to look for the optimum balance between heating and cooling loads. The optimum in this case, leads to the lowest possible annual energy consumption for heating, cooling and lighting. Next to the energy-related benefits, an appropriate amount of daylight increases work-productivity (SOURCES) and improves the perception of indoor environment quality (SOURCE).

6.4.4.1 Single skin facades
Gratia & De Herde found that placing windows higher allowed the natural light to penetrate deeper into their test office and another study (Bokel, 2007) found that placing windows too low (measured from floor level) leads to higher energy consumption. Bokel simulates the energy loads for heating, cooling and lighting for an office with a window to wall ratio of 10.2% to 90%, for windows placed low, medium and high within the façade area. Three different user profiles are used to simulate the energy consumption by lighting: passive, active and manual. The results show that a window to wall ratio of 30% is optimal, but the range of 20% to 40% provides acceptable results. The positive effects on lighting energy consumption are negligible when the window to wall ratio passes 50%. The heating load starts to increase from this point onwards and the cooling load increases significantly with the increase of window area. These findings are comparable to other studies (Ochoa, Aries, van Loenen, & Hensen, 2012) involving simulations for different window areas. Ochoa et al. also studied the effect of different orientations on energy consumption and found that the total energy consumption was highest for East and West orientated room and lowest for North orientated rooms. The study also introduces visual comfort into the simulation by computing the Daylight Glare Index and shows that the lower the total energy consumption, the lower the visual comfort. This relates to the optimal amount of windows concerning energy consumption, which is approximately 30%. The energy demand for heating and cooling at a high window to wall ratio (30% -WWR) outweigh the energy demand for lighting at a low window to wall ratio (WWR<30%).

6.4.4.2 Double skin facades
A double skin façade usually consists of two layers of glass. The exterior and interior pane can consist of double glazing, triple glazing or single glazing and is often a combination. The depth of the cavity can vary. When a double façade consists of only two glass panes, the greenhouse effect sets in. In some cases (SOURCES) this can be beneficial to heating loads. The cavity forms an extra thermal barrier between in and out. It also makes buildings less vulnerable for wind at the façade. Higher wind velocities create pressure differences and increase infiltration (SOURCE). There is however no consensus on double skins being profitable to energy consumption or not. Temperatures can rise to 40 degrees Celsius above the outdoor temperature when the sky is clear (Gratia & De Herde, 2007) within a closed double skins cavity. For double skin facades, the inner pane can be designed to contain less glass, reducing heat transfer between the cavity and interior and the greenhouse effect. The extra mass in the inner pane has a higher thermal mass than glass. Gratia & De Herde simulated the effect for an interior pane with 39.5%
glazed surface. For East, West en South orientated facades this would reduce the internal temperature of the cavity by 5 – 8 degrees Celsius between March and September. By increasing the depth of the cavity from 0.3m to 2.4m the maximum temperature drop increased to 5.8 degrees Celsius in September.

6.4.4.3 Solar control systems
Several research projects have shown the positive effects on solar control systems that reduce solar gains in the hot seasons (Bakker & van Dijk, 2008), (Lee, Kim, Lee, & Lee, 2013). Solar control systems can be placed on the outside of the glazed area, the inside or, in the presence of a double façade, within the cavity. Reducing the cooling loads means reducing the indoor temperature, which leads to a more comfortable indoor temperature and/or to less energy consumption by the cooling system.

6.4.5 Solar control
6.4.5.1 Facades with blinds or screens on the outside
The research report by Bakker & van Dijk shows results of a simulation for residential units and small and large offices for exterior solar screens with a sunlight transmittance of 15% and 25%. The cooling loads, during the summer months, were reduced within ranges of 54%-72% and 49%-67% respectively.

6.4.5.2 Facades with blinds or screens on the inside
In Ottawa, Canada, which lays on the border of the cold and temperate climate zone interior reflective shading was installed in a test house on the West and South façade. Test results showed a 12% drop in cooling load for a 24-hour period (Manning, Swinton, & Ruest, 2007). Previous tests by Canadian Centre for Housing Technology showed results of <1% for interior venetian blinds. The reflective sheets covered the entire windows in the test, thus reducing the available daylight significantly.

6.4.5.3 Facades with blinds or screens within a cavity
Lee et al simulated cooling loads for a residential unit with venetian blinds, with and without reflective coating, inside a cavity. The cavity has operable windows on the inside and outside. The baseline cooling load, without blinds was 1799kWh from May to October. With both windows closed and the blinds closed, the cooling load dropped up to 40%. When the windows were operated the cooling load dropped by 50% - 70%.

For larger cavities, often the case with double skin facades, solar protection and operability of the cavity becomes a must. Gratia & De Herde simulated an office building with a double skin where the temperature in September would rise to 65.8ºC, which was 43.2 ºC above the outdoor temperature. With the addition of blinds, the temperatures in the cavity was around 7 – 10 degrees lower on the East, West and South orientated models. In winter, the high temperatures can be used to preheat ventilation air, but from March to September, the temperatures still rise to 40ºC – 59.3ºC. However, by opening the cavity through a 10cm slit, the temperature is reduced from 59.3ºC to 34.4ºC. By increasing the size of the slit to 50cm, the temperature drops to 28.2ºC. Because of the high ventilation rate and the relatively low temperature, the 10cm opening and the 50cm opening reduce the cooling load by 8.1% and 14.3% respectively. During winter, the slit must remain around 5cm to keep the temperature inside the cavity above 20ºC. That way, transmission losses from within the building are reduced and the air inside the cavity can be used to preheat ventilation air.

6.4.6 Climate adaptive façades
Innovation in façade technology takes place on three scales according to Aksamija (2013). On the smallest scale (micro) there’s material innovation which involves e.g. coatings and thin film. On a façade system scale, double-skin façades keep being improved and on a full climate system scale, façades are starting to integrate climate installations and energy production. This paragraph will go further into the details of climate adaptive façade design. Climate adaptive façades contain dynamic elements that can be (or automatically) changed according to climate conditions with the aim to reduce energy consumption or increase indoor comfort. The definition of the climate adaptive building shell is formulated by Loonen et al. and stated below in the green text box. Loonen et al. use the terminology ‘building shell’ to indicate a building’s façade and roof.

A climate adaptive building shell has the ability to repeatedly and reversibly
change some of its functions, features or behaviour over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance. (Loonen, Trčka, Čostola, & Hensen, 2013, p. 485)

Loonen, Trčka, and Hensen (2011) studied the potential of climate adaptive façades on an office with dimensions (d x w x h) 5.4m x 3.6m x 2.7m. They used variables as input for the parameters as shown in Table 6.1. The red dots in Figure 6.6 show the boundary of an optimal static façade in terms of energy demand (the sum of the cooling and heating loads) and overheating hours (a criterion for thermal comfort). These dots represent cases for which a changing the variables will lead to either higher energy consumption or more overheating hours. In order to find the potential of CAFs, a year is divided into 12 parts with the length of a month. Each month then gives its own set of red dots. A combination of all these sets, results in the green dotted line in Figure 6.6. The case presented by Loonen et al. is a form of long-term adaption (month-to-month), but CAFs could also adapted to changes over shorter periods of time: hours, minutes or even seconds.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>50 – 8000</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>Surface absorptance</td>
<td>0.1 – 0.9</td>
<td>[-]</td>
</tr>
<tr>
<td>Thermal capacity</td>
<td>800 – 2000</td>
<td>[J/kgK]</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.3 – 2.5</td>
<td>[W/mK]</td>
</tr>
<tr>
<td>Window to wall ratio</td>
<td>0.1 – 0.9</td>
<td>[-]</td>
</tr>
</tbody>
</table>

Table 6.1: Parameters used by Loonen et al. (2011) to represent a climate adaptive façade.
6.5 Conclusions on façade design

This chapter answers the following questions:

a. How does façade design influence the indoor climate and energy consumption?
b. What are the different façade systems used in high rise?
c. Which façade systems lend themselves for implementation of energy producing elements?

The relation between energy consumption and the building envelope is evident through the impact of climate conditions on energy consumptions, by climate characteristics:

1. Dry-bulb air temperature
2. Relative humidity
3. Precipitation
4. Solar radiation and daylight
5. Wind direction and velocity

Façade systems are designed to protect people from the outside climate conditions. The climate conditions people are sheltered from are thermal discomfort and to some extent, visual discomfort. Façades are either single-skin or double-skin façades and both types try to maximize:

1. Thermal comfort;
2. Visual comfort;
3. Lowest energy demand for cooling;
4. Lowest energy demand for heating;

A very important factor in maximizing 1 to 4 is the window to wall ratio. WTW of between 20% and 40% are most optimal for adequate daylight availability, and minimal cooling and heating loads. High placed windows provide better daylighting than windows placed low. When the WTW is higher than 40%, cooling loads start to increase. The cooling loads can be reduced by adding shading, which is most influential when placed on the exterior surface. Solar protection can also improve visual comfort and thermal comfort, but it also reduces daylight availability.

Naturally ventilated buildings usually have a lower energy use intensity than their air-conditioned counterparts, but this requires façade openings. The operability of these elements give users influence on indoor conditions and energy consumption. Night time ventilation can be quite effective in reducing indoor temperatures.

Climate adaptive façades show potential to reduce energy consumption by 50% compared to static façades. Considering solar tracking elements can also improve power generation, combining an adaptable façade with energy production can have beneficial effects, although it will increase complexity.
<table>
<thead>
<tr>
<th>Design requirements</th>
<th>Design guidelines</th>
</tr>
</thead>
<tbody>
<tr>
<td>WTW</td>
<td>WTW &lt; 20%</td>
</tr>
<tr>
<td></td>
<td>WTW&gt;50% increases cooling loads and should be combined with low G-values or shading to compensate for this effect.</td>
</tr>
<tr>
<td>G value &amp; LT value</td>
<td>Should be low on Facades with high solar gains, especially when there are no shading devices</td>
</tr>
<tr>
<td>Shading</td>
<td>Shading can significantly reduce cooling loads for East, West and South facing facades.</td>
</tr>
<tr>
<td>Placement</td>
<td>High placed transparent areas are more beneficial to daylight availability than lower placed windows.</td>
</tr>
<tr>
<td>Operability</td>
<td>Allow for natural ventilation</td>
</tr>
<tr>
<td></td>
<td>Allow for night time ventilation</td>
</tr>
<tr>
<td>Double skins</td>
<td>If used, must have large operable areas to increase ventilation rate in summer.</td>
</tr>
</tbody>
</table>

Table 6.2: Design guidelines and boundary conditions that are used for energy modelling and energy demand and production potential calculations.
Assessing the energy potential of a building requires prioritizing energy production systems and stocktaking of the available resources in terms of wind and sun. The energy production systems are:

- **Solar electric systems (Se)** in the form of photovoltaic cells with an efficiency of 20% and photovoltaic thin film with an efficiency of 2.5%.
- **Solar thermal systems (St)** in the form of evacuated tubes or flat plate collectors with a thermal efficiency of 40%.
- **Wind systems (W)** in the form of vibrational systems with a different energy yield for different wind speeds.
- **Algae systems (A)** in the form of tubular systems or flat plates with a yield depending on the volume and whether the system is in a climate controlled space.

The assumptions for the calculations are summarized in Table 7.1. A flowchart is developed to help designers prioritize between these systems. It gives a preliminary answer to the research question: *How can high rise envelopes be utilized as energy production units?*

### 7.1 A strategy for energy production system choice

The goal of a strategy complies with the objective of the thesis, which is:

> To show the potential of energy production on envelopes of high rise.

The strategy formulated in the flowchart is one that should be usable for people who write regulations, planners and designers. The flowchart helps them assess and decide on the amount of energy production, the type of energy production systems and placement. Going through the flowchart will result in:

> Maximizing energy production whilst considering its potential in lowering energy demand.

The strategy should incorporate or evoke decisions considering a building's climate system, but also be applicable to buildings that are to be refurbished or undergoing renovation. Ideally a strategy would also be applicable to all the climate zones.

Criteria for the strategy are:

- **Incorporate the climate system of the building in choosing the form of energy production.**
  
  If the input energy for the climate system can be produced on-site, a building can become closer to net-zero-energy and transport losses are minimised.

- **Apply general thresholds for applying different energy production systems.**
  
  This addresses the feasibility of applying certain systems. When the renewable resources are limited, the benefits of energy production may not outweigh costs of maintenance and replacement. If the expected lifetime of the system is below the payback period or the energy consumed during production is more than the energy produced during a system's technical life, placing the system does not make sense.

- **The implementation of production systems should not increase the energy demand of the building.**
  
  This is about changing the layout or the window to wall ratio of the façade. The more opaque surfaces a building has, the more high performance energy systems can be incorporated, however, a design can already be optimized in terms of energy demand and the layout of the façade should not be changed to incorporate energy production systems. In the new stepped strategy the first step is always to reduce the demand.

- **Applicability for different climate zones.**
  
  This would increase the usefulness of the strategy.

- **Easy to understand:**
  
  Thus making it usable for people with a different knowledge background.

- **Minimal starting knowledge:**
  
  The flowchart can be put to use early in the design process when little knowledge about the design is necessary.
Figure 7.1: The flowchart is shown on top and the table on the bottom shows source demand by different systems. Dark grey = high demand, medium dark grey = medium demand, light grey = low demand. Own ill.
THE POTENTIAL FOR HIGH RISE ENVENLES AS ENERGY PRODUCTION UNITS | ANNE LEEUW
7.1.1 General questions

The flowchart is described step-by-step:

1. Is the irradiation on the surface more than 400 kWh/m²/year?
   The energy efficiency of photovoltaic modules is around 20%. Photovoltaics thus have an energy potential of $400 \cdot 20\% = 80 \text{kWh/m}^2$, which is less than the potential output of wind energy at wind speeds of >7m/s (192kWh/m²), but more than the output at 5m/s (8,7kWh/m²), which is a more common mean wind speed measured across the world. While it can be discussed that wind speed should have first priority (the first question could be: Is the mean wind speed higher than 7m/s?), its unpredictability in urban areas and lack of data proving that projects reach the theoretical output, lead to giving solar energy first priority with a threshold at 400kWh/m².

In itself, the question accounts for building (or surface) orientation. By asking this particular question, it does not matter if the reviewed surface faces East, South or North.

7.1.2 Wind

1. Does the façade lay facing or sideward to prevailing wind direction(s)?
   If the façade does not lay facing or sideward to a prevailing wind direction, than wind will only flow there a few hours a year, thereby lowering the wind energy potential.

2. Is the window to wall ratio between 0% and 40%?
   Wind systems in front of transparent façade areas will cause annoyance in terms of visual comfort, it is not desirable to place moving systems in front of transparent building elements. Furthermore the higher the WTW on a façade the higher the energy transmission through the façade.

3. What is the wind velocity at the façade surface?
   If the wind velocity is below 4m/s, wind energy systems will have a low energy production potential. However, when there are no other options for energy production, vibrational wind systems will still produce some energy if the speed remains above 2 m/s.

7.1.3 Climate system & energy choice

An active or mixed system has heat or cold generators which require cooling. It make sense to first attend to the fuel or source which is required most by the climate system. Examples of climate systems are listed below the chart. The grey boxes indicate the need for a specific source. Light grey is a low demand, the darker grey is a medium demand and the darkest grey represents a high demand.

For a mixed system, there is often some energy storage involved. Seasonal storage for example can be a water basin or another type of closed loop system where heated water can be stored during the hot months to be used in the colder months.

7.1.4 Maximizing production

1. Is the window to wall ratio between 0% and 40%? (No? -> 6)
   Different studies show that for energy consumption, especially on south, west and east facing façade surfaces, the optimal window to wall ratio is below 40%. Electricity consumption for artificial lighting is minimal at a WTW of 50%, but the solar gain causes a higher cooling demand which renders the lower demand for lighting energy insignificant.

2. Can de demand be met and is there space left?
   If all the space for solar thermal energy systems is used up and there is space left, implement photovoltaic systems. If the current design uses glass with a light transmittance lower than 65%, the coating can be kept out of the design and replaced by transparent thin film.

3. Lower the WTW of the design.
   This will free up more space for high efficiency energy production and reduce solar gain leading to higher cooling loads.

4. Use glass with a high LT value and add exterior shading with integrated photovoltaic cells.
   A higher LT value will ensure more light entry, this might mean a higher g-value. The building needs more cooling than heating, so solar gain becomes a problem. Therefore, shading is added, which at the same time produces energy. The goal is to keep the light...
transmittance as high as possible and the solar heat gain as low as possible.

5. **Use glass with a high LT value and add solar thin film.**

Efficiency of thin film is much lower than opaque cells that can be integrated with shading, but if shading cannot be added, add thin film to the transparent surfaces instead. For example, in colder climates a transparent façade can be integrated to make use of solar gain. In this case lowering the window to wall ratio is not an option, but using opaque cells is, because they will still let a lot of solar radiation through. The opaque cells only make use of a small range of the light spectrum of which the most falls into the visible light spectrum. Adding transparent thin film reduces to LT to 50% - 65%.

### 7.2 Quantifying energy potential

The energy potential of an envelope must be quantified. Based on literature the assumptions used for assessing the energy potential are presented in Table 7.1.

*Energy production potential = EPP [kWh]*

\[ E_{\text{P}} = E_A + E_W + E_{SE} + E_{ST} \]

- **E_A** = Algae energy potential
- **E_W** = Wind energy potential
- **E_{SE}** = Solar electric energy potential
- **E_{ST}** = Solar thermal energy potential

#### 7.2.1 Wind

The measure of availability of wind energy is velocity or speed in m/s. In paragraph 5.3.2: Wind it is explained how unpredictable wind speed in the urban environment is. However, at mean wind speeds greater than 7 m/s, vibrational systems theoretically outperform photovoltaic systems. So the important factors are:

- **Wind speed**
- **Wind direction**
- **Turbulence**
- **Wind frequency**

Turbulence is not taken into account in this thesis, because of its complexity. So the strategy accounts for (mean) wind speeds, wind direction and frequency.

Wind energy potential is calculated as follows:

\[ E_W[kWh] = A \cdot F_i \cdot E_{out,\text{wv},i} \]

For which:

- **A** [m²] = surface area covered with wind system
- **F_i** [%] = frequency of wind direction for velocity i

\[ E_{out,\text{wv},i} \left[ \frac{kWh}{m^2} \right] = \text{Energy output depending on wind speed in [m/s]}; E_{out,4-6}, E_{out,6-10}, E_{out,10+} \]

#### 7.2.2 Sun

The measure of availability of solar energy is insolation in kWh/m². The insolation is the yearly sum of irradiation. Solar energy is proven to be predictable and is therefore the preferred method of energy production over wind energy. Furthermore it can be used to produce both electricity and thermal energy. The sun (or rather illuminance) is also the resource needed for biomass production.

Algae energy potential is calculated as follows:

\[ E_A[kWh] = (V \cdot m \cdot cv \cdot n) \cdot (3.6 \cdot 10^9)^{-1} \]

\[ = (V \cdot 1.5 \cdot 10^{-3} \cdot 37 \cdot 10^3 \cdot 365) \cdot (3.6 \cdot 10^9)^{-1} \]

For which:

- **V** [dm³] = total volume of photobioreactor tubes
- **m [kg] = mass of lipid content per l of water per day**
- **cv [kJ/kg] = calorific value for algae biofuel**
- **n [-] = days of calculation; if annual; n = 365**

Solar electric energy potential is calculated as follows:

\[ E_{SE}[kWh] = A \cdot I \cdot E_{st,eff} \]

For which:

- **A** [m²] = surface area covered with solar systems
- **I [W/m²] = annual insolation**

\[ E_{SE,eff} [%] = \text{photovoltaic system conversion efficiency} \]

Solar thermal energy potential is calculated as follows:

\[ E_{ST}[kWh] = A \cdot I \cdot E_{st,eff} \]

For which:

- **A** [m²] = surface area covered with solar systems
- **I [kW/m²] = annual insolation**

\[ E_{st,eff} [%] = \text{thermal system conversion efficiency} \]
<table>
<thead>
<tr>
<th>Energy production system</th>
<th>Production potential</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algae</td>
<td>1.5 grams of lipids per litre per day</td>
<td>Controlled climate conditions tubular reactors</td>
</tr>
<tr>
<td></td>
<td>1.0 grams of lipid per litre per day</td>
<td>Controlled climate flat plate systems</td>
</tr>
<tr>
<td></td>
<td>0.5 grams of lipids per litre per day</td>
<td>Uncontrolled climate conditions</td>
</tr>
<tr>
<td></td>
<td>65L/m$^2$ or 300kWh/m$^2$ (120kWh/m$^2$)</td>
<td>For rough calculations / controlled (uncontrolled)</td>
</tr>
</tbody>
</table>

**Wind (vibration)**

<table>
<thead>
<tr>
<th>Wind speed (m/s)</th>
<th>Energy output (kWh/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-6</td>
<td>50</td>
</tr>
<tr>
<td>6-10</td>
<td>150</td>
</tr>
<tr>
<td>&gt;10</td>
<td>450</td>
</tr>
</tbody>
</table>

**Solar electricity**

<table>
<thead>
<tr>
<th>Type</th>
<th>Conversion Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV opaque</td>
<td>20%</td>
</tr>
<tr>
<td>PV transparent</td>
<td>2.5%</td>
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</tbody>
</table>

**Solar thermal**

<table>
<thead>
<tr>
<th>Type</th>
<th>Efficiency</th>
<th>Temperature Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat panel</td>
<td>40%</td>
<td>$\Delta T (T_{output} - T_{input}) &lt; 50^\circ C$</td>
</tr>
<tr>
<td>Evacuated tubes</td>
<td>40%</td>
<td>$\Delta T (T_{output} - T_{input}) &lt; 50^\circ C$</td>
</tr>
</tbody>
</table>

Table 7.1: Energy output for different systems
8 FAÇADE DESIGN OPTIONS

The previous chapter explains how the energy production potential can be estimated. The next step to take is translating the acquired information into a design. To aid a designer it useful to know where the energy production systems can be placed and what the advantages or consequences are for stereotypical designs. Figure 8.1 shows an overview of where energy production systems could be placed. The options are numbered and described in a short s.w.o.t. -analysis. Next to the s.w.o.t.-analysis is design catalogue with examples of how energy systems could be integrated into a façade design. The catalogue provides a rating on several aspects:

1. **Production potential**
   Depending on kWh/m² production if placed on a south facing façade

2. **System complexity**
   There are numerous criteria one can think of when describing a systems complexity. In this case the following questions determine the classification:
   - A. Does the system require additional climate control?
   - A. Does the system contain rotating or moving elements?
   - A. Does the system require pumps or fans?
   - B. Is the system added onto the façade with spacing?
   - B. Does the system require additional piping systems?

3. **Maintenance**
   The same can be said about maintenance as for system complexity. The following questions have determined the classification:
   - Does the system require cleaning of the surfaces (besides façade integrated surfaces, because these will need to be cleaned anyway)?
   - Does the system contain rotating or moving parts that need cleaning and/or greasing?
   - Does the system need to be cleaned internally (for example the piping system)?
   - ?

4. **Accessibility**
   Accessibility assesses how easy the energy production system can be reached.
   - A. Can the system be reached from inside the building?
   - A. Is the system integrated in the façade surface and thus lies in the same line?
   - B. Is the system added onto the façade with spacing?
   - B. Is the system placed horizontally and is it offset from the rest of the façade surface?

5. **Cost of investment**
   The system's complexity, accessibility and maintenance are all contributors to the cost of a system. The production potential could be the deciding factor in whether a system is economically feasible. While it is difficult to really assess the cost of investment, systems can be compared to each other based on the previously rated criteria. The cost factor is thus not based on real prices of systems.
1. Production potential classification

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Condition</th>
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<tbody>
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<td>++</td>
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</tr>
<tr>
<td>+</td>
<td>120 &gt; EPP &gt; 90kWh/m²</td>
</tr>
<tr>
<td>+-</td>
<td>90 &gt; EPP &gt; 60kWh/m²</td>
</tr>
<tr>
<td>-</td>
<td>60 &gt; EPP &gt; 30kWh/m²</td>
</tr>
<tr>
<td>--</td>
<td>EPP &lt; 30kWh/m²</td>
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</table>

2. System complexity classification

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
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<td>All questions answered with NO</td>
</tr>
<tr>
<td>+</td>
<td>1 B question is answered with YES and all A questions with NO</td>
</tr>
<tr>
<td>+-</td>
<td>2 B questions are answered with YES and all A questions with NO or 1 A question is answered with YES and all B questions with NO</td>
</tr>
<tr>
<td>-</td>
<td>2 A questions are answered with YES or if 1 A question is answered with YES and 2 B questions are answered with YES or if 2 A questions are answered with YES</td>
</tr>
<tr>
<td>--</td>
<td>More than 2 A questions are answered with YES or more than 3 questions in total are answered with YES</td>
</tr>
</tbody>
</table>

3. Maintenance classification

<table>
<thead>
<tr>
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<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>++</td>
<td>All questions answered with NO</td>
</tr>
<tr>
<td>+</td>
<td>1 question is answered with YES</td>
</tr>
<tr>
<td>+-</td>
<td>2 questions are answered with YES</td>
</tr>
<tr>
<td>-</td>
<td>3 questions are answered with YES</td>
</tr>
<tr>
<td>--</td>
<td>More than 3 questions are answered with YES</td>
</tr>
</tbody>
</table>

4. Accessibility classification

A plus is received for answering questions with an A with YES. A minus is received for answering questions with a B with YES. Plusses and minuses cancel each other out.

5. Cost of investment classification

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>++</td>
<td>The system has no ‘-’ or ‘--’</td>
</tr>
<tr>
<td>+</td>
<td>The system has only 1 ‘-’</td>
</tr>
<tr>
<td>+-</td>
<td>If there are the same amount of plusses and minuses but no ‘-’</td>
</tr>
<tr>
<td>-</td>
<td>The system has plusses and multiple minuses</td>
</tr>
<tr>
<td>--</td>
<td>If the system has more minuses than plusses and one or more ‘--’</td>
</tr>
</tbody>
</table>

**Table 8.1: Rules applied for the categorization of different facade designs**

**Figure 8.1: Placement possibilities for photovoltaic systems (PV), algae (AL), solar thermal systems (ST) and wind systems (WD) on double skin or single skin facades, own ill.**
### 8.1 Photovoltaic systems

#### Integrated into facade

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Can replace facade cladding</td>
<td>• Efficiency limit on currently economic systems; new technology is very expensive</td>
</tr>
<tr>
<td>• High density energy production</td>
<td></td>
</tr>
<tr>
<td>• Easy to integrate into curtain wall</td>
<td></td>
</tr>
</tbody>
</table>

**Opportunities**

| • Easy to replace with newer technology | • Shadow of framing influences output |
| • Market still growing                 | • Accumulation of dirt reduces output |

**Threats**

#### On opaque surfaces (with spacing)

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Can be replaced independently of façade</td>
<td>• Makes façade behind panels difficult to clean</td>
</tr>
<tr>
<td>• Air space keeps system cooler during hot months</td>
<td>• Construction and framing need to go through the façade</td>
</tr>
</tbody>
</table>

**Opportunities**

| • Easy to replace with newer technology | • Construction and framing need to go through the façade |

**Threats**

#### Integrated with solar control

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Reduces solar gain</td>
<td>• Relatively smaller surfaces</td>
</tr>
<tr>
<td></td>
<td>• More vulnerable on high rise, possible over dimensioning due to peak wind loads.</td>
</tr>
</tbody>
</table>

**Opportunities**

| • Solar tracking further reduces solar gain and electricity output | • Shading elements can shade each other |
| • Flexible placement and spacing                                      |                                                                                             |

**Threats**

#### Integrated in glass

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Reduces solar gain (but minimal)</td>
<td>• Low efficiency</td>
</tr>
<tr>
<td>• Makes use of ‘unused’ transparent surfaces</td>
<td></td>
</tr>
</tbody>
</table>

**Opportunities**

| • Growing field of research | • Can affect visual experience due to colour distortion and different refraction indexes. |
| • Use of relatively cheap organic materials                             |                                                                                             |

**Threats**

---

**Table 8.2: S.W.O.T.-Analysis of Photovoltaic Systems Integration**
<table>
<thead>
<tr>
<th></th>
<th>PRODUCTION POTENTIAL</th>
<th>SYSTEM COMPLEXITY</th>
<th>ACCESSIBILITY</th>
<th>MAINTENANCE</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV01</td>
<td>++</td>
<td>++</td>
<td>--</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>PV02</td>
<td>++</td>
<td>++</td>
<td>--</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>PV03a</td>
<td>++</td>
<td>+</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>PV03b</td>
<td>++</td>
<td>+</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>PV04</td>
<td>--</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>PV05a</td>
<td>++</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>PV05b</td>
<td>++</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
### Figure 8.3: Roof Mounted Photovoltaic Systems

<table>
<thead>
<tr>
<th>PV-R01</th>
<th>Production Potential</th>
<th>System Complexity</th>
<th>Accessibility</th>
<th>Maintenance</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>++</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PV-R02</th>
<th>Production Potential</th>
<th>System Complexity</th>
<th>Accessibility</th>
<th>Maintenance</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>++</td>
<td>++</td>
<td>--</td>
<td>++</td>
<td>--</td>
<td>++</td>
</tr>
</tbody>
</table>

### Figure 8.4: Mixed Photovoltaic Systems in a Unitized Curtain Wall System

<table>
<thead>
<tr>
<th>PV-C01</th>
<th>Production Potential</th>
<th>System Complexity</th>
<th>Accessibility</th>
<th>Maintenance</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>++</td>
<td>++</td>
<td>--</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PV-C02</th>
<th>Production Potential</th>
<th>System Complexity</th>
<th>Accessibility</th>
<th>Maintenance</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>++</td>
<td>++</td>
<td>--</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PV-C03</th>
<th>Production Potential</th>
<th>System Complexity</th>
<th>Accessibility</th>
<th>Maintenance</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>++</td>
<td>++</td>
<td>--</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PV-C04</th>
<th>Production Potential</th>
<th>System Complexity</th>
<th>Accessibility</th>
<th>Maintenance</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>++</td>
<td>--</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>
### 8.2 Solar thermal systems

#### Integrated into facade

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Can replace facade cladding</td>
<td>• Heavy systems</td>
</tr>
<tr>
<td>• High density energy production</td>
<td>• Large and rigid piping</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Can be integrated into a curtain wall system</td>
<td>• Piping needs to go through façade</td>
</tr>
<tr>
<td></td>
<td>• Difficult and expensive to replace because of weight</td>
</tr>
</tbody>
</table>

#### On opaque surfaces (with spacing)

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Can be replaced independently of façade</td>
<td>• Makes façade behind panels difficult to clean</td>
</tr>
<tr>
<td></td>
<td>• Construction, framing and piping need to go through the façade</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Construction and framing need to go through the façade</td>
</tr>
<tr>
<td></td>
<td>• Difficult and expensive to replace because of weight</td>
</tr>
</tbody>
</table>

#### Integrated with solar control

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Reduces solar gain</td>
<td>• Makes façade behind panels difficult to clean</td>
</tr>
<tr>
<td></td>
<td>• Construction, framing and piping need to go through the façade</td>
</tr>
<tr>
<td></td>
<td>• Heavy system with static parts</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Difficult combination of static piping and dynamic shading.</td>
</tr>
</tbody>
</table>

#### Inside the cavity / glazing

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Reduces solar gain</td>
<td>• Less direct radiation, reduces output</td>
</tr>
<tr>
<td>• Easy access</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Benefits from the greenhouse effect</td>
<td>• Hot systems in cavity</td>
</tr>
</tbody>
</table>

Table 8.3: S.W.O.T. Analysis of façade integrated solar thermal systems
**Figure 8.5: Facade Integrated Solar Thermal Systems**

<table>
<thead>
<tr>
<th></th>
<th>Production Potential</th>
<th>System Complexity</th>
<th>Accessibility</th>
<th>Maintenance</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST01</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>ST02</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>ST03</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>ST04</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>ST05</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>
### Figure 8.6: Roof Mounted Solar Thermal Systems

<table>
<thead>
<tr>
<th></th>
<th>Production Potential</th>
<th>System Complexity</th>
<th>Accessibility</th>
<th>Maintenance</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST-R01</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
</tbody>
</table>

The table above highlights the performance of the roof mounted solar thermal systems, indicating their potential for high rise envelopes as energy production units.
### 8.3 Wind systems

#### On opaque surfaces (with spacing)

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Can be replaced independently of façade</td>
<td>• Makes façade behind panels difficult to clean</td>
</tr>
<tr>
<td></td>
<td>• Construction, framing and piping need to go</td>
</tr>
<tr>
<td></td>
<td>through the facade</td>
</tr>
</tbody>
</table>

#### Opportunities

<table>
<thead>
<tr>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Construction and framing need to go through the façade</td>
</tr>
<tr>
<td>• Difficult and expensive to replace because of weight</td>
</tr>
</tbody>
</table>

#### Integrated with solar control

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Reduces solar gain</td>
<td>• Reduces visual comfort because of moving parts</td>
</tr>
</tbody>
</table>

Table 8.4: S.W.O.T.-analysis of integrating wind systems into a façade
### Figure 8.7: Facade (top) integrated wind systems and roof mounted (bottom) wind systems

<table>
<thead>
<tr>
<th></th>
<th>Production Potential</th>
<th>System Complexity</th>
<th>Accessibility</th>
<th>Maintenance</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>WD01</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>WD02</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>--</td>
</tr>
<tr>
<td>WD-R01</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>--</td>
<td>+</td>
</tr>
<tr>
<td>WD-R02</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>--</td>
<td>+</td>
</tr>
</tbody>
</table>
Figure 8.8: Wind system as part of a unitized curtain wall system
### 8.4 Algae systems

<table>
<thead>
<tr>
<th>On opaque surfaces (with spacing)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strengths</strong></td>
<td><strong>Weaknesses</strong></td>
</tr>
<tr>
<td></td>
<td>• Climate cannot be controlled, reduction of production</td>
</tr>
<tr>
<td></td>
<td>• Difficult to access</td>
</tr>
<tr>
<td><strong>Opportunities</strong></td>
<td><strong>Threats</strong></td>
</tr>
<tr>
<td></td>
<td>• Construction and framing need to go through the facade</td>
</tr>
<tr>
<td></td>
<td>• Difficult and expensive to replace because of weight</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Integrated with solar control (flat panels)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strengths</strong></td>
<td><strong>Weaknesses</strong></td>
</tr>
<tr>
<td>• Reduces solar gain</td>
<td>• High energy consumption for climate control</td>
</tr>
<tr>
<td><strong>Opportunities</strong></td>
<td><strong>Threats</strong></td>
</tr>
<tr>
<td>• Possibility to control climate</td>
<td>• Possibility to control climate</td>
</tr>
<tr>
<td></td>
<td>• Difficult combination of static piping and dynamic shading.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Behind glass (indoors)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strengths</strong></td>
<td><strong>Weaknesses</strong></td>
</tr>
<tr>
<td>• Cheaper solution</td>
<td>• High energy consumption for climate control</td>
</tr>
<tr>
<td>• Accessibility</td>
<td></td>
</tr>
<tr>
<td><strong>Opportunities</strong></td>
<td><strong>Threats</strong></td>
</tr>
<tr>
<td>• Possibility to control climate</td>
<td>• Chinks lead to higher cooling loads</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inside the cavity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strengths</strong></td>
<td><strong>Weaknesses</strong></td>
</tr>
<tr>
<td>• Reduces solar gain</td>
<td></td>
</tr>
<tr>
<td>• Easy access</td>
<td></td>
</tr>
<tr>
<td><strong>Opportunities</strong></td>
<td><strong>Threats</strong></td>
</tr>
<tr>
<td>• Easy climate control</td>
<td>• Natural ventilation not an option through climate controlled cavity</td>
</tr>
<tr>
<td>• Extraction of dirty indoor air through algae cavity to reduce heat demand</td>
<td>• More shading, less illuminance, reduction of output</td>
</tr>
</tbody>
</table>

Table 8.5: S.W.O.T. - Analysis of integrating algae systems into a facade system.
### Figure 8.10: Facade integrated algae systems

<table>
<thead>
<tr>
<th>AL01</th>
<th>PRODUCTION POTENTIAL</th>
<th>SYSTEM COMPLEXITY</th>
<th>ACCESSIBILITY</th>
<th>MAINTENANCE</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>--</td>
<td>--</td>
<td>++</td>
<td>+</td>
<td>--</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AL02</th>
<th>PRODUCTION POTENTIAL</th>
<th>SYSTEM COMPLEXITY</th>
<th>ACCESSIBILITY</th>
<th>MAINTENANCE</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>--</td>
<td>--</td>
<td>++</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AL03</th>
<th>PRODUCTION POTENTIAL</th>
<th>SYSTEM COMPLEXITY</th>
<th>ACCESSIBILITY</th>
<th>MAINTENANCE</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>--</td>
<td>--</td>
<td>++</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

### Figure 8.9: Roof mounted algae systems

<table>
<thead>
<tr>
<th>AL-R01</th>
<th>PRODUCTION POTENTIAL</th>
<th>SYSTEM COMPLEXITY</th>
<th>ACCESSIBILITY</th>
<th>MAINTENANCE</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>+</td>
<td>--</td>
<td>++</td>
<td>+</td>
<td>++</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AL-R02</th>
<th>PRODUCTION POTENTIAL</th>
<th>SYSTEM COMPLEXITY</th>
<th>ACCESSIBILITY</th>
<th>MAINTENANCE</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>-</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>++</td>
</tr>
</tbody>
</table>
8.5 Mixed systems

Figure 8.11: Facade integrated solar thermal and photovoltaic/thin film systems as part of a unitized curtain wall element
**Figure 8.12:** Mixed algae/photovoltaic systems integration into a unitized curtain wall element
THE POTENTIAL FOR HIGH RISE ENVELOPES AS ENERGY PRODUCTION UNITS | ANNE LEEUW
PART 3

USING THE FLOWCHART AND
CALCULATING ENERGY PRODUCTION
POTENTIAL
APPLYING THE FLOWCHART AND CALCULATING ENERGY POTENTIAL

The goal of the strategy is to provide guidance in selecting the energy production systems and assessing the energy production potential of high rise. The flowchart presented in the previous chapter must be tested for several high rise buildings, because if it results in the same output for different buildings that would imply that there is a best solution to apply to the high rise building stock. Therefore 3 buildings are chosen to apply the flowchart to. The same buildings are used that were compared in a study by Raji, Tenpierik, and van den Dobbelsteen (2015) in which sustainable high rise are compared to conventional high rise buildings in different climate regions. The buildings in the moderate climate zone are used here. The questions from the flowchart are answered in tabulated. The results can be seen in Table 1.1. The analysis of insolation and wind speed and direction were performed with Rhinoceros 5.0, Grasshopper and Ladybug. The epw-files (weather data) used for the different locations vary from the exact location and are given in Table 1.1. The energy potential is calculated using the formula:

\[
\text{Energy production potential} = EPP [kWh] = E_A + E_W + E_{SE} + E_{ST} \\
E_A = \text{Algae energy potential} \\
E_W = \text{Wind energy potential} \\
E_{SE} = \text{Solar electric energy potential} \\
E_{ST} = \text{Solar thermal energy potential}
\]

Which was explained in paragraph 8.2 Quantifying Energy Potential.

The Energy production potential is divided by the floor area of the building to be able to compare the EPP to the energy use intensity (EUI) of the building. The window to wall ratios are all lowered to 40% for the calculations.

The hot water demand was left out of the buildings EUI, because some of the data used for the EWI building and Post Tower was metered, so it could already include part of the hot water demand.
9.1 Mary Axe building
The Mary Axe building uses two different climate systems. The top section has a fully conditioned space and the lower floors are naturally ventilated. The air is passively heated in the cavity by the sun, but if insufficient, heated by an air handling unit. The climate system is active, but some passive strategies are used to reduce the cooling and heating loads. In both the mixed system part of the building and the fully conditioned building, the energy requirement for lighting, pumps & fans is higher than the energy demand for heating and cooling. The first energy requirement is thus electricity. The Insolation study shows that for areas where the insolation is higher than 400kWh/m² per year, the average insolation is 714.72kWh/m². The average wind speed is 3.24m/s, but higher for approximately 8% of the time. For wind energy potential 50kWh/m² was used to estimate the production. The top section of the building has a EUI of 73.6kWh/m² and the lower section 63kWh/m². The EPP divided by the floor area gives an EPP/m² of 9,83kWh/m², which 14% of the energy demand averaged over the two building sections.

9.2 Post Tower
The Post Tower has the lowest energy use intensity. Water from the Rhine is used to cool the building and the building is connected to district heating. The heating demand remains higher than the electricity demand for pumps, fans and lighting, but heating is provided externally and in the current design there are no options for seasonal storage. Solar thermal systems should therefore only be applied to provide hot water. However, it is difficult to assess the demand for hot water. Therefore the EPP for the Post Tower is based on electricity production. The average insolation is lowest at this tower. The average insolation for surfaces where I > 400kWh/m² is 606.49kWh/m². The wind speed is 3.97m/s, thus 50kWh/m² is used to calculate wind potential. The EUI of the Post Tower is the lowest of the three towers, but so if the EPP/m², which are 42.8kWh/m² and 5.65kWh/m² respectively. Energy production could cover 13% of the energy demand.
9.3 EWI building
This is the oldest building, but it features a double façade. The façade however functions badly, resulting in a high heating load and the cooling load is also highest of the three towers. The energy for heating is now provided by a ground coupled heat pump and district heating and cooling is done through air conditioning. This building contains lecture rooms and laboratories, which consume more energy than offices. The heating demand is highest and thus the thermal demand, but a ground source is already used and it is unknown if there is seasonal storage capacity. Therefore the electricity demand is fulfilled first. The average wind speed is highest for this building at 5.35m/s, but higher speeds are frequent, thus a production potential of 50kWh/m² (33% of the time) and 150kWh/m² (12% of the time) are used to calculate the potential wind energy production. The EUI of the building is 204.4kWh/m² and the EPP/m² is 7.53kWh/m². While the EPP/m² is comparable to the other buildings, the EUI is much higher. Only 4% of the energy demand can be produced on the façade.

9.4 Conclusion
Three buildings were put through the flowchart and the energy production potential (EPP) for the envelopes was calculated. The EPP per square meter of floor area shows how much of the energy demand can be compensated. All buildings have EPP/m² < 10kWh/m², but this number would be higher if solar thermal energy was incorporated, because thermal efficiency of thermal collectors is roughly twice as high as electricity conversion efficiency of photovoltaic modules. The Mary Axe building shows the highest average insolation, which may be due to its shape at the top of the building. Tilted surfaces catch more radiation than vertical surfaces.
<table>
<thead>
<tr>
<th>Building name</th>
<th>Mary Axe</th>
<th>Post Tower</th>
<th>EWI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>London</td>
<td>Bonn</td>
<td>Delft</td>
</tr>
<tr>
<td>EPW location</td>
<td>Gatwick</td>
<td>Düsseldorf</td>
<td>Amsterdam</td>
</tr>
<tr>
<td># stories</td>
<td>40</td>
<td>42</td>
<td>22</td>
</tr>
<tr>
<td>year built</td>
<td>2004</td>
<td>2002</td>
<td>1969</td>
</tr>
<tr>
<td>approx floor area [m²]</td>
<td>47950</td>
<td>55000</td>
<td>67270</td>
</tr>
<tr>
<td>Lighting, pumps &amp; fans</td>
<td>46,7</td>
<td>38</td>
<td>12</td>
</tr>
<tr>
<td>Heating</td>
<td>14,1</td>
<td>17,3</td>
<td>30,8</td>
</tr>
<tr>
<td>Cooling</td>
<td>12,8</td>
<td>7,7</td>
<td>0</td>
</tr>
<tr>
<td>total kwh/m²</td>
<td>73,6</td>
<td>63</td>
<td>42,8</td>
</tr>
</tbody>
</table>

Is the climate system active, mixed, passive or unknown?

<table>
<thead>
<tr>
<th></th>
<th>active</th>
<th>mixed</th>
<th>mixed</th>
<th>active</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>Passive gain, air heating through cavity and air handling unit</td>
<td>Passive gain, air heating through cavity and air handling unit</td>
<td>district heating, cavity is buffer zone</td>
<td>ground coupled heat pump &amp; district heating</td>
</tr>
<tr>
<td>Cooling</td>
<td>Air conditioning</td>
<td>Natural ventilation or Air conditioning</td>
<td>Rhine water</td>
<td>Ground coupled heat pump &amp; Air conditioning for labs/lecture rooms</td>
</tr>
<tr>
<td>Electricity</td>
<td>grid</td>
<td>grid</td>
<td>grid</td>
<td>grid</td>
</tr>
<tr>
<td>First need:</td>
<td>electricity</td>
<td>electricity</td>
<td>electricity</td>
<td>electricity</td>
</tr>
</tbody>
</table>

Is the window to wall ratio higher than 40%?

<table>
<thead>
<tr>
<th></th>
<th>Window surface [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95%</td>
</tr>
</tbody>
</table>

Is the insolation on the facade higher than 400 kWh/m²?

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>Yes</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approx. average insolation for areas where I &gt; 400 kWh/m²</td>
<td>714,72</td>
<td>606,49</td>
<td>700,23</td>
</tr>
<tr>
<td>Approx. available area</td>
<td>2947</td>
<td>2206</td>
<td>2908</td>
</tr>
<tr>
<td>EPP_Se in kWh</td>
<td>421200</td>
<td>267600</td>
<td>407192</td>
</tr>
<tr>
<td>EPP_St in kWh</td>
<td>842400</td>
<td>535200</td>
<td>814392</td>
</tr>
<tr>
<td>EPP_Se in kWh/m²</td>
<td>9</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

Is the wind speed higher than 4 m/s?

<table>
<thead>
<tr>
<th></th>
<th>On average</th>
<th>Higher speeds % from directions of interest</th>
<th>Approx. available area</th>
<th>EPP_W in kWh</th>
<th>EPP_W in kWh/m²</th>
<th>Is the demand met and is there space left?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3,24</td>
<td>8%</td>
<td>4000</td>
<td>15000</td>
<td>0,31</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>3,97</td>
<td>12%</td>
<td>3500</td>
<td>21000</td>
<td>0,38</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>5,35</td>
<td>33%/12%</td>
<td>915/5200</td>
<td>65218,5</td>
<td>0,97</td>
<td>No</td>
</tr>
</tbody>
</table>

integrate transparent PV into transparent surfaces

<table>
<thead>
<tr>
<th></th>
<th>available area</th>
<th>efficiency</th>
<th>EPP_Se-tf in kWh</th>
<th>EPP_Se-tf in kWh/m²</th>
<th>total EPP (this uses the EPP for PV and not for ST) kWh/m² floor area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1964</td>
<td>2,5%</td>
<td>35100</td>
<td>0,73</td>
<td>9.83</td>
</tr>
<tr>
<td></td>
<td>1471</td>
<td>2,5%</td>
<td>22300</td>
<td>0,41</td>
<td>5,65</td>
</tr>
<tr>
<td></td>
<td>1938</td>
<td>2,5%</td>
<td>33933</td>
<td>0,50</td>
<td>7,53</td>
</tr>
</tbody>
</table>

Table 9.1: Results of using the flowchart for three high rise buildings
9.5 De Rotterdam: Analysis

9.5.1 Energy demand

The energy demand of De Rotterdam is described for the office section and the residential sector. For the office sector, one story of one tower is analysed. For the residential sector, one apartment is analysed. The literature review has shown that seasonal climate variations influence internal conditions. That is why the annual energy demand was analysed, but December 21st, March 21st and June 21st are chosen to show energy demands on a daily basis in greater detail. The annual energy demand is given in kWh per year for the heating and cooling load. The loads are not to be used directly or copied as such, because the energy model does not incorporate the complete climate system. For example, it does not incorporate the use of Maas water for cooling. Using this free source will in reality reduce the cooling load presented in the next paragraph as is shown by the example of the Post Tower in Bonn, which is described in the previous chapter. The models used for simulation are meant for comparison. It shows the effect of lowering the window to wall ratio, increasing the visible light transmittance and g-value and adding vertical or horizontal shapes to the structure that provide shading.

9.5.1.1 Office

For the office energy demand, it was assumed that:

- The WTW is 0.9
- The solar heat gain coefficient is 0.27
- The visible light transmittance is 0.51
- The total floor area for all office floors is 60.000m².
- The energy required to heat 22 litres of water per person from 14°C to 50°C can be computed as follows:

\[ Q \ [\text{kJ}] = c \cdot m \cdot \Delta T \cdot n_{\text{people}} \cdot n_{\text{days}} \]

\[ Q = 4.19 \cdot 22 \cdot 36 \cdot 3333 \cdot 243 \]
\[ = 2.69 \cdot 10^9 \text{kJ} \text{ or } 12.46 \text{kWh/m}^2 \]

For which:

- \( c \ [\text{kJ/kg}] = \text{specific heat of water} = 4.19 \)
- \( m \ [\text{kg}] = \text{mass of heated body} \)
- \( \Delta T = T_{\text{input}} [\text{°C}] - T_{\text{output}} [\text{°C}] \)
- \( n_{\text{people}} = \text{number of people in offices} \)
- \( n_{\text{days}} = \text{annual work days} = 243 \)

The calculations with these number form the benchmark case. The energy use intensity (EUI) of De Rotterdam amounts to 78,3kWh/m², which is close to that of the Mary Axe building, so this is plausible, although it is expected that the actual EUI is lower due to the use of ‘free’ cooling with Maas water. The hot tap water demand is

9.5.1.2 Apartments

For the residential block in the building, which contains 240 apartments, national averages are used to estimate the energy demand. In the Netherlands the average gas consumption for apartments is 900m³ per year. The average apartment has 86m² floor area. However, the average house is 38 years old (Centraal Bureau voor de Statistiek [CBS], 2000), so the apartments in De Rotterdam will have a higher energy performance, due to tightened building standards. Infiltration losses and heat losses through the walls will be much lower than for the average flat. Standards provided by ISSO publication 83.1 and 83.2 use an Rₚ value of 1.3 for buildings built 38 years ago and 3.5 for buildings built after 2008. The average gas consumption for heating is therefore lowered to 500m³ per apartment. The energy density of natural gas is 35,17MJ/m³ or roughly 9,8kWh/m³. A two-person household (average) uses 2,950 kWh of electricity per year. It is assumed that the

\[ Q = 9.5.1.1 \text{ Office} \]

\[ Q = 9.5.1.2 \text{ Apartments} \]

\[ Q = 9.5.1.3 \text{ Residential} \]

\[ Q = 9.5.1.4 \text{ Miscellaneous} \]
apartments do not have cooling systems, because: most residential units do not incorporate cooling systems and on the south east side, shading is provided by balconies for most apartments. The hot water demand is computed with:

\[
Q \ [kJ] = c \cdot m \cdot \Delta T \cdot n_{\text{people}} \cdot n_{\text{days}}
\]

\[Q = 4.19 \cdot 22 \cdot 36 \cdot 3333 \cdot 243 \]

\[= 2.69 \cdot 10^9kJ \text{ or } 12.46 \text{kWh/m}^2\]

For which:

\[c \ [kJ/kg] = \text{specific heat of water } = 4.19 \]

\[m \ [kg] = \text{mass of heated body} \]

\[\Delta T = T_{\text{input}} \ [\degree K] - T_{\text{output}} \ [\degree K] \]

\[n_{\text{people}} = \text{number of people in offices} \]

\[n_{\text{days}} = \text{annual work days } = 243\]

9.5.1.3 Daily internal and external gains

The current design of De Rotterdam has a window to wall ratio of 90%, seen from floor to ceiling height. The effect of the window to wall ratio and low g-value of 0.27 are observed in the first simulation of the buildings energy demand. This way, a benchmark is created. Graph 1.1, Graph 9.2, Graph 9.3 show the curves for the load by people, lighting and equipment (Qp + Qe + Ql), the loads through transparent fabric (Qf_tr), opaque fabric (Qf_op), solar gains (Qs), ventilation losses (Qv) and infiltration losses (Qi). Qp + Qe + Ql is the highest adds most heat to the space.
Graph 9.1: Energy gains and losses for the benchmark model on the 21st of December.

Graph 9.2: Energy gains and losses for the benchmark model on the 21st of June.

Graph 9.3: Energy gains and losses for the benchmark model on the 21st of March.
9.5.2 Environmental analysis

In order to find the energy potential of De Rotterdam, the energy resources need to be mapped. A wind analysis and solar analysis provide information on wind direction, wind velocity, insolation, daylight hours and luminance levels.

9.5.2.1 Insolation analysis

For the solar analysis the Rhinoceros model is again used with the plugins Grasshopper, Ladybug and Honeybee. The maximum insolation in The Netherlands is 1000kWh/m² and for vertical surfaces the insolation is 74% of the maximum insolation. From the legend and figures it is clear that the results match that expectation. The Rijnharbor façade and the roof receive most irradiation, most parts of the evening façade are also above 400kWh/m².

![Figure 9.7: solar irradiance for de Rotterdam measured in kWh per square meter](image)

![Figure 9.8: Results of radiation analysis showing the insolation of the North-west facade, South-east facade, North-east facade, South-West facade.](image)
9.5.2.2 Illuminance analysis

The illuminance analysis is of importance because of two things:

- It allows for comparison between designs in terms of daylight entry
- Algae require an illuminance between 5400lux and 13500lux. The analysis shows if the front glass surface lets enough light through for optimal algae growth.

The simulation was run with two different skies and different properties for glazing at 12.00 in March:

- The illuminance is calculated for an intermediate sunny sky (20,000lux) and a uniform sky (10,000lux).
- Glazing with a visible light transmittance of 80% and 60% were tested, because if algae are to be produced on the façade, different glazing would be used for the outermost layer than for a façade that separates the interior from the exterior directly.
- When algae systems are placed in front of the façade, the window to wall ratio (WTW) decreases, thus the simulation was run using a WTW of 90% and 40%.

At the façade perimeter the illuminance is always enough at the Rijnharbor (South East) façade. Except on really dark days, the daylight will be insufficient. At the Maas façade, a uniform sky and a LT-value of 0.8 are just about at the bottom threshold for algae growth. This façade will also get less daylight hours than the Rijnharbor façade or the short sides of the building, so for most part of the day, the illuminance will be below the threshold.

The roof was left from the analysis, but provides the most daylight availability and the illuminance will be close to sky intensity * LT-value. So if the sky intensity is 20,000 lux, the illuminance behind glazing with a LT of 0.8 will be 16,000. If algae were to be placed on the roof, a lower LT-value is necessary or algae growth will slow down.
9.5.2.3 Wind analysis

To see if vibrational wind energy at the envelope of De Rotterdam is a viable option, a minimal wind speed of 2 m/s is required. Using the epw-file for Amsterdam wind roses can be plotted that show the wind velocity and direction. Earlier it was concluded that mean wind speeds in Rotterdam at the Maas can be as high as 6.9 m/s, which is 53% higher than the mean wind speed for Amsterdam (4.5 m/s) represented by the wind roses. For the energy calculation the categorization is as follows (for legend colours see Figure 1.9):

| 50 kWh/m² | Wind speed 2-6 m/s | Bottom 2 legend colours |
| 150 kWh/m² | Wind speed 6-10 m/s | Middle 3 legend colours |
| 450 kWh/m² | Wind speed >10 m/s  | Top 5 legend colours |

| Table 9.4: Wind speed energy production categories |

Wind roses are plotted in the Rhino geometry using Grasshopper and Ladybug.

<table>
<thead>
<tr>
<th>Façade</th>
<th>Speed [m/s]</th>
<th>#R</th>
<th>Freq.</th>
<th>Dir.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rijnharbor</td>
<td>2-6</td>
<td>6</td>
<td>9%</td>
<td>SE - NW</td>
</tr>
<tr>
<td></td>
<td>6-10</td>
<td>18</td>
<td>27%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 &lt;</td>
<td>3.5</td>
<td>5.25%</td>
<td></td>
</tr>
<tr>
<td>Maas</td>
<td>2-6</td>
<td>9.5</td>
<td>14.25%</td>
<td>NW - SE</td>
</tr>
<tr>
<td></td>
<td>6-10</td>
<td>6</td>
<td>9%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 &lt;</td>
<td>1.5</td>
<td>2.25%</td>
<td></td>
</tr>
<tr>
<td>SE</td>
<td>2-6</td>
<td>8</td>
<td>12%</td>
<td>NNE – WSW*</td>
</tr>
<tr>
<td></td>
<td>6-10</td>
<td>10</td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 &lt;</td>
<td>3.5</td>
<td>5.25%</td>
<td></td>
</tr>
<tr>
<td>NW</td>
<td>2-6</td>
<td>11.5</td>
<td>17.25%</td>
<td>SW – NE</td>
</tr>
<tr>
<td></td>
<td>6-10</td>
<td>12</td>
<td>18%</td>
<td></td>
</tr>
</tbody>
</table>

Table 9.5: Wind speed and frequency (Freq.). The frequency is found by multiplying the number of rings (#R) per colour category by 1.5. The SE-façade profits from a wind tunnel, so two more rings are added, but the rings for wind from the SE-direction are not counted because they are blocked by the KPN-building.

The New Orleans building is also located to the West of De Rotterdam. Autodesk Flow design was used to analyse the wind flow around De Rotterdam, to see the influence of the surrounding buildings on the wind flow around its envelope. The results are shown in XX and Figure 1.8. A wind tunnel is created around the geometry with a starting wind speed of 5 m/s. The dark blue areas represent a wind speed of up to 3 m/s. The red areas represent the highest wind speed of between 9 and 11 m/s. All around the building, wind speeds are low and range from 0 to approximately 3 m/s. Figure 1.7 shows the formation of vortexes when the wind comes in from the South West.

More images of wind roses and wind tunnel simulation can

![Figure 13: Wind flow from South West around De Rotterdam](image13.png)

![Figure 14: Wind flow around De Rotterdam. Autodesk Flow Image](image14.png)
9.5.2.4 Analysis summary

The analysis is complete so the required knowledge for using the flowchart is present:

- **Insolation:**
  It is evident that on the Rijnharbor façade (South East) and on the Evening façade (South West) the illumination on most parts of the façade is higher than 400kWh/m².

- **Illumination:**
  Is highest on the roof and on the Rijnharbor façade. With an LT-value of 0.8 enough light penetrates to grow algae. With an LT-value of 0.6, the values will be too low in dark weather or for most hours of the day, slowing down algae growth.

- **Wind:**
  Speeds are highest on the morning façade and Rijnharbor façade, but solar energy is preferred over wind energy. The morning façade and the KPN building form a wind tunnel where wind speed increases. At the Maas façade wind is not blocked by other buildings.

9.5.2.5 Climate installation

- **De Rotterdam** has an estimated energy demand of 94.07kWh/m². The highest demand is for electricity which is used for lighting, pumps and fans and to run the cooling system.

- **De Rotterdam** makes use of a CHP-system, which is already set in place. The system has a maximum capacity of 600kW. To be self-sufficient, the fuel demand should be met. This will diminish transport costs.

- The hot water demand for the entire building is 15.55kWh/m².

- There are no large storage options for hot water, so it would not be useful to focus on thermal energy to reduce the energy demand for cooling (with absorption chilling, which could be connected to a CHP-system or it could be stand-alone).

Table 1.5 shows the results.
9.5.3 Energy potential

The energy potential of an envelope must be quantified. Based on literature the assumptions used for assessing the energy potential are presented in Table 7.1.

Energy production potential = EPP[kWh]

\[ E_{E} = E_{A} + E_{W} + E_{Se} + E_{St} \]

\[ E_{A} = \text{Algae energy potential} \]

\[ E_{W} = \text{Wind energy potential} \]

\[ E_{Se} = \text{Solar electric energy potential} \]

\[ E_{St} = \text{Solar thermal energy potential} \]

9.5.3.1 Wind

Wind energy systems are to be applied on the Maas façade and the South East façade (surfaces 4, 5, 6, G, H, I, J, K and L). The frequencies are given in Table 1.4. The wind energy potential is calculated as follows:

\[ E_{W}[kWh] = A \cdot F_{i} \cdot E_{out:w,v,i} \]

For which:

\[ A \left[ m^2 \right] = \text{surface area covered with wind system} \]

\[ F_{i} \left[ \% \right] = \text{frequency of wind direction for velocity } i \]

\[ E_{out:w,v,i} \left[ kWh/m^2 \right] = \text{energy output depending on wind speed in} \]

\[ [m/s]: E_{out:4-6}, E_{out:6-10}, E_{out:10<} \]

\[ E_{W}[kWh] = A_{Maas} \cdot F_{Maas,i} \cdot E_{out:w,v,i} + A_{Southeast} \]

\[ F_{Southeast,i} \cdot E_{out:w,v,i} \]

\[ E_{W}[kWh] = 5076 \cdot 0.1425 \cdot 50 + 5076 \cdot 0.09 \cdot 150 \]

\[ + 5076 \cdot 0.025 \cdot 450 + 2933 \cdot 0.12 \]

\[ \cdot 50 + 2933 \cdot 0.15 \cdot 150 + 2933 \]

\[ \cdot 0.035 \cdot 450 \]

\[ = 2.92 \cdot 10^5 kWh \]

9.5.3.2 Sun

The measure of availability of solar energy is insolation in kWh/m². The insolation is the yearly sum of irradiation. The average insolation (I) for surfaces where I < 400kWh/m² is 662.8kWh/m².

Solar systems are placed on the roofs of the service core and on the Rijnharbor and North West façade (surfaces A-F, 1, 2, 3 and R4, R5, R6). Algae are placed on the roof that surrounds the service core (surfaces R1, R2, R3).

Algae energy potential is calculated as follows:

\[ E_{A}[kWh] = (V \cdot m \cdot cv \cdot n) \cdot (3.6 \cdot 10^5)^{-1} \]

\[ = (V \cdot 1.5 \cdot 10^{-3} \cdot 37 \cdot 10^3 \cdot 365) \cdot (3.6 \cdot 10^5)^{-1} \]

\[ = (62100 \cdot 1.5 \cdot 10^{-3} \cdot 37 \cdot 10^3 \cdot 365) \cdot (3.6 \cdot 10^5)^{-1} \]

\[ = 3.34 \cdot 10^5 kWh \]

For which:

\[ V \left[ dm^3 \right] = \text{total volume of photobioreactor tubes} \]

\[ m[kg] = \text{mass of lipid content per l of water per day} \]

\[ cv[kJ/kg] = \text{calorific value for algae biofuel; } cv = 37MJ/kg \]

\[ n \left[ - \right] = \text{days of calculation, } if \text{ annual; } n = 365 \]

Solar electric energy potential is calculated as follows:

\[ E_{Se}[kWh] = A_{i} \cdot I \cdot E_{se,eff} \]

\[ = (1500 + 1056 + 984 + 1920 + 1500 + 1500 + 150 \]

\[ \cdot 3 + 1920 + 1920 + 104 \cdot 0.3 \cdot 60\% \]

\[ = 1.04 \cdot 10^6 kWh \]

For which:

\[ A \left[ m^2 \right] = \text{surface area covered with solar electric systems} \]

\[ I \left[ W/m^2 \right] = \text{annual insolation} \]

\[ E_{se,eff} \left[ \% \right] = \text{photovoltaic system conversion efficiency} \]
The potential for thin film, is:
\[ E_{Se}[kWh] = A_1 \cdot I \cdot E_{Se,eff} \]
\[ = (1500 + 1056 + 984 + 1920 + 1500 + 1500 + 150 + 3 + 1920 + 1920 + 104 \cdot 0.3) \cdot 40\% \]
\[ \cdot 662.8 \cdot 2.5\% \]
\[ = 8.66 \cdot 10^6 kWh \]

Considering that the efficiency is used here is twice the efficiency of photovoltaic systems, the potential for solar thermal energy is twice that of the solar electric potential. Thus:
\[ E_{St}[kWh] = 2 \cdot E_{Se} = 2.08 \cdot 10^6 kWh \]

Or:
\[ E_{St}[kWh] = A \cdot I \cdot E_{st,eff} \]

For which:
\[ A [m^2] = \text{surface area covered with solar electric systems} \]
\[ I [kWh/m^2] = \text{annual insolation} \]
\[ E_{st,eff} [%] = \text{thermal system conversion efficiency} \]

The thermal energy demand for hot water is 14.69kWh/m² or 1.184.602kWh. If this demand would be met 446.813kWh of electricity could be produced with photovoltaic systems with an efficiency of 20%. A total of 1.631.415kWh could be produced, 57% more than for a completely photovoltaic system. This increase depends on the hot water demand. The lower the demand the lower the increase, with a maximum increase of 100%, when the thermal demand can be met, but then there is no space left for photovoltaic systems (on opaque surfaces).

The energy potential becomes:
\[ \text{Energy production potential} = EPP[kWh] \]
\[ = 3.34 \cdot 10^5 + 2.92 \cdot 10^5 + 4.47 \cdot 10^5 + 8.66 \cdot 10^4 \]
\[ + 1.18 \cdot 10^6 = 2.33 \cdot 10^6 kWh \]

By covering the entire building in energy producing systems, 85% of the energy demand of all apartments could be fulfilled and 41% of the energy demand for De Rotterdam designed with a window to wall ratio of 40%. Of the total building, with a window to wall ratio of 40%, 31% of the energy demand could be met. If a building would be designed with a passive cooling system, 42% of the energy demand could be met.

If, in the future system efficiencies would increase to 10% for transparent thin film, 40% for PV-systems and 65% for solar thermal systems, the potential would grow to 65% for the total building. If the building would use free sources for heating (0 kWh/m² demand) and cooling, and energy for pumps, lighting and fans would stay the same 97% of the buildings energy demand could be met.

**Figure 9.110: surface areas for the surfaces of interest for wind or solar energy.own ill.**
<table>
<thead>
<tr>
<th>Lighting, pumps &amp; fans</th>
<th>Offices</th>
<th>Offices low wtw</th>
<th>Apts</th>
<th>Total building</th>
<th>Total building without cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>31,40</td>
<td>31,40</td>
<td>33,90</td>
<td>32,04</td>
<td>32,04</td>
</tr>
<tr>
<td>Heating</td>
<td>14,30</td>
<td>10,80</td>
<td>56,90</td>
<td>22,60</td>
<td>22,60</td>
</tr>
<tr>
<td>Cooling</td>
<td>32,60</td>
<td>32,10</td>
<td>-</td>
<td>23,88</td>
<td>-</td>
</tr>
<tr>
<td>Hot water</td>
<td>12,46</td>
<td>12,46</td>
<td>21,16</td>
<td>14,69</td>
<td>14,69</td>
</tr>
<tr>
<td>total kWh/m²</td>
<td>90,76</td>
<td>86,76</td>
<td>111,96</td>
<td>93,21</td>
<td>69,33</td>
</tr>
<tr>
<td>floor space offices</td>
<td>60.000</td>
<td>60.000</td>
<td>-</td>
<td>60.000</td>
<td>60.000</td>
</tr>
<tr>
<td>floor space apartments</td>
<td>-</td>
<td>-</td>
<td>20.640</td>
<td>20.640</td>
<td>20.640</td>
</tr>
</tbody>
</table>

Is the climate system active, mixed, passive or unknown? > active/mixed

What input does the system require mostly?

- **Heating**
  - District heating and a CHP system running on biofuel
- **Cooling**
  - Apartments do not have cooling systems. Offices through mechanical ventilation and natural ventilation. The water of the Maas river is used to reduce the cooling load.*
- **Electricity**
  - CHP & grid
- **First need:**
  - Electricity/fuel (for cooling)

Is the window to wall ratio higher than 40%? > YES: 53% - 75% (seen from outside)

Is the insolation on the facade higher than 400 kWh/m²? > YES

| average insolation where I > 400 kWh/m² | 663 kWh/m² |
| approx available area                  | 7.839 m²   |
| EPP_Se [kWh]                           | 1.039.114  |
| EPP_St [kWh]                           | 2.078.228  |
| EPP_Se [kWh/m²]                        | 17,32      |
| EPP_St [kWh/m²]                        | 34,64      |
| Algae                                  | 62.100 (in a tubular system on roofs R1, R2, R3, annually) |
| Can the system be climate controlled?  | yes        |
| EPP_A [kWh]                            | 333.975    |
| EPP_A [kWh/m²]                         | 5,6        |

Is the wind speed higher than 4 m/s? > YES

| On average? [m/s]                      | 5/6        |
| Higher speeds % from prevailing directions | 15%/31.5% |
| approx available area                  | 5.076 m² / 2.933 m² |
| Epp_W [kWh]                            | 291.583    |
| Epp_W [kWh/m²]                         | 4,86       |

Integrate transparent PV into transparent surfaces

| Approx available area [m²]             | 5,226      |
| efficiency                             | 2,5%       |
| EPP_Se-tf [kWh]                        | 86.593     |
| EPP_Se-tf [kWh/m²]                     | 1,44       |
| Total EPP                              | 29,19      |
| EPP electric [kWh/m²]                  | 29,19      |
| EPP electric/thermal [kWh/m²]          | 35,42      |
| % of demand all electric               | 32%        |
| % of demand thermal/electric           | 39%        |

Table 9.6: Flowchart and EPP results for De Rotterdam with different profiles
10 DE ROTTERDAM: DESIGN AND TESTING

10.1 Energy consumption for different designs

It is important to know how changes to the façade translate to changes in energy consumption. The design catalogue shows options for integration energy production systems into solar shading and the flowchart asks the designer to reduce the window to wall ratio (WTW). These two design choices will have influence on the buildings performance. Different models were built to recreate these designs with high and low window to wall ratios. The set-point temperature for cooling is 25 degrees Celsius and 20 degrees Celsius for heating. The results are shown in table 14. The different energy gain and loss profiles for the 21st of March, June and December are shown in graphs 10.1 through 10.15. The energy calculations are based on heating and cooling loads and do not take into account the demand for hot tap water.

The energy use intensity (EUI) of the Rotterdam is comparable to that of the Mary Axe building. However the simulation does not incorporate the use of Maas river water to reduce the cooling load. Nonetheless, the EUI is representative for modern high rise buildings which use active climate systems. It is obvious that lowering the WTW has a positive effect on the heating and cooling load (-5%). Horizontal shading has a similar effect (-4%) and performs slightly better than vertical shading (-2%). Mixed shading performs not better, but in between at (-3%). Mixed shading and a lower WTW show the largest improvement (-7%), but do not create more surface for energy production, because the shading also shades some of the opaque surfaces. Adding mixed shading increases the heating demand for De Rotterdam by 14% or 2 kWh/m². The cooling load is reduced by 14% or 4.6 kWh/m². This is effective, but less so than reducing the window to wall ratio. To see how De Rotterdam would compare to a conventional office building with glazing with a G-value of 0.6, a LT-value of 0.8 and a U-value of 1.6, a ‘basic’ model was created. The results of heating gains and losses are shown in Graph 10.13 – 10.15. It is noticeable that the current building already performs much better in terms of solar gain. Therefore, high performance glazing along with a small window to wall ratio is likely to be the best strategy for energy efficient buildings in moderate climates.

To see what passive strategies could do, a simulation was run where there the flow of outdoor air could be maximized for cooling purposes and the WTW is low. This leads to a drop of 38% in energy demand compared to the current design. However, increasing the air flow rate means that draught could arise. The heating load is only a little smaller, because the drop in heating demand caused by the lower WTW is partially lifted due to colder (outdoor) air entering the space.

The building is also simulated for a scenario where the set-point temperature is set at 40 degrees Celsius for cooling and 18 for heating. This scenario represents allowing more overheating days and thereby changing the comfort requirements. This model results in a drop in energy demand of 8%. 
<table>
<thead>
<tr>
<th></th>
<th>WTW [%]</th>
<th>G-value</th>
<th>plug loads &amp; lighting [kWh/m²]</th>
<th>Heating [kWh/m²]</th>
<th>Cooling [kWh/m²]</th>
<th>Total [kWh/m²]</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotterdam</td>
<td>90%</td>
<td>0,27</td>
<td>31,4</td>
<td>14,3</td>
<td>32,6</td>
<td>78,3</td>
<td>0%</td>
</tr>
<tr>
<td>Rotterdam low WTW</td>
<td>40%</td>
<td>0,27</td>
<td>31,4</td>
<td>10,8</td>
<td>32,1</td>
<td>74,4</td>
<td>-5%</td>
</tr>
<tr>
<td>Horizontal shading</td>
<td>90%</td>
<td>0,27</td>
<td>31,4</td>
<td>16,3</td>
<td>27,9</td>
<td>75,5</td>
<td>-4%</td>
</tr>
<tr>
<td>Vertical shading</td>
<td>90%</td>
<td>0,27</td>
<td>31,4</td>
<td>16,0</td>
<td>29,6</td>
<td>77,0</td>
<td>-2%</td>
</tr>
<tr>
<td>Mixed shading A</td>
<td>90%</td>
<td>0,27</td>
<td>31,4</td>
<td>16,3</td>
<td>28,0</td>
<td>75,7</td>
<td>-3%</td>
</tr>
<tr>
<td>Mixed shading B</td>
<td>40%</td>
<td>0,27</td>
<td>31,4</td>
<td>11,3</td>
<td>29,8</td>
<td>72,6</td>
<td>-7%</td>
</tr>
<tr>
<td>Mixed shading with maximum natural ventilation</td>
<td>40%</td>
<td>0,27</td>
<td>31,4</td>
<td>13,9</td>
<td>3,4</td>
<td>48,7</td>
<td>-38%</td>
</tr>
<tr>
<td>No setpoint for cooling</td>
<td>40%</td>
<td>0,27</td>
<td>31,4</td>
<td>10,8</td>
<td>29,6</td>
<td>71,8</td>
<td>-8%</td>
</tr>
</tbody>
</table>

Table 10.1: results for different energy simulation models

Figure 10.1: No shading with WTW=40%
Figure 10.2: Vertical shading with WTW=90%
Figure 10.3: Horizontal shading with WTW=90%
Figure 10.4: Mixed shading A (mixed shading B has a WTW of 40%) with WTW=90%
Graphs 10.1 to 10.3: De Rotterdam office with a WTW of 90%, glazing with G-value 0.27 and vertical exterior shading.

Graphs 10.4 to 10.6: De Rotterdam office with a WTW of 90%, glazing with G-value 0.27 and horizontal exterior shading.
Graphs 10.7 to 10.9: De Rotterdam office with a wtw of 90%, glazing with G-value 0.27 and vertical exterior shading on the SE facade and horizontal on the SW facade.

Graphs 10.10 to 10.12: De Rotterdam office with a wtw of 90%, glazing with G-value 0.27 and no shading.
The potential for high rise envelopes as energy production units.

**Graph 10.13:** Energy gains and losses for a model with G-value 0.6 and LT-value of 0.8 on March 21st.

**Graph 10.14:** Energy gains and losses for a model with G-value 0.6 and LT-value of 0.8 on June 21st.

**Graph 10.15:** Energy gains and losses for a model with G-value 0.6 and LT-value of 0.8 on December 21st.

The diagrams show energy gains and losses in kWh for different models over time, with various labels such as Qp+Qe+Ql, Qf_tr, Qf_op, Qs, Qv, and Qi.
10.2 Solar energy availability for different designs

This paragraph describes how shape and context affect the availability of solar energy.

10.2.1 Façade shape

Three different façade shapes were tested for insolation. The results were compared to the flat design which represents the current design of De Rotterdam. 11 designs were tested for 5 orientations. The angled design is tested in 3 modes: with the outward facing point located in the centre as shown in Figure 10.1, or with the outward facing point located at 25% or 75% from the side. The curved façade is tested for a curve that ends in a sharp corner as shown in Figure 10.2 or a soft curve with no end points but a smooth wave across the entire façade. The results are shown in Table 10.4, Table 10.5 and Table 10.3. The higher the insol:area percentage, the better. On north facing façades, changing the shape from flat to curved or angled increases the available solar energy by 47% to 69% (or a 4% to 34% insolation increase) for each unit increase in surface area. For each and west facing façades the insol:area percentage ranges between 31% and 38% (or a 3% - 17% insolation increase). The effect is smallest for south facing facades. Changing the façade shape of the current façade facing 225 degrees from the North to an angled façade with an offset of 2 meters from the current façade (shape as shown in Figure 10.1), the insolation increases by 20%.
10.2.2 Envelope shape and orientation

The buildings in Figure 10.4 were used to test the solar energy availability for different envelope shapes, to see if De Rotterdam’s shape catches most irradiation. The shapes are chosen to have roughly the same volume. The geometry of De Rotterdam was also tested to see if the current design would receive more insolation if rotated around its centre.

<table>
<thead>
<tr>
<th>shape</th>
<th>Insolation [kWh]</th>
<th>kWh/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder</td>
<td>4.927e+6</td>
<td>481</td>
</tr>
<tr>
<td>Cube</td>
<td>5.3412e+6</td>
<td>480</td>
</tr>
<tr>
<td>Rec SN</td>
<td>5.8548e+6</td>
<td>477</td>
</tr>
<tr>
<td>Rec EW</td>
<td>5.8869e+6</td>
<td>479</td>
</tr>
<tr>
<td>Rotterdam</td>
<td>2.20370E+07</td>
<td>343</td>
</tr>
</tbody>
</table>

Table 10.1: Insolation for different shapes with roughly the same volume and De Rotterdam

The cylinder has a diameter of 42.5m and a height of 54m. The cube has sides of 40m and the rectangles are 20m wide, 60m long and 56m high. In terms of heat loss, cylinders are shaped efficiently, because they have little façade area. The rectangles have the most façade area and are therefore least efficient. In terms of energy production however, the rectangles score highest. The rectangular shape is closest to De Rotterdam’s shape. De Rotterdam was rotated and insolation was simulated for each rotation step of 30 degrees. Figure 10.6 shows the rotated geometry. The average insolation of the entire building geometry is 343kWh/m². The total radiation for the building as it stands now is 2.2037e+7 kWh. The volume is much larger than for the simple shapes, but because of it has a more complex geometry and the towers have gaps in between, the average insolation per square metre is a third lower than for the simple shapes.

<table>
<thead>
<tr>
<th>Rotation [°]</th>
<th>Insolation [kWh]</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2,20370E+07</td>
<td>0,00%</td>
</tr>
<tr>
<td>30</td>
<td>2,20860E+07</td>
<td>0,22%</td>
</tr>
<tr>
<td>60</td>
<td>2,21660E+07</td>
<td>0,59%</td>
</tr>
<tr>
<td>90</td>
<td>2,20960E+07</td>
<td>0,27%</td>
</tr>
<tr>
<td>120</td>
<td>2,20140E+07</td>
<td>-0,10%</td>
</tr>
<tr>
<td>150</td>
<td>2,20400E+07</td>
<td>0,01%</td>
</tr>
<tr>
<td>180</td>
<td>2,20230E+07</td>
<td>-0,06%</td>
</tr>
</tbody>
</table>

Table 10.2: Resulting insolation and difference from the current design for irradiation.
<table>
<thead>
<tr>
<th>Facade shape</th>
<th>facade area [m²]</th>
<th>area increase</th>
<th>total insulation [kWh]</th>
<th>insolation increase</th>
<th>insol.area</th>
<th>average insulation [kWh/m²]</th>
<th>total insulation [kWh]</th>
<th>insolation increase</th>
<th>insol.area</th>
<th>average insulation [kWh/m²]</th>
<th>180</th>
<th>270</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat 0.0/0.0</td>
<td>116.64</td>
<td></td>
<td>26666.55</td>
<td></td>
<td></td>
<td></td>
<td>226.26</td>
<td></td>
<td></td>
<td></td>
<td>53991.83</td>
<td>454.72</td>
</tr>
<tr>
<td>H_Angle 1.0/0.6</td>
<td>140.24</td>
<td>20%</td>
<td>30152.09</td>
<td>13%</td>
<td>65%</td>
<td>213.10</td>
<td>57483.63</td>
<td>7%</td>
<td>36%</td>
<td>410.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H_Angle 1.0/1.8</td>
<td>133.43</td>
<td>14%</td>
<td>29187.93</td>
<td>9%</td>
<td>66%</td>
<td>217.22</td>
<td>56518.85</td>
<td>5%</td>
<td>38%</td>
<td>419.73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H_Angle 1.0/3.0</td>
<td>140.24</td>
<td>20%</td>
<td>30259.51</td>
<td>13%</td>
<td>67%</td>
<td>214.20</td>
<td>57485.86</td>
<td>7%</td>
<td>36%</td>
<td>398.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H_Angle 1.5/0.6</td>
<td>161.02</td>
<td>38%</td>
<td>33357.37</td>
<td>25%</td>
<td>66%</td>
<td>206.04</td>
<td>60982.30</td>
<td>14%</td>
<td>36%</td>
<td>377.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H_Angle 1.5/1.8</td>
<td>151.83</td>
<td>30%</td>
<td>32202.10</td>
<td>21%</td>
<td>69%</td>
<td>210.73</td>
<td>59616.47</td>
<td>11%</td>
<td>37%</td>
<td>389.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H_Angle 1.5/3.0</td>
<td>161.02</td>
<td>38%</td>
<td>33497.76</td>
<td>26%</td>
<td>67%</td>
<td>206.73</td>
<td>60901.41</td>
<td>14%</td>
<td>36%</td>
<td>368.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H_Angle 2.0/1.8</td>
<td>174.36</td>
<td>49%</td>
<td>35749.37</td>
<td>34%</td>
<td>69%</td>
<td>204.08</td>
<td>63498.74</td>
<td>18%</td>
<td>37%</td>
<td>361.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curved hard</td>
<td>139.33</td>
<td>19%</td>
<td>29829.46</td>
<td>12%</td>
<td>61%</td>
<td>211.32</td>
<td>57086.29</td>
<td>7%</td>
<td>34%</td>
<td>402.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curved soft</td>
<td>127.36</td>
<td>9%</td>
<td>27826.64</td>
<td>4%</td>
<td>47%</td>
<td>214.11</td>
<td>55370.24</td>
<td>3%</td>
<td>36%</td>
<td>427.34</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 10.5: Insolation and area increase for north and east facing facades**

| Facade shape | facade area [m²] | area increase | total insulation [kWh] | insolation increase | insol.area | average insulation [kWh/m²] | total insulation [kWh] | insolation increase | insol.area | average insulation [kWh/m²] | 90 | 0 |
|--------------|-----------------|---------------|------------------------|---------------------|------------|----------------------------|------------------------|---------------------|------------|----------------------------|    |    |
| Flat 0.0/0.0 | 116.64          |               | 57288.35               |                     |            |                            | 486.08                 |                     |            |                            | 86093.80 | 730.49 |
| H_Angle 1.0/0.6 | 140.24        | 20%           | 61211.12               | 7%                  | 34%        | 424.43                    | 89519.11               | 4%                  | 20%        | 628.16                    |     |     |
| H_Angle 1.0/1.8 | 133.43         | 14%           | 60198.89               | 5%                  | 35%        | 447.30                    | 88555.40               | 3%                  | 20%        | 658.36                    |     |     |
| H_Angle 1.0/3.0 | 140.24         | 20%           | 61111.64               | 7%                  | 33%        | 435.88                    | 89637.55               | 4%                  | 20%        | 627.87                    |     |     |
| H_Angle 1.5/0.6 | 161.02         | 38%           | 64670.39               | 13%                 | 34%        | 393.55                    | 92789.08               | 8%                  | 20%        | 569.16                    |     |     |
| H_Angle 1.5/1.8 | 151.83         | 30%           | 63285.42               | 13%                 | 35%        | 413.08                    | 91580.40               | 6%                  | 21%        | 598.01                    |     |     |
| H_Angle 1.5/3.0 | 161.02         | 38%           | 65434.65               | 14%                 | 37%        | 400.01                    | 92962.28               | 8%                  | 21%        | 567.58                    |     |     |
| H_Angle 2.0/1.8 | 174.36         | 49%           | 67161.61               | 17%                 | 35%        | 382.37                    | 95180.90               | 11%                 | 21%        | 541.34                    |     |     |
| Curved hard    | 139.33         | 19%           | 60689.98               | 6%                  | 31%        | 429.32                    | 89406.41               | 4%                  | 20%        | 630.71                    |     |     |
| Curved soft    | 127.36         | 9%            | 59169.58               | 3%                  | 36%        | 455.27                    | 88028.24               | 2%                  | 24%        | 687.73                    |     |     |

**Table 10.4: Insolation and area increase for north and east facing facades**

<table>
<thead>
<tr>
<th>Facade shape</th>
<th>facade area [m²]</th>
<th>area increase</th>
<th>total insulation [kWh]</th>
<th>insolation increase</th>
<th>average insulation [kWh/m²]</th>
<th>225°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat 0.0/0.0</td>
<td>116.64</td>
<td></td>
<td>34349.60</td>
<td></td>
<td></td>
<td>291.45</td>
</tr>
</tbody>
</table>
10.2.3 Conclusions on design and testing

The designs shown in the design catalogue have effects relating to energy consumption. They were tested in this chapter. It was found that shading increases the heating load and reduces the cooling load, whereas lowering the window to wall ratio reduces both. A combination reduces energy demand the most, so this advocates for integration of energy systems in shading elements as well as lowering the window to wall ratio to create more space for energy production systems. The shape and orientation of a building’s envelope are also important. A cylindrical shape has good energy performance when looking at heat loss, but also has less surface to produce energy on. Energy production per m$^2$ could outweigh heat loss m$^2$ for well insulated facades. The façade shape of De Rotterdam shades itself and has a much lower average insolation (kWh/m$^2$) than simple shapes. Increasing the façade area with shapes that move outward increase insolation. This effect is most effective on north facing facades, because it increases the area facing east and west. This short and limited study shows that envelope and façade shape design can greatly influence the availability of solar energy.
It has become clear that a design with a window to wall ratio (WTW) of 40% has a lower energy demand than a design with a high WTW. Therefore the design focuses on reducing the WTW to around 40% and thereby clearing as much space as possible for integrating energy producing systems. The SW office façade is designed and therefore no wind systems are integrated into the technical drawings that are shown in this chapter. Algae, photovoltaic and thermal systems are all integrated into the façade fragment.

The starting point for the design was to fit systems into a unitized curtain wall. Second, the energy producing elements should be suitable for prefabricating, such that a single element (in between transoms and mullions) could be replaced or repaired.

For the design, the unitized curtain wall system CW 86 sold by Reynaers was used. This system allows for water and dirt to get into the space between two elements (there is a horizontal gap between them). This problem has not been resolved, but this gap can easily be cleaned when windows have to be cleaned.

Each prefabricated element consists of an aluminium curtain wall with three mullions and three transoms. Within the mullion and transoms there are four fields. The top two fields are opaque and the bottom two fields contain glazing and are (partially) transparent, see Table 12.1. Each field is designed so that it can be taken out separately from the mullions and transoms, so that defect parts can easily be replaced. The weight of each system is considered to be close to the weight of triple glazing, so comparable fixation should be sufficient. Otherwise, the fields would need additional fixation. This could be realised by using corner anchors that are attached onto the mullions.

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</tr>
</tbody>
</table>

Table 11.1: Schematic view of façade element with its fields
11.1 Building fragment 1:50

The construction drawings in this paragraph will show how different designs from the design catalogue that are combined and integrated into a façade system. In the top 3 floors of the buildings (including the roof) photovoltaic, thermal and an algae system are all incorporated. It should be noted that no attention was given to detailing a full algae cultivation system.

**Roof**

In the existing design, the curtain wall extends beyond the highest floor, creating the illusion that the building has no clear roof edge. A small sloped roof is added to cover the algae photobioreactor. By creating an indoor area on the roof it is easier to control the climate around the algae. The sloped curtain wall that forms the new roof has worked glazing which diffuses the light that falls onto it, limiting the amount of direct sunlight hitting the algae tubes.

**Photovoltaic element**

The floor below the roof contains some elements where single clear glass solar cells are added onto a layer of double glazing. The parapet is made from a photovoltaic panel (glass layer, cells and back substrate plate) and a sandwich panel.

**Solar thermal element**

The lowest shown floor has a parapet with a flat plate collector and a sandwich panel behind that. The bottom part of the element has evacuated tubes in a closed cavity with double glazing on the interior side and single glazing on the exterior side. The latter design might form problems, because the closed cavity can reach extremely high temperatures.
11.2 Building fragment 1:20

vertical building fragment scale 1:20
showing a combination of details
integrating multiple systems

Double glazing with diffuser coating

Double glazing

Lightning fixtures for algae growth

nutrition supply
tubular algae photobioreactor
Algae in- and outflow pipe
curtain wall anchor

Bubbledock floor
sandwich panel: 12mm aluminum front plate, 12mm Trespa, 100mm PIR, 12mm Trespa

photovoltaic panel: clear coated glazing, solar cells, back sheet (sedal, polyester, nellular)
junction box
junction box connecting photovoltaic modules within a curtain wall element
suspended ceiling with composite panels in aluminum framing

photovoltaic layer: clear glazing, solar cells, adhesive
double HR+ glazing

Figure 11.2: Vertical building fragment, roof 1:50
vertical building fragment scale 1:20
showing a combination of details
integrating multiple systems
11.3 Building details 1:5 with photovoltaic systems

The vertical details show how the photovoltaic systems in a curtain wall element are connected. A junction box is fitted in a recessed part on the bottom of the sandwich panel. This is where the lower photovoltaic panel (below the transom) is connected to the upper photovoltaic panel. From element to element, the photovoltaic panels can be connected horizontally through the suspended ceiling. PV arrays are thus connected per floor of the building. The inverter is located in the service core of the building. The solar cells are fixed onto single glazing and the entire panel is glued to double glazing. If it breaks, the 3 layered panel needs to be removed and replaced.

Figure 11.4: Horizontal building detail 1:5 of photovoltaic system in front of double glazing
This detail shows the parapet style system. A window frame is fixed onto a sandwich panel and the photovoltaic panel is fixed in the frame. The sandwich panel and photovoltaic panel can be placed together as one panel. When the photovoltaic panel defects, it can be taken out and replaced separately. The sandwich panel can endure the same weather conditions, but to keep the cavity as dry and clean as possible, it would be better to place a single glazed panel temporarily. The sandwich panel is fabricated with tubes inside through which the cables run. The cable is already connected to the junction box, so PIR can be used to fill the tube after the panel is placed. A cap should be added on the cavity side to stop the PIR from getting behind the panel too much.
vertical details 1.2
photovoltaic systems integration
opaque solar cells on double glazing and solar panels in front of sandwich panels

Figure 11.6: Vertical details 1:5 of photovoltaic systems
11.4 Building details 1:5 with solar thermal systems

The first set of horizontal details shows the evacuated tubes system which is placed between a layer of single glazing on the exterior side and double glazing on the interior side. Thermally this detail is not ideal, because the temperature in the closed cavity will reach high levels. Making the inner window operable, would lead to decreased thermal performance and higher risk of excessive heat gain from the cavity to the interior. The in- and outlet pipes for hot and cold water are placed within a coving and connect to piping that is casted into the concrete top layer of the bubbled deck floor or distribution takes place in the space above the suspended ceiling. The rounded parts of the piping are flexible to allow movement and easier installation.
The flat plate collector in this design features a limited sized insulation layer at the back of 260mm. Usually this layer is bigger, but heat loss at the back of the collector will be low, because of the closed cavity and sandwich panel right behind it. The piping is connected in the same manner as the evacuated tubes. The flat plate collector is hung onto the sandwich panel with 3 anchors: two near the top and one near the bottom. The entire system is fixed the same way glazing is fixed in a curtain wall.

*Figure 11.8: Horizontal building detail 1:5 of solar thermal flat plate collector in front of a sandwich panel.*
PART 3

DISCUSSION, CONCLUSION, RECOMMENDATIONS
THE POTENTIAL FOR HIGH RISE ENVELOPES AS ENERGY PRODUCTION UNITS | ANNE LEEUW
12 ROUND UP

In short this thesis deals with the problem of rising energy consumption in urban areas, where a big chunk of energy consumption takes place in buildings. Buildings consume most energy during their operation phase. Energy consumption contributes to CO₂-emissions and speeds up climate change. To mitigate these effects strategies for lowering energy consumption are formulated. One of those strategies is to build only nearly zero energy buildings from 2020 onwards. To see if this is possible for high rise, a building type strongly related to urban areas, where most energy is consumed, this research was conducted. This thesis has looked into how high rise envelopes can be utilized as energy production units by developing a strategy for assessing which systems should go where and how much energy could be produced. Furthermore it looked more into detail how energy production systems could be integrated into envelope design.

12.1 Conclusion

12.1.1 Sub research questions

The questions introduced in chapter 1 are stated and answered below.

12.1.1.1 Energy demand & consumption

a. What does the energy consumption distribution in high rise look like?
It is difficult to really find data showing the energy distribution of high rise alone. High rise would mainly be different due to vertical transport, but metered data often measures the total electricity or gas consumption.

b. What factors influence energy consumption in high rise?
Factors that cannot be altered by human behaviour/interaction, factors which are established in the design phase of a building and factors that can be influenced when a building is in operation.

c. Which climate installations can use renewables-based systems as energy input?
All systems that require electricity or thermal energy. This question was not that thorough, but research provided that energy production and climate systems can and should be adapted to each other.

d. What is the energy supply and demand balance for a building and its context?
Mostly depending on the function, a building has a different energy curve. During peak hours of energy demand, building sections with a specific function can exchange energy with building sections with other functions. Offices and residential functions complement each other and can provide energy to each other during peak hours.

12.1.1.2 Energy production

a. Which renewables-based energy production systems are suitable for façade-integration?
In general solar thermal collectors and photovoltaic systems are currently used most. Their yield is predictable and the lifespan of the systems are long. Wind turbines provide difficulties concerning additional loads to buildings and unpredictable wind conditions. However, vibrational systems provide interesting applications for buildings. Algae have seen few-to-none applications on buildings, but are much researched. Algae biomass has the advantage that it is a fuel and thus stores energy in mass. The energy can then be used when needed. Systems require a lot of piping and climate control and integration into the façade is thus difficult.

b. What is the efficiency of different renewables-based energy production systems?
Photovoltaic modules have efficiencies of 20% and up, but new technology promises much higher efficiencies. Transparent photovoltaic systems have an efficiency below 5%, but new technology promises efficiencies in the range of current conventional photovoltaic modules. Thin film is somewhere in between these two. Solar thermal system efficiency depends on input and output temperature differences, but is generally higher than 40%. Algae systems have a high efficiency if the algae density is high. This is difficult to put a number on, so mostly assumptions are made on growth rates. Tested growth rates range between less than 0.5 grams per litre per day to more than 2 grams per litre per day.
Wind energy efficiency often turns out to be lower in practice than in theory for systems with urban applications.

c. How can you assess the availability of renewable resources around high rise?
Local weather data can be used to predict the availability of solar energy (irradiance) and wind. Wind energy is highly dependent on urban structure. Buildings influence wind direction and turbulence. So weather data misses the unpredictability. The uncertainty for solar energy comes from clouding, but the sun hours per location are also fairly predictable.

12.1.1.3 Façade & envelope design

a. How does façade design influence the indoor climate and energy consumption?
The design of the façade influences indoor climate and energy consumption through its thermal characteristics and window to wall ratio.

b. What are the different façade systems used in high rise?
Both single and multi-layered façade systems are applied in the shape of curtain walls. The curtain walls are fitted with glazed panels, parapets or sandwich panels.

c. Which façade systems lend themselves for implementation of energy producing elements?
The curtain wall and unitized curtain wall lend themselves for implementation of energy producing elements because the systems are already based on repetitive elements. Elements can be replaced by new elements that produce energy.

12.1.2 General conclusions

12.1.2.1 Low energy buildings
Modern buildings that are seen as energy efficient, such as the Mary Axe building or the Post Tower still have an energy demand of 73.6 kWh/m² and 42.8 kWh/m². De Rotterdam is also in this range, considering the use of Maas water for cooling. It has become clear that for these buildings, the internal loads are the biggest reasons for high cooling loads. The internal loads are higher than the solar gain, due to low-e glazing (low g-value), but adding shading is still an effective measure in reducing solar gain. Since these buildings stand in a moderate climate, there are often sources around (water, air) that provide free cooling, because their temperature is lower than the indoor temperature. Using free sources for air- and water systems seems the most energy efficient way to cool a space. A clear example is natural ventilation, provided by operable windows, but increasing natural ventilation is not straightforward considering turbulence, higher wind speeds and different pressure levels at greater altitudes.

Buildings that already perform well in terms of solar gain, will profit less from external shading than from a lower window to wall ratio. In moderate climates, the lower window to wall ratio will reduce both heating and cooling loads. Systems that make use of free sources of thermal energy perform well, but they only make sense when the building is designed to reduce energy consumption as can be seen from the difference between the Post Tower in Bonn (DE) and the EWI building in Delft (NED).

The flowchart makes clear that the context and orientation of a building is of importance. The Mary-Axe building profits from its shape at the top, where it is not shaded by other buildings the angles are more towards the ideal angle to harvest solar energy. The Post tower has a good orientation (E-W) in terms of reducing solar gain, but it could reach a higher energy production potential when the long axis would be orientated N-S.

12.1.2.2 Energy production
The flowchart gives different results depending on the user's knowledge of the building and its climate design. Although it can aid a designer in choosing from sustainable climate installations, it does not help in choosing the most energy efficient climate system design. After applying the strategy to different high rise buildings, it becomes evident that energy production potential is relatively low: 14%, 13% and .4% for the Mary-Axe building, Post Tower and EWI building respectively. In case of De Rotterdam, energy potential was higher at 23% if only electricity was produced and 31% if both thermal and electric energy were produced.
12.1.2.3 Integrating the systems into the envelope

The design catalogue offers a designer a guide in design possibilities and the accompanying consequences through a plusses and minuses diagram and a S.W.O.T-analysis. Every building project however is unique, so it is up to the designer to adapt the energy production system to the project's design. The design catalogue does show that façade integration of some energy production systems does not have to be complicated. Its shortcoming is that the comparison in terms of cost is not based on actual maintenance and material costs.

How can high rise envelopes be utilized as energy production units?

High rise envelopes can be used as energy production units by implementing energy production systems into existing façade systems. That way, modern buildings can produce over 30% of their total energy demand on-site. This will increase the global and national share of clean energy production, reduce negative environmental impacts of energy production and keep fossil fuels available for longer time periods. Changing policies and regulation along our own comfort standards can further increase the potential of energy production on high rise.

12.2 Discussion & recommendations

The potential for high rise envelopes as energy production units is small, considering that buildings must become zero energy, but therefore definitely important. For a modern building, 30% of its energy demand could be compensated by integrating energy production systems into its façade. This can be more if a building makes use of free sources for heating and cooling and if the building shape and orientation is adapted to energy production. However, this can be contrary to designing for minimal solar gain. When a (high rise) building is built to modern standards, the potential for energy production on the façade will probably remain too low to get it to zero energy. But technology is improving. If solar thermal systems would have an efficiency of 65%, PV (opaque) 40% and transparent thin film 10%, the energy potential would grow to 48%. If on top of that free sources would be used for heating and cooling and the energy demand for pumps, fans, lighting and equipment would stay the same, a residential and office tower like De Rotterdam could become energy neutral with an energy production potential of 97%.

The conclusion at the end of chapter 4 states that factors that influence energy consumption can be organized in three categories:

- Factors that cannot be altered by human behaviour/interaction:
- Factors which are established in the design phase of a building
- Factors that can be influenced when a building is in operation:

How can high rise envelopes be utilized as energy production units?

High rise envelopes can be used as energy production units by implementing energy production systems into existing façade systems. That way, modern buildings can produce over 30% of their total energy demand on-site. This will increase the global and national share of clean energy production, reduce negative environmental impacts of energy production and keep fossil fuels available for longer time periods. Changing policies and regulation along our own comfort standards can further increase the potential of energy production on high rise.

What needs to change?

Factors which are established in the design phase of a building

- Design using free sources of energy:
  District heating, using heat from the industry should be chosen over local heating through a boiler. Geothermal energy should be applied whenever possible. Water bodies need to be used for cooling purposes. Suspended ceilings hide wiring and piping, but reduces the energy demand reduction potential of a buildings thermal mass.

- Integration of energy production:
  If energy production systems are not integrated from the start, high rise buildings will probably be a building of the past. A building like De Rotterdam could not have been built in the future, when energy consumption regulations tighten. Reducing solar gain, a strategy used for low energy buildings counteracts a design that maximizes solar energy production. A low window to wall ratio will have the same effect, so fully glazed offices should become a concept of the past, because they are not optimized for energy production.
Change of focus in building codes and policy-making:
De Rotterdam has a good energy label, even though it produces no energy. If labelling was more dependent on energy production, buildings would automatically be energy-efficient. If high rise designs like De Rotterdam are required to produce 25% of its total energy demand in 2020, 35% in 2030 and so on, these buildings are energy-efficient. It is shown in chapter 9 that the Post tower can only produce 14% of its energy demand, but this is a building with relatively low energy consumption. With its façade surface, it would have been possible to produce more energy if it was orientated differently. Focussing on energy production first instead of reducing the demand, works both ways.

Factors that can be influenced when a building is in operation:
- User behaviour:
  By gaining knowledge of climate systems and energy consumption people could be educated to use less energy. For example: people living or working in a fully climate controlled space should not try to influence the climate themselves.
- User comfort demands:
  In moderate climates the preferred indoor temperature lies between 20 and 25 degrees Celsius. If the range is widened to 18 and 30 degrees, this would already reduce the energy consumption. What this often means is that we relate indoor temperature stronger to outdoor temperatures.

Concerning this thesis
- The design catalogue could be expanded to provide more detailed systems that could be plug-and-play. The catalogue is not very detailed, some of the designs might prove to be very difficult to apply and produce less energy than computed, because the actual production surface decreases.
- The energy potential for De Rotterdam is not calculated using the technical design, which would make it more accurate. Furthermore its energy demand is probably too high, because the free water source (the Rhine) which is used for cooling is not accounted for. In the first case, the energy potential (as percentage) would decrease and in the second it would increase.

Future research
- Wind energy potential is difficult to predict: there is a lack of data for wind energy in urban context and wind modelling is more complex than solar modelling. This could result in underdevelopment of wind energy systems, while urban canyons can form wind tunnels, so they are interesting, especially when they are shaded for large parts of the day.
- The same could be said for algae production on buildings, although algae cultivation in general is a widely researched topic.
- Cost vs. production. What is the added cost of a façade that integrates energy production systems and what will be the payback time? Keeping in mind that energy prices might rise over the technical life time of for example a photovoltaic system.
- How does the life cycle energy of a façade with integrated energy production systems compare to that of a conventional façade.
- How much (noise, air) pollution or CO₂-emmission is avoided by energy producing envelopes?
13 REFERENCES

Web pages


Tetlow, R., Beaman, C., Elmualim, A., & Couling, K. (2012). The impact of occupant behaviour on the variation between the design and in-use energy consumption of non-domestic buildings: An experimental


Yemer, F. (2010). *Urban wind map for delft, rotterdam and zoetermeer*. (Bachelor of science), Delft University of Technology.


THE POTENTIAL FOR HIGH RISE ENVELOPES AS ENERGY PRODUCTION UNITS | ANNE LEEUW
APPENDIX B: WIND DATA

To find an accurate way to calculate wind power potential, data by Yemer (2010) was used. The data was
gathered at a measuring station at Geulhaven, Rotterdam (NED).

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Mean annual system output: 6,882965
THE POTENTIAL FOR HIGH RISE ENVELOPES AS ENERGY PRODUCTION UNITS | ANNE LEEUW

**Figure 0.1:** Wind flow around New Orleans and De Rotterdam. Autodesk Flow Image

**Figure 0.2:** Wind flow around New Orleans and De Rotterdam. Autodesk Flow Image

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1. SEP 1:00 - 30 Nov 24:00
   Hourly Data: Wind Speed (m/s)
   Calm for 1.24% of the time = 27 hours.
   Each closed polyline shows frequency of 1.5%. = 32 hours.

2. 1 Mar 1:00 - 31 May 24:00
   Hourly Data: Wind Speed (m/s)
   Calm for 6.59% of the time = 33 hours.
   Each closed polyline shows frequency of 1.5%. = 33 hours.
APPENDIX D: GRASSHOPPER MODELS

This appendix shows the models built in grasshopper. Two grasshopper files are built and used for analysis or simulation on the following subjects:

- Insolation & wind (file A)
- Energy simulation (file B)
- Daylight simulation (file B)

13.1 Insolation & wind

Insolation & wind step 1:
The epw-file (weather file) is imported and the analysis period, in this case a full year, is set. Next, a sky is simulated. A dome is created and divided into patches. This can either be a Reinhart sky, which has 580 patches or a simplified sky with 145 patches. The simplified sky dome was used for this thesis, because it gave sufficient results. With the select sky component the analysis period is linked to the sky dome.

Insolation & wind step 2:
The components from step 1 are plugged into the radiation analysis component. The geometry of De Rotterdam and the context buildings are plugged as well. The context provides shading bodies, which reduce the radiation received by De Rotterdam. The grid size is set at 2, which means a grid of two by two meters is used and for every centre point the radiation is calculated. The grid is slightly set-off from the façade surface to avoid inaccuracies because the grid lies in the same plane as the centre points. The legendPar component is set to use certain colours and the number of segments (10) and the maximum value (highBound_ = 1000kWh/m²) for the legend.
Insolation & wind step 3:

First the Sort component sorts the radiation results measured at all the centre points. In the Larger-component all values greater than 400 are given a 'True' value and all other a 'False' value. The Integer-component (Int) translates all True-values to 1 and all False-values to 0. The multiply-component (AxB) multiplies the original list with radiation values with the 0 and 1 list, so that all values below 400 are now 0. Now it is possible to use this set of 0 and 1 to cull the list. The new list is much shorter and contains only the values above 400. The average of this value is then multiplied with the surface area for which I > 400.

The calculation has run. The CreateAtts and Bake component at the top lets the user transfer the newly create geometry to Rhino. This geometry is used to subtract the surfaces for which the insolation is greater than 400kWh/m². In a Brep-component (Srf for which I>400) the area can be found.

Insolation & wind step 4:
The maximum production for the surfaces for which $I > 400$ can be calculated as well as the total radiation (all surfaces for which $I \geq 0$).

**Insolation & wind step 5: The wind model**

The wind analysis shows the wind directions, speed and frequencies of occurrence. The analysis period covers a full year and the .epw-file is used for a specific location. In this case Amsterdam.
13.2 Energy simulation

**Energy simulation step 1:** The Rhinoceros geometry is connected to the Honeybee ‘Masses to zones’ component. It takes the mass of the core and the office and creates a Honeybee zone. Vertical and horizontal surfaces, used as shading are represented by Horizontal pv shading, Vertical pv shading and mixed shading. The Shadow plane is a surface that represents the middle tower which shades the south west tower of De Rotterdam.

**Energy simulation step 2:** Glazing is added to the honeybee zone and the WTW is set to 41% for all facades. The zones are then split and the core zone and office zone get different internal loads appointed to them. The lighting density is 4W/m² (for LED systems) and the equipment load is 7W/m². The ventilation per person is based on the Dutch building decree which sets 6.5dm³/s as minimum ventilation rate for office zones.
**Energy simulation step 3:** The material properties of the walls and glass are added to the elements of the honeybee zones. The aluminium, insulation and gypsum represent the parapets.

**Energy simulation step 4:** An occupancy schedule is added to the zones, which regulates the time and how much people are in the zones. The set-point temperatures determine above or below which temperature the heating or cooling system will be put to use. In this case the set-points are 20 (degrees Celsius) for heating and 40 for cooling. Usually 20 and 25 are used. Because the zone represents only one floor, the roof and ceiling are made adiabatic, because the surrounding zones will have roughly the same temperature. The north direction is set to 225, to match the geometry to the existing situation of De Rotterdam.

**Energy simulation step 5:** Here it is decided which output of EnergyPlus to use for further examination. The analysis period is set to a year and the filename for the .csv-file is determined. The simulation is run and it shows some warnings for the system sizing, but no severe errors. The warnings can be ignored when results
are compared to each other. Of course, when the goal of the energy simulation is to design a system which will be used, they need to be addressed.

**Energy simulation step 6**: The data can be analysed in grasshopper to see if it matches with the .csv files. It assists in interpretation. Therefore this part is not discussed further.
13.3 Daylight simulation

**Daylight simulation step 1:** The materials need a different formulation, one that works with Radiance (RAD). The light transmittance of the glass is matched to the model used for energy simulation. The RAD materials are added to the honeybee zone created for the energy simulation.

**Daylight simulation step 2:** The ground floor of the office zone is used to create a grid. The grid is lifted 1m above the ground surface, because this is the height where daylight measurements are usually taken. A sky is constructed and read from the Sky-file path. The sky and the grid are loaded into an analysis recipe. The accuracy can be adjusted with the lowest component (quality, ab, ad, etc.), but by doing so, the speed of the computation increases quickly. The recipe (Illuminance) goes into the upper right component which runs the daylight analysis.

**Daylight simulation step 3:** The computation is read by the read study folder component and it is checked if the analysis was run for the correct type (in this case two panels show Illuminance, which validates this).
Daylight simulation step 4: The data is analysed and translated into a gradient which is projected onto the grid created in step 2.

Daylight simulation result: the result for this simulation is shown in the image below.