Stirling Solar cooling in office façades.

Wouter Streefkerk

Final thesis graduation work
Master Building Technology, façade design

1st Mentor: Dipl. Ing. Tillmann Klein
2nd Mentor: Dr. R. M. J. Bokel
Examiner: Ir. D. van den Heuvel

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Abstract

The requirements, comfort needs and expectations for facades have increased, so has the need for energy efficient design. Present climate systems are using a lot of energy, especially to control heat and cooling loads. The cool load and solar power often occur at the same time and an increase of solar power often increases the cool load of a building. In the development of solar harvesting plants the Stirling engine is used as a clean, low maintenance and efficient engine to create electricity. In this research the possibilities are explored for a Stirling system driven by solar energy, the consequences of integrating such a system into the facade and the possible performance. In this system the increase of solar power can increase the cooling power. This leads to an increase of a free source of energy when the cool load is increasing.

The development and research on the Stirling engine is still in progress and is not yet been integrated in a system in the facade for the purpose of cooling an office building. This causes the calculations on performance and comparison to other system to be an estimation which in time could be revised and updated.

A system powered by solar power harvested from an office facade and put into cooling power is considered likely to work. It is feasible that this system can contribute to the reduction of the annual cooling load of an office building. For an office building this system will always need an additional climate system and therefore additional costs.
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Preface

I would like to take this opportunity to thank all people who were involved in my graduation process. For the final results of this thesis I have had many people who in some way have assisted, inspired, mentored or just been there for me. I would like to give special thanks to my girlfriend, Inge, who supported, edited and commented all of my work throughout my graduation.

Further my two mentors, Regina Bokel and Tillmann Klein, who had the patience and interest to support my research into the Stirling engine.
1. Introduction

The need for energy in the world is increasing by the day and fossil fuels are starting to run out. In the process of energy transport and generation substantial problems occur because of the polluted emissions or hazardous waste. People are starting to realize the inconvenient truth that changes are inevitable if we want to keep living with the same standards we live now. The present prospect for 2035 even indicates an increase of 49% of the global need for energy. This strong increase is for the most part due to the growth of economic progressive nations like China and India. Due to the lack of international legislation concerning energy generation and its limits it is plausible that the increase of the emission of carbon dioxide will hugely increase (42.4%) with all its consequences (U.S. Energy Information Administration (EIA), 2010). Planet earth has no trouble surviving us, the trouble is we need to survive on planet earth.

So the need for clean, everlasting energy is increasing by the day and the awareness of this among people is growing. Where do we start? If we want to improve this situation, where is it best to start? Where lie the best potentials? Recent development concerning this problem are the generation of electricity by fossil fuel free ways’ like tidal plants, wind turbines and solar plants. This last one captures the power of the sun, focuses it to one point and converts this to electricity. This conversion is done by a heat engine called the Stirling engine, which generates motion out of the temperature difference looking at the division of the global energy needs 20% is represented by (the use, construction or production of) buildings (U.S. EIA, 2010) and this is even bigger within the European energy budget (Balaras, et al., 2007). So if we are able to either reduce the consumption or increase the generation of the energy in buildings it can have a substantial effect on the global need for energy.

The Dutch government is well underway towards meeting its Kyoto target of 6 % reduction of greenhouse gas emissions by 2012. However, the Kyoto targets will not be sufficient to prevent dangerous global climate change. Therefore the Dutch government has formulated ambitious new climate and energy targets for 2020 in order to become one of the cleanest and most efficient energy countries in the world (VROM, 2007; Opstelten, et al., 2007a). An example of how they want to achieve that is the target for the Energy Performance Coefficient (EPC). The EPC is now (2011) 0,8 and is set to 0 by 2020, so all new buildings should be energy neutral by then. The government wants to set a good example too by encouraging projects with the cradle-to-cradle philosophy. It has to be said that the Kyoto targets are mostly met because of the economic crisis, which caused a big temporary reduction of the emissions. And the present focus of the government is to come out of the economic crisis by cuts in all budgets so there will probably be no large budgets for research and development. Recent research by McKinsey & Company (2010) shows the time to act is now, wait 10 years longer and the abatement potential is cut in half.

Where you would like to start is by the investment with the biggest effect, so the best value for your money. According to Enkvist, Nauclér and Rosander (2007) the biggest potential lies in the improvement of insulation, fuel-efficiency of commercial vehicles, lighting systems and air conditioning. This extensive research has been done to a prospect for 2030 on the size and costs of measures to reduce greenhouse gas emissions. Figure 1.1 represents a cost curve graph which indicates the whole range of reducing measurements in euro per ton of CO2 predicted for the year 2030. From easy and inexpensive (even economic savings) in green on the left, to higher cost
According to this study three out of the four best investments are building related.

**Strategic options for climate change mitigation**

Global cost curve for greenhouse gas abatement measures

Figure 1.1: Cost curve of the reduction greenhouse gas emissions by 2030 (Enkvist, Nauclér and Rosander, 2007).

The improvement of insulation concerns for the most part the replacement of old (or no) insulation for new improved insulation. Therefore the potential for improvement is more biochemical instead of building technical. Also the potential for lighting system is for the most part based on changing the energy inefficient light bulb for LED and therefore more a matter of legislation. The third best potential for the reduction of CO2 is the improvement of air-conditioning. This is one of the biggest energy consuming applications in buildings due to possible occurrence of heavy heating and cooling loads, so from the energy point of view an interesting part of the building to research (Frank, 2005). An important role in the conditioning of air in buildings is played in and around the façade or the whole wrap around a building called the building envelope.
The requirements, comfort needs and expectations of the building envelope have increased throughout the years due to the larger amount of time spend indoors. For people living in industrialized countries this is about 90% (Höppe and Martinac, 1998). Buildings are there to provide a certain level of comfort to its users, they create a climate. This climate is formed by numerous of different factors which either intended or unintended influence the comfort, even the way the users perceive this comfort is influenced in many ways. The performance of the human body flourishes in optimal comfort. This can increase the productivity, concentration and health of the users (Daniels, 2003). Providing a good climate is important for the building itself too. It will prevent condensation, which can lead to wood decay and corrosion. Therefore controlling the climate and influencing the comfort can have big advantages.

To reduce the excessive energy waste, reach the ambitious requirements set by the government and realize the comfort that meets the high standards of people, we need a building envelope that instantly reacts on the changing environment. In the present technology these climate systems cost a lot of energy, need a lot of maintenance, are complex (so have higher chance of malfunction), difficult to control and have a limited lifetime. With the increasing need for energy efficient design, present solutions can’t fulfil this need.

The immense power of the sun gives a possible clean and free energy source, while one of the biggest energy consumptions of an air-conditioner, the cooling load, is caused by the sun. It seems that the energy supply and demand in a façade intersect.

“The desirable procedure would be work with, not against, the force of nature and to create better living conditions.”
(Olgyay, 1962).

1.1 Problem definition
The main objective of this research is to develop and design the possibilities of a system in the facade which can react to the fluctuating cooling demands of an office building. One of the biggest factors of the cool load of a building is the sun, which makes the cool load increase when the solar power increases. To reduce the energy load and help the reduction of greenhouse gasses, the development of fossil fuel independent technologies has to be stimulated. A Stirling engine can generate power out of the energy from the sun without dangerous emissions, without high maintenance and without using fossil fuels (Thombare and Verma, 2008). The development and research of the technology of the Stirling engine is still in progress and applying a system with a solar driven Stirling engine in a facade has never been done before or researched for this purpose. For this research the climate in the Netherlands is chosen.

1.2 Research questions
Main research question:

To what extent can a Stirling engine in a facade driven by solar energy contribute to the generation of sustainable cooling for a building?
Sub questions:

1. Where and why is there a need for sustainable cooling in facades?
2. Where and in what way is sustainable cooling currently generated in facades?
3. What is the working principle of the Stirling engine?
   a. What is the most effective way to create a temperature difference for a Stirling engine in a facade?
      i. What is the most effective way to convert sunlight to high temperature for a Stirling engine in a facade and what is its maximum?
      ii. What is the most effective way to cool a Stirling engine in a facade?
   b. What is the most effective location for a Stirling engine in a facade to profit from the greatest temperature difference?
4. What is the generated power output of a Stirling engine in a facade driven by sunlight, with the different configurations?
5. What are the benefits of the Stirling engine in a facade compared with current systems and how can they be compared?
6. What is its impact on architecture, design of construction and the way of production processes?
2. Research method

This research will be about the possibilities, potentials, restrictions and opportunities of the reduction and/or generation of energy by a Stirling engine system in a façade. The public availability of recent information on the technology of the Stirling engine is limited and still under development. The field of using Stirling engines in facades is not yet been discovered and has to be widely explored, which results in the absence of any study case or leading journals. This leads to a broad research field.

The research is based on the problem definition and the hypothesis of combining a Stirling engine and an office façade to reduce the cooling load. The potential and limits of the Stirling engine will be explored by looking at the consequences of implementing it to the facade. The best suited facade construction will be determined and the design parameter for this facade will be determined. For this facade the potentials of the corresponding energetic concept will be explored. Due to the limited information on the Stirling engine, the calculations made on this system will be limited to a simplified case design covering annual cool load to a small office room.

![Figure 2.1: Research method scheme.](image-url)
3. State of the art

3.1 Location of the system

As described in the introduction the need for sustainable cooling is growing and because of that the global energy consumption asks for a better way to cope with the growth. One reduction that can be made is the distance between the problem causing the need for energy and the solution. Electricity is mostly generated in electricity plants but rarely in short distance to its use. The electricity must be transported from the plant into electricity cabinets through wires which of course need energy for production, transportation maintenance and so on. In short the closer the energy generation is to its destination the better (U.S. EIA, 2010).

The big cooling demands of buildings are largely caused by the warming up of the building by the sun. The sun is causing the inside temperature to rise to a temperature that people are not comfortable with. To lower the inside temperature often electricity is used to operate an air-conditioning device which cools down the air and blows the cooled air back into the room. The higher the solar power gets, the higher the cooling load becomes and more energy is used by the air-conditioning unit to control the room temperature. This relation of solar power and cooling demand is clearly seen in figure 3.1.

If we could use the problem (the sun warming up the building) to help the solution (cooling the building to a comfortable temperature) then it would give us a head start.

![Figure 3.1: Relationship between heating, cooling and solar power (Society, 2010).](image)
The biggest cooling loads are concentrated in high rise buildings because of the big glass surface. Most of these high rise building are situated in industrialized countries with high density areas with no room for big fields of solar harvesting devices. The roof is often an excellent place for the harvest of solar power, but since we’re dealing with high rise building the roof surface is much smaller than the surface the facade has to offer. In most cases the energy that can be generated on a roof surface will not be sufficient to cover the cooling loads in a high rise building.

### 3.2 System scheme

When the solar power is directly used for the cooling of a building, the term solar cooling is often used. In this research it will be solar cooling by a Stirling engine. The sun is directly used for driving the Stirling engine; the power output of the engine provides the input of a cooling unit, which provides cooling power for the building. The cooling power should increase with the increase of the solar power during the day and seasons.

![Diagram of solar cooling system](image-url)

Figure 3.2: The schematic system.
3.3 Present technology

How do present building systems cope with the cooling loads? To provide and control the climate of a building in general there are two ways to do so: passive climate control and active climate control. An active climate control system means that the system actively reacts on influences like rain, overheating and sun. With the regulation of the temperature the system senses it is getting too hot, a cooling unit is switched on which cools down the room to the wanted temperature and switches off when a certain temperature is reached. This needs sensors, operating systems and a computer system to direct all the input and control the output. In the present technology this costs a lot of energy, there is a risk of malfunction and will always need maintenance.

In passive climate control the system reacts automatically. An example of this passive climate control system is the smart implementation of sun shading. The sun is blocked in the summer and brought inside in winter by the design of the blades, this way the sun is used in a clever way and provides climate control without the need of energy. Passive climate control is mostly preventing and reducing the cooling and heating loads, while active climate control is often reacting on it.

![Figure 3.3: Example of smart permanent sun shading (Fabricolor-Ltd, 2011).](image)

3.3.1 Passive climate control

For passive climate control some of the obvious ways are the best ways; For instance taking the local solar radiation into account by the choice of the colour of a building (Synnefa, Santamouris and Akbar, 2007), the direction of parts of the building that needs light and so on.

A great deal of the passive climate control is done in the design stage, where the plans still can be altered. The trajectory of the sun is one of the influences on a design where a great deal of energy
can be saved. The design should try and make the most of the sun in winter time and prevent high cooling loads in the summer. A solar blind can be very effective when used in the right way. This can be simulated in data based programs like Solar tool and further studied in Ecotect.

Figure 3.4: The trajectory of the sun (Lechner, 2001).

There are ways to passive ways of ventilation too. For example you have passive daytime ventilation, or natural ventilation, where fresh air enters the building without mechanical interference. This can’t be applied to all designs, like high rise or fierce wind climates, while the air speed would become too high. As can be seen in figure 3.5, there are air-flow techniques to promote the natural air flow in buildings (Lechner, 2001).
Passive ventilation can be done by night too and this is called night flush cooling. This way the latent heat which the building collected during the day can be revealed overnight, as simple as opening some strategic chosen (and designed) windows (Lechner, 2001).

### 3.3.2 Active climate control

Active climate installations can be divided into three different concepts central systems, decentralized systems and hybrid systems.

![Diagram of active climate control concepts](image)

*Figure 3.6: The three concepts of active climate control (van Diepen, 2010).*

**Central systems**

The basics of a central system consist out of a central location (machine room) in, on or on top of a building where the cooling, heating and ventilating is being taken care of. From there big ducts go
through the building usually via a big central shaft and are split into smaller sub ducts throughout
the rest of the building. The exhaust air is taken out of the rooms by a second system of ducts and
end up in the machine room as well. This way the whole building is covered and can be regulated by
the system. It is not possible to regulate the room climate by the user himself. The exhaust air ends
up in the machine room, therefore heat recovery can be applied. Because of the centralized units
the ducts are often very big and difficult to integrate into a building design.

Decentralized systems
A decentralized system is situated in the façade on each floor of a building and provides climate
control directly into a room. So each room which is to be regulated needs a separate unit. This way
the users can have direct control over the climate. The units have a ventilator and an air handling
unit which provide the control but heat recovery is not possible. Because of the direct air intake no
big ducts are needed and the floor height of a building can be reduced by 15% (Franzke, et al.,
2003). Another advantage is that defect units only affect the room where they are installed.

Hybrid systems
A hybrid system is a combination of a central and a decentralized system. This system has at least
one central climate system and an air handling unit in each room separately. It provides a more
direct control to the climate and a lot of different combinations can occur. Heat recovery is possible
when the heat of the exhaust air is passed to a heating system.

3.3.3 Overview
The main climate system is an active one while the passive systems are contributing in the
reduction of the energy load. Examples of passive systems are mostly based on design or user
strategies.

Examples of passive systems are:

- Taking the solar radiation into account by choosing the colour of a building.
- Think about the direction of the building, where are the open parts, what functions need
  light.
- Taking the trajectory of the sun into account while designing
- The design should try and make the most of the sun in winter time and prevent high cooling
  loads in the summer.
- Smart use of solar blinds is very effective
- Natural ventilation with use of air-flow techniques
- Night flush cooling.

A big part of the present energy consumption in the active climate systems is caused by coping with
the heat and cooling loads. In the present technology so called active thermoregulation is used to
deal with these loads. The biggest part of the thermoregulation is done by the active systems and a
minor part by passive (van Diepen, 2010).
3.4 Stirling engine

The potential of a Stirling engine in a facade driven by solar power is the automatic increase of power supply when the cooling load rises. A Stirling engine is a hot air (or heat) engine which can be externally heated and internally carries a fixed amount of air through a closed continuous cycle. The technical elegance and simplicity of this engine has always been enchanting to scientists and technically interested people (Senft, 1993; Thombare and Verma, 2008).

The Stirling engine is rapidly finding its way into applications of society. Next to applications for NASA like an electricity generator for outer space, the appliance of the Stirling engine entered the normal life as well in the form of the central heating unit with power generation, mirror fields focusing all the solar power to one tower to generate electricity, laboratory refrigerators for super low temperatures and even automobiles reusing the waste heat of the IC engine (Lane, Wood and Unger, 2003).

The Stirling engine was invented in 1816 by Robert Stirling who was a minister of a church in Scotland. In these days metal fatigue occurred often turning the then used steam engines into dangerous machines, causing many deaths by explosions. The Stirling engine was safe (low pressure) economic and was a more powerful alternative to the steam engines of the day. Until about 1915 the Stirling engine was used to run a variety of things like fans, run small machines and water pumps. The lack of a good material for the hot side of the engine was causing the engine to fail and with electricity and gasoline becoming more widely available the electric motor and the internal combustion engine began to take over from the Stirling engine (Sakaris, 2009).

So why is the Stirling engine still a promising technology for present days and future? First of all the Stirling engine can operate very silent unlike for example an internal combustion engine (like in a car). It can run on almost any fuel due to the external supply of energy, gas, wood chips, cow chips or even focused solar power. Next to the fact that the external-combustion allows for a continuous and therefore better and cleaner combustion, there is no need for the removal of residue so it doesn’t even need an exhaust pipe. On top of that the efficiency is very high and in theory has even the highest potential according to the Carnot theory, which will be explained later on.

3.4.1 Principle

What is it that the Stirling engine drives? The working principle of the engine is said to be surprisingly simple and the basics are. While the working cycle of the Stirling engine is of great importance and interest, the fact that it works is more important.

To understand the principle some basic thermodynamic understanding is needed, in fact it is based on three basic things to understand from the universal gas law:

- Gas expands when heated and contracts when cooled.
- Gas absorbs heat when expanded and gives off heat when compressed.
• The pressure of a gas increases when heated and decreases when cooled.

![Diagram of heat engine cycle]

Figure 3.7: The common process for all heat engines (Martini, 2004).

When we look at the scheme of a heat engine we see the closed cycle of heating, expanding, cooling and compressing. This applies for the Stirling engine too. The Stirling working cycle can be divided into four stages which explain the way the heat travels. It is important to understand that heating and cooling both apply to the heat. Cooling something is moving the heat to somewhere else. That’s why we can’t just get rid of the heat, it has to go somewhere.

This example will describe the Stirling engine gamma-type used for small (educational) models. This engine consists of a hot side where heat is applied and a cold side where heat is subtracted. A piston is driven by the inside pressure causes the inside displacer to go up and down by a crank mechanism.

The first stage is applying heat to the hot side of the engine; this will cause the internal gas to expand driving the working cylinder up. The working cylinder is connected to a displacer and uses the upward energy to push the displacer down, transferring the heated air up to the cold side arriving in the second stage. Because all the heated air is now on the cold side, the heat is removed by the cold sink causing the air to compress. Due to the compression the working cylinder is pulled back, the displacer is pulled up leading the cold air to transfer to the hot side starting all over again.

![Diagram of Stirling engine cycle stages]

Figure 3.8: The four stages of the Stirling cycle (Animated engines, 2009).
Robert Stirling made another important invention concerning the efficiency of the Stirling engine, the regenerator. It was set between the hot and the cold side, the heat drawn from the cold side by the heat sink was used again in the supply of the heat on the hot side. The regenerator is still an important part of the heat engine, back then he liked to call it: *the economizer* as it saved money by reusing the heat (Thombare and Verma, 2008).

### 3.4.2 Efficiency
One of the other things why people admire the Stirling engine is that it has the highest possible efficiency according to the theory of the Carnot cycle. The clever regenerator system causes the Stirling cycle to be very efficient. The Carnot cycle is proposed by Nicolas Carnot and represents the most efficient cycle a heat engine can make. Although this perfect engine exists only in theory it is commonly used to compare different heat engines (like the IC and Diesel engine) and the Stirling engine has the highest percentage.

![Graph of pressure to volume with the work of the Stirling engine displayed](Martini, 2004)

In figure 3.9 on the left the relation between the temperature and the pressure is shown. The same stages as described before can be recognized. Starting the earlier described cycle by the supply of heat from 3 to 4, here the inside temperature rises due to the supply of heat leading the volume to increase (gas expands when heated) pushing the piston out. From 4 to 1 the temperature decreases by the rejected heat of the heat sink causing the volume to decrease as well (gas contracts when cooled) and making the displacer to move down. Because the displacer brings the air from the hot to the cold side, point 1 to 2 shows the shift of the heat to heat sink causing the volume to reduce even more. The supply of the heat is causing the hot side to rise in temperature leading to an increase of temperature pushing the displacer back up again. This brings the air back to the hot side starting the sequence all over again. The figure on the right shows the relation between pressure and volume which lead to the power of
the engine, or as thermodynamics say, the work. This relation is described by the formula, \( W = P \times V \). The power of the engine is determined by the volume multiplied by the inside pressure (Thombare and Verma, 2008).

3.4.3 Configurations

The Stirling engine is build and revised in thousands of different configurations. These configurations usually involve four basic types. The alpha type is using two pistons and a regenerator in between but no displacer. With the beta type the piston and displacer are inline and cleverly brought together into one cylinder using an outside regenerator. With the gamma type or split cylinder type the piston is offset from the displacer, this type is often used for the small models also referred to as low temperature difference (LTD) types (Martini, 2004).

![Diagram of Alpha, Beta, and Gamma settings](image)

Figure 3.10: Alpha, Beta and Gamma settings (Martini, 2004).

![Diagram of Alpha, Beta, and Gamma settings](image)

Figure 3.11: Alpha, Beta and Gamma settings (Thombare and Verma, 2008).
Here a problem occurs the Stirling engine seems to have. The low power output, as previously indicated, is defined by the pressure multiplied by the volume. To create this high pressure the seals become very important as they have to keep the air inside the engine when it is heating up. If there is a leakage the pressure drops down and so does the power. The many researches completed by for example Philips and General Motors in the 1970's and 80’s were mostly based on the improvement of these seals.

3.4.4 Free Piston Stirling Engine

In 1993 William Beale ended this problem by the invention of the Free Piston Stirling Engine (FPSE). This engine worked with the same principle of the beta Stirling configuration but in a hermetically sealed container.

![FPSE Components](image)

Figure 3.12: Components of a FPSE (Kim, Huth and Wood, 2005).

The working principle is still the same as the one before but then without the crank mechanism between the displacer and the piston. The working principle is actually even more simple by the reduction to just two moving parts. Now there is reciprocal movement inside a sealed box, making the increase of pressure a lot easier by the lack of seals where normally the crank would puncture the engine. To get the work out the motion inside the container, magnets can be used for the transfer (Bowman, 1993). The transfer by magnets and the reciprocal movement is an excellent
match for the generation of electricity as this is a common way of generating AC electrical output. The hermetically sealed engine and the small amount of moving parts have given the FPSE a maintenance free and long life. This improvement has opened the doors to a catch up on the IC engines (Thombare and Verma, 2008).

![Figure 3.13: The FPSE cycle (Bowman, 1993).](image)

The principle of the FPSE is shown in figure 3.13, covering the four Stirling cycles. In the FPSE the piston is connected to the displacer by a rod in such a way that the piston can move freely inside (as the name already suggested). Because of the simple design, only two moving parts and silence operation this configuration has big potentials.
3.4.5 Overview

Overall good points:

- Runs on any heat source, solar, biological and waste heat.
- The combustion is continuous, leaving no dead moments.
- Very low ware by FPSE design with very few parts, causing almost no maintenance.
- Very simple design and materials, so economic savings possible.
- Reliable operation
- FPSE is totally sealed with no pistons or mechanics sticking out, leading to a very low risk of explosions.
- They run very quiet
- Very low vibrations
- Start is easy
- Highest Carnot efficiency, theoretically and achieved.

Down sides:

- Price is high in comparison to other engines, partly because of development costs and not yet produced in series. The other part is the regenerator which has to take care of the optimal transfer of the heat, the use of high performance materials increasing the costs of the engine.
- The technology is still in development
- High operating temperatures (650 degrees)
- Cooling needed on the cold side to maintain the highest temperature difference.
- Not very fast in controlling the speed, so difficult application for automobiles.
The general performance of a Stirling engine is listed in Figure 3.14.

<table>
<thead>
<tr>
<th>Stirling engine general data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power range [MWe]</td>
</tr>
<tr>
<td>0.003-0.1</td>
</tr>
<tr>
<td>Power to heat ratio</td>
</tr>
<tr>
<td>1.2-1.7</td>
</tr>
<tr>
<td>Electrical efficiency [%]</td>
</tr>
<tr>
<td>10-40</td>
</tr>
<tr>
<td>Therman efficiency [%]</td>
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</tr>
<tr>
<td>Fuel type</td>
</tr>
<tr>
<td>All fuels</td>
</tr>
</tbody>
</table>

Figure 3.14: Table of general data about the performance of the Stirling engine (PolySMART, 2008).

3.4.6 Stirling Cooler
The cycle of the heat engine can be reversed, so put motion in and get cooling power out. This cooling capacity can be controlled very well and obtain very low cooling temperatures up to minus 100 degrees. This is commercially one of the most successful applications, being used in laboratories and other divisions where high cooling is needed. The version of this Stirling cycle can be made as a FPSE configuration as well (Lane et al., 2007). The research and development on the cooling for building purposes has not yet been done, yet is a potential market. A Stirling cooler can be very efficient (30% Carnot), without the use of dangerous or environmental harmful liquids and is very silent (Opstelten et al., 2007a). The efficiency even increases when building cooling temperatures (±12-15 degrees Celsius) have to be achieved (Global cooling, 2007).
3.4.7 Duplex Stirling Engine
The duplex Stirling engine is a heat-driven cooling machine. It takes in heat and produces cold without producing any other external effect. Due to the basics of only three moving parts it is very simple and is very fuel-efficient if carefully designed. Figure 3.26 shows a typical cross-section. Although their potential is confirmed in numerous occasions (Beal, 1984; Opstelten et al., 2007; Opstelten, Bakker and Kester, 2007b; PolySMART, 2008) there are no test or efficiencies results available.
“The basic idea behind the operation of the duplex Stirling engine is that when driven, it becomes a heat pump. In the duplex Stirling, a Stirling engine is used to drive a Stirling heat pump. This can be done with only three moving parts: the hot displacer, the piston which acts as the piston for both the heat engine and the heat pump, and the cold displacer. It is compact, self-starting, requires no electronic or carburetion system accessories. It can be hermetically sealed to be free of maintenance or any adjustments. This combination of parts makes a simple and effective heat-drive heat pump, which can be scaled to any size or temperature range. The duplex Stirling engine will be commercially available within the next few years” (Beale, 1984).
Figure 3.17: Duplex Stirling (Lane, 1996).

Rough dimensions of the duplex Stirling machine are 800mm in length and 500mm in diameter.
3.4.8 State of the art

“Schone Worte sind nichts, wenn keine Taten folgen.”
(Werdich, 1994)

Although the Stirling engine is beginning to gain reputation, compared to other technologies like PV cells and IC engines at the moment, just few of them are in the daily use. Although the technology is still only developing the achieved efficiencies are very promising (PolySMART, 2008). Present obtained maximum Carnot efficiency for 80eW Stirling generator is 60% (Kim, Huth and Wood, 2005) compared to the IC engine with 38% and Diesel with 43%. The thermal to electricity efficiency of this generator is 36% compared to standard Silicium PV cells of 15-20% efficiency and a theoretical limit of 29% (Society, 2010).

Figure 3.18: EG- 1000, EE-80 and EE-35 Units (Kim, Huth and Wood, 2005).

For the present state in the development of the Stirling engine possibly suitable for building use some of the achievements of Sunpower incorporated are being discussed. It is one of the most progressive companies developing Stirling applications for the commercial market and one of the few with information available to the public. Their interest is very broad, covering Stirling engines, FPSE, Stirling coolers, cryogenic coolers and duplex machines. So almost anything Stirling related and with success. They developed the 1 kW PFSE (the EEG-1000) with a thermal to electrical efficiency of 33%. Used in a central heating unit the fuel to electricity and heat efficiency overall is 90% (Kim, Huth and Wood, 2005) which is very high compared to other micro CHP units (Opstelten, Bakker and Kester, 2007b). These engines are appropriate for the use of solar power, have low maintenance, low vibrations and noise levels and low emissions. The properties of the EEG- 1000 will be used as reference engine in this study case.
Figure 3.19: Table with list of properties of the EEG-1000 (Kim, Huth and Wood, 2005).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating volts</td>
<td>130 – 260 Volts, on a 50Hz grid</td>
</tr>
<tr>
<td>Maximal electrical production</td>
<td>1100 eW</td>
</tr>
<tr>
<td>High temperature</td>
<td>600 degrees Celsius</td>
</tr>
<tr>
<td>Low temperature</td>
<td>50 degrees Celsius</td>
</tr>
<tr>
<td>Piston amplitude</td>
<td>9mm</td>
</tr>
<tr>
<td>Mean pressure</td>
<td>3.0 MPa</td>
</tr>
</tbody>
</table>

The power of the engine will increase with a higher temperature leading to a bigger temperature difference, but the efficiency (of the EG-1000) will slightly drop. Therefore the aim is to create 600 degrees on the hot side and 50 on the cold side but higher temperatures will not lead to malfunction of the engine.

The best available for Stirling cooling is the SC-UE15 (Global cooling, 2009). This Stirling cooler is being used for applications in need of much lower temperatures but from the graph can be derived that it can produce 150 Watt of cooling capacity on ±12 degrees Celsius. The input of the cooler is 400 Watt.
Figure 3.21: Stirling cooler unit SC – UE15 (Global cooling, 2010).

<table>
<thead>
<tr>
<th>List of properties of the SC UE15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating</td>
</tr>
<tr>
<td>Maximal cooling production</td>
</tr>
<tr>
<td>at temperature</td>
</tr>
<tr>
<td>COP</td>
</tr>
<tr>
<td>Mean pressure</td>
</tr>
</tbody>
</table>

Figure 3.22: Properties of the Stirling cooler unit SC – UE15 (Global cooling, 2010).
Figure 3.23: Performance of Stirling cooler unit SC –UE15 (Global cooling, 2010).

The widely use of Stirling engines in present applications are listed in the bibliography of this report.
4. Design

4.1 System scheme

The Stirling engine needs some conditions to work, filling them into a scheme the set up of figure 4.1 can be made. The solar power has to be converted into 600 degrees by a collector to create a hot side on the engine. The cold side of the engine must be cooled to 50 degrees. The cooling water have to be radiated and could be reused for instance for creating hot water suitable for pre heating a boiler or the heating of a room by a radiator. The temperature difference in the engine creates reciprocal movement. This will be converted to cooling power. When there is no need for cooling power (on a clear winter day for instance) the generated power can be converted to electricity.

![Figure 4.1: Stirling solar cooling system scheme.](image)

4.2 Solar concentrator

To create such temperatures by the power of the sun, the sun has to be concentrated. The concentration of solar power is generally done in two ways, with the use of reflectors and by the focus of lenses. Both can concentrate the sun to a point (point focus) or to a line (line focus), creating a focal spot or a focal line. In the Stirling solar cooling system there is a small surface to conduct the high temperature and because the point focus is faster in creating high temperatures through a more concentrated focus, for this research only the point focus concentrators will be considered.

To determine the rough size we need to create 600 degrees by solar power with a lens we first define a possible situation.

We take a lens of 1m² and assume the solar power will be unobstructed. The focus will be on a copper plate of 100 x 100 x 2mm this is the conducting plate on the hot side of the Stirling engine which have to reach the desirable 600 degrees.
Now we determine what concentrated solar power can do. We take 600 W/m² of ready-to-use solar power for a clear sunny day in the Netherlands (Society, 2010) and focus this on the copper plate of 0.01 m² with a thickness of 2mm for 1 hour. The applied power per second (Watt = Jules /s.) is 600 W/m² * 3600 s. (1 hour) = 2.160.000 Joules. The thermal conductivity (C) is the amount of joules needed to raise the temperature of a certain mass of material 1 degree (in J kg⁻¹ K⁻¹). For 1 kg copper to rise 1 degree 390 Joules will have to be added to the material (Ashby, 2007). This brings us to:

\[ \Delta T = \frac{\text{solarPower}}{C} \times kg \]

- \( \Delta T \) = rise in temperature of the copper plate after 1 hour
- solar power = Watts/m² applied to the lens over 1 hour = 2.160.000J/h.
- C = Joules needed to raise a certain mass of copper 1K. = 390 J/kg/K
- Mass = \( \rho \) (density of the material) x the volume =8900 kg.m³ * 0.1m * 0.1m * 0.002m. = 0.178 kg.

\( \frac{2.160.000}{390} \times 0.178 = 985 \text{ Kelvin} \)

This confirms the potential power of the sun to create high temperature and the danger, while copper melts around 1000 degrees. So a concentrator of 1m² creates too much heat, what surface will be sufficient to create the 600 degrees? Rewriting the formula to see when temperatures can be created of 600 degrees will get the next equation:

\[ \frac{\Delta T \times C}{kg \times 3600} = \text{Solar radiation} \]

Filling in the formula with the next parameters will give us the amount of solar radiation needed to reach 600 degrees:

- Solar radiation = amount of Watts over 1 hour.
- \( \Delta T \) = 600° Kelvin
- C = 390 J/m./K
- Weight = 0.178 kg.

\( \frac{600 \times 390}{0.178 \times 3600} = 365W \)
With a mean radiation of 600 W/m² that means 365W / 600W/m² = 0.6m² surface is needed for 0.01m² of copper to get to 600 degrees.

The collector should be able to concentrate 0.6m² of solar power to a 0.01m² conductor in a facade. For many of the big solar projects reflectors are used. They can be made for large surfaces, vary in materials and have basically two shapes, linear focusing reflectors and spot focusing reflectors. Looking at their size, shape and material they are a relatively expensive way to concentrate the solar power and hard to blend in a facade.

For being bend or parabolic shaped next to the collection of sun the collection of dust also occurs, leading to high maintenance costs to prevent collection loss of the sun. The integration of reflectors in a facade was thought to be possible but very hard to integrate architecturally, so they are not being considered in this research.

4.2.1 Lenses
Another way to concentrate the sun is the lens. For the possible appliance in facades three different lenses can be distinguished; glass, polyester and Fresnel lenses.

A point lens focuses the light to one point, the focal point (f). This is determined in every lens and varies by the thickness, curvature and design of the lens. Next to focal point the f-number is a way to describe performances of lenses. The F-number is the focal distance divided by the diameter of the lens (f / Φ) and is called the speed of the lens. A lens with a high f-number is called slow, one with a low f-number is called fast.
Architects want to keep facades as thin as possible to keep the costs down, reduce the loss of surface and keep the view open. Therefore to implement a lens in the facade as a solar concentrator a fast lens should be chosen.

The lens should focus as much solar power as possible to a small surface; this is not about optics but about focusing flux power. The glass lens has the best performance in focusing and transmitting light but creating a big fast glass lens is very heavy and will get very expensive. An improvement could be the use of acryl or polyester lenses while they are lighter and cheaper than glass lenses and still keep high performance. The combination of the surface of 0.6m$^2$ and the short focal point will increase the thickness so much that it is hard to manufacture and hard to blend in the facade (Smith, 1997).

**4.2.2 Fresnel lens**

The discovery of the Fresnel lens in 1822 by A. J. Fresnel has a solution to this; it has the same focal options as a glass or polyester lens but a huge reduction in thickness. This clever lens is based on the curvature of a normal lens but divides it in small sections following the same slope of the desired focus. Each section is brought back to its bare minimum thickness but because the slopes match the curvature of the normal lens it can focus with the same properties. The only performance loss compared to normal lenses is the slight deformation of the image at the edges, but this doesn’t affect the focusing of (heat) flux (Leutz and Suzuki, 2001).
The production of the lens can be done in series by a computer controlled mold. This way the design of the lens is highly flexible and with a material like acryl very large surfaces can be created to low costs and low weight (Yike, 2007).

Fresnel can be purchased/made in a few different settings. One of the options is few or less grooves per inch. For optics a high number leads to higher quality. For collecting every groove has a dead spot at the top (rim) and will therefore admit less light, so be less powerful. The growing demand for solar collecting is creating a developing jump in Fresnel lenses for power collecting purposes which brings solutions to this problem.

Because the lens has grooves on one side and is smooth on the other side, the desirable way to integrate it into the facade is with the grooves on the inside of the collector. This will keep the dust and dirt to a minimum, therewith the maintenance and the reduction in performance. The use of the lens inside out has a slight reduction on the performance shown in figure 4.7 (Davis and Kühnlenz, 2007).

The focal length has limitations which occur when the fraction of the incoming sunlight to the focal spot exceeds a critical angle. For the Fresnel lens this is determined to be 42.16 degrees (Leutz and Suzuki, 2001). This determines the minimal distance of a Fresnel lens with dimensions 800 x 800mm ($0.6m^2$) to the conductor plate of the Stirling engine to 360mm.
In practice for a design in the facade the limit of the focal length won’t occur while the transmittance is important to collect the power. The transmittance of the lens is highly influenced by the speed.

Figure 4.7 shows the very important relationship between the F-number and the transmittance efficiency. For concentrating with the grooves on the inside the desirable F-number should exceed 0.8, having a 75% transmittance, as the drop of the efficiency is large from there. This has consequences for the facade design. The minimum surface of the Fresnel lens for creating 600 degrees at peak load was 0.6$m^2$ leading to a diameter of 0.8m.

\[
f = \varnothing \times F
\]

\[
f = 0.8 \times 0.8 = 0.64m.
\]
Figure 4.8: Focus of an 800x800 Fresnel 0.8 F-number.

To increase the transmittance efficiency and keep a as slim as possible facade the Fresnel lens in the collector will be split into separate divisions aiming at the same focal spot on the conductor plate.

Figure 4.9: Devised in four Fresnel lenses 400x400 with 1,25 F-number.

The lenses are much slower and therefore more efficient with divisions of 400 x400 mm and a reduced focal length of 500 mm the F-number is (0,5/0,4) 1,25 leading to a approximate transmittance efficiency of 86%. The amounts of focal (or hot) spots are increased providing the heat to be distributed more evenly providing a more consistent supply of solar power.

Figure 4.10: Example of multiple Fresnel circles (Sunflower, 2009).
The core of the design is collecting solar power to make the system run. Collecting the sun can be done with or without a tracking device, where off course the tracking device can optimize the performance. Present tracking devices contain a lot of different mechanisms and control systems leading very often to malfunction, high maintenance and high costs. Not to mention when this happens, the complete loss of power of the system. Therefore tracking systems will not be considered in this research and for the design a reliable and stationary collector will be chosen.

For the optimal collection of solar power by a stationary collector in central Europe the inclination towards the horizontal surface of the earth should be between 30° and 60° and the collector should be oriented between south-east and south-west. Any angles between these setting have minimum effect and compared to the optimal angles will lead to a loss of solar radiation of less than 15% (Society, 2010).

Figure 4.11: The trajectory of the sun (Society, 2010) Figure 4.12: Defining the angle for collection (Society, 2010).

For this design the choice to have a straight panel design is not made due to two reasons. First of all the building should represent the use of solar power. Second, when the façade part of the concentrator is not tilted the amount of surface of Fresnel needed for the system to work would be double than when the panel is tilted. Due to the incident angle the sun reaches the panel and the same power is spread over twice the surface as shown in figure 4.13. This leads to double the surface of the conducting plates and double the F-number. A straight panel design is possible by twice the collecting surface and twice the width of the facade and could be considered in an early design stage.
4.3 Cooling the Stirling engine

To get the highest efficiency of the Stirling engine it has to maintain a cold side of 50 degrees this cold side is kept this way by the use of a water pump. While the water pump and cooling unit are integrated in a duplex configuration, the influences and performances are hard to determine. For this research the fact that this water can be reused as room heating will be used. The water pump will have a closed circuit with the Stirling engine and pump the water through a radiator in the parapet. The parapet has rosters to the inside and to the outside of the building which can be controlled to be opened and closed. This way the excess heat can be reused when the room needs heating and transferred outside when it has to get rid of it.

4.4 Coolers

The output of the Stirling engine has to be converted to cooling power and for this research a couple of systems were considered. Next to common piezo cooling and Stirling coolers, common cooling units are shortly studied, while the Stirling engine will generate 1100 Watts on peak solar power and for common cooling units this is quite low. The piezo cooling is a relative new technique creating a hot side and a cold side by putting an electric current on a thin piezocrystal plate. While it seemed to be a similar thermal system concerning heat, cold and electricity it was tried to look for intersecting heat and cold losses to try to regenerate it. But no match was found and the electricity need was too high for the Stirling solar system.

The Stirling cooler works as a heat pump working on the reversed Stirling principle. This means when you put mechanical work in a hot and cold side is created. Because the Stirling engine creates mechanical movement the conversion to electricity can be skipped creating a more efficient system.

To get the cooling power into the room a cooling ceiling will be used and in this case dimensioned 2000mm x 600mm x 100mm. It must be connected by two ducts and can be mounted on the ceiling.
4.5 Construction system

The system which must be implemented into the façade is getting complex because of the number of components. Also the fine-tuning of the focus of the collector is crucial and some parts are fragile. The construction system should support the design and reduce the error margin. According to the table in figure 4.14 the amount of errors on the planning of a solar system is 45%. This is due to the relatively little experience on such systems. The other big error field is the assembly which counts for 39%. The Stirling engine and cooler are delicate machines and must be precisely put together in combination with the Fresnel lens. When the focal point of the Fresnel lens is not rightly installed the generated power of the system will be severely less due to the lower temperatures occurring on the collecting plate and the chance of malfunctioning is high. And due to the fact that the many piping and wiring (for cooling the Stirling engine, for cooling the room and for the generated electricity) needed for the system the preference for manufacturing this façade is in a controlled environment. To reduce the amount of installing on the construction yard and make the error rate as little as possible.

![Graph showing assembly errors of solar systems.](image)

The following are the most salient and common defects when assembling, from the view of an expert. Apart from planning, the sources of error and causes for faults predominantly (39%) occur during installation.

This leads to the use of a prefab panel system, where the most of the elements can be manufactured and put together in a factory. The product standard is higher and the chance to reduce the costs is too (Knaack et al. 2007).
4.6 Study case office building.

Because of the lack of information on the Stirling engine and the limited time a study case office building has been assumed and assumptions have been made. We consider a room in the middle of a five floored office building. The room has a depth of 5m and a width of 5,4m and will be covered by three panels in the facade of 1,8m. The average annual need for cooling on a medium load class office building is determined on 50 W/m² (Schalkoort, 2004).

<table>
<thead>
<tr>
<th>Office</th>
<th>Room</th>
<th>Panel</th>
<th>M2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>5,4</td>
<td>1,8</td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Cool load</td>
<td>50</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Total cooling demand</td>
<td>1350</td>
<td>450</td>
<td>50</td>
</tr>
</tbody>
</table>

Figure 4.17: Office study case dimensions in mm and Watts.

For the calculation the average annual cooling load of one panel will be considered being 450 Watt. Taking an average of 1000 sun hours per year for the Dutch climate the total annual cooling will become 450.000 Watt per panel.

The calculations of the peak cooling load are calculated by the formulas given by attachment B which is included at the end of the thesis. The following data is being considered in the calculation of the peak cooling load.
The total cooling per room comes to 3.402 Watts making a 126 Watts/m². Per panel a peak cooling load should be covered of 1.134 Watts.

### 4.7 Calculations

It is hard to estimate a real performance or feasibility on this system while there are so many factors where no or very limited information is available. To make an estimation the following steps have been considered.

For the solar power the total global irradiance is taken determined by the next formula:

\[ G_g = G_{dir} + G_{diff} \]
Gg = Global solar irradiance
Gdir = Direct radiation
Gdiff = Diffuse radiation

The total global irradiance on a clear summer day in the Netherland without any obstructions can be set on 1000 Watt/m² according to Society (2010).

To determine how much power reach the surface of the concentrator the absorption, rayleigh scattering, mie scattering and the angle of the of the panel are being considered. The average loss is 25% (Society, 2010) what will result in 750 Watt/m² of solar power to be focused.

The minimum surface area of the Fresnel lens was determined to be 0,7 m² resulting in 750/m² * 0.7 m² = 525 Watt. 2% reduction for dust is taken (Society, 2010) so 515 Watt of solar power to be focused by the Fresnel lens. Two 0,4m. by 0,4m. Fresnel lenses with F-number 1,25 were taken, resulting in a transmittance loss of 86% according to the graph in figure 4.7 by Davis and Kühnlenz (2007) (this is covered in the overview by refraction (95%) and focus (90%)).

The total amount of solar power concentrated on the conductor of the Stirling engine thus is 86% of 515 Watt = 440 Watt. The heat will not be totally conducted causing a transmission loss of 15% ending with a total solar power input to the system of 374 Watt.

$$\Delta T = \frac{\text{solarPower}}{\lambda} \cdot \text{Mass}$$

$$\Delta T = \text{rise in temperature of the copper plate after 1 hour}$$
$$\text{solar power} = \text{Watts/m}^2 \text{ applied to the lens over 1 hour} = 379 \cdot 3600$$
$$\lambda = \text{Joules needed to raise a certain mass of copper 1K.} = 390 \, \text{J/kg/K}$$
$$\text{Mass} = \rho \text{ (density of the material) x the volume}$$

$$=8900 \, \text{kg.m}^3 \cdot 0.1m \cdot 0.1m \cdot 0.002m. = 0.178 \, \text{kg.}$$

$$\frac{374 \cdot 3600}{390} \cdot 0.178 = 622 \, \text{Celsius}$$

So the best efficiency is met when the peak load is occurring.

<table>
<thead>
<tr>
<th>Sun</th>
<th>Solar Power (Watt/m²)</th>
<th>Angle (degrees)</th>
<th>Area (m²)</th>
<th>Lens</th>
<th>Dust (%)</th>
<th>Refraction</th>
<th>Focus</th>
<th>Heat</th>
<th>transmission loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.7</td>
<td>25</td>
<td>Western Europe</td>
<td>90%</td>
<td>90%</td>
<td>15%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.20: Global calculations sequence.

Now we have confirmed that the Stirling engine could work and on peak solar irradiance and therefore on peak cooling loads. The reference engine, the EG-1000, can generate max. output of 1100 electrical Watt with that. According to the Bakker et al. (2010) the COP (Coefficient of
Performance) for the duplex Stirling for cooling is 1,0. This means the amount of power submitted to the system can be transferred to cooling power by a coefficient of 1,0. The way of expressing performance of climate systems with numbers higher or equal than 1 is common and is due to the fact that the (pre heated) outside air is not considered as input. So it is actually thermally incorrect but for global calculations it is a good way of estimating results.

<table>
<thead>
<tr>
<th>Appliance</th>
<th>COP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground temperature to 60/70 °C</td>
<td>1,2</td>
</tr>
<tr>
<td>Cooling 6/12 °C</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 4.21: Performance of a duplex Stirling system on heating and cooling (Bakker, 2010).

The cooling power of the 0,7m² Fresnel lens after 1 hour of peak solar power is thus 374 Watts.

### 4.8 Design images

The image, integration possibilities and aesthetics are very important in the (commercial) success of a system, therefore a study into these was made before any more calculations.

As a possible elaboration for the facade design the tilted collecting surface is taken as a starting point. The ratio in the panel of the collector and the window surface is set by the need of solar power but also results in the reduction of the cooling load because it works like sun shading. This way in summer it blocks the high sun from coming in the room and still let the sun in to the room by winter when the sun is much lower.

Figure 4.22: Sun blocked at summer and gained in winter.

The repetition in the prefab panel reduces the costs and with the tilted side it creates a lively facade. To continue the fluent line and to decrease the surface of the façade the window in the panel is tilted too, to make the connection to the collector.
To achieve the image created all the system elements and the panel have to be integrated in to the building envelope. To begin with the end goal, cooling the room, a ceiling has to be lowered to integrate the cooling ceiling device. This has to be connected to the duplex Stirling engine by piping and the machine has to be situated so it can generate power out of the sun. This resulted into three options; above, in or under the buildings floor.

Figure 4.23: Sketch design process.
To reduce the floor height, have an optimal angle to the sun and keep a normal sized parapet, the second location is chosen with the Stirling engine in the floor. This way the Stirling engine is central in the system having the shortest connections to the cooling ceiling and the radiator and although the maintenance of the system is very low it must be possible to access the engine to adjust or repair parts.

Figure 4.24: Study to the different locations of the Stirling engine.
Figure 4.25: A possible representation of the solar cooling façade.
For the solar cooling system to work it has to fit easily in the architecture facades. Therefore two design were made. The first design (Alpha) is optimized for the best performance of the system. What is, given the architectural façade impression, the maximum output the system could get? The second (Beta) is optimal for the implementing the system into the present view of architecture and will consist of the minimum Fresnel lens of 0.7m².

### 4.9 Design Alpha, Design Beta

The beta design is made for the maximum performance of the solar cooling system. What is the system capable of? The total input and performance of system alpha and beta is shown in attachment C.

For this design the Fresnel lens covers the entire bottom panel leading to a surface of 1.7m x 1.2m = ±2m². The mean temperature will rise but because of the division of Fresnel focal points this should be designed so the ideal temperature of 600 degrees is the average but on a bigger surface.
Increase to solar power = \( \frac{2m^2}{0.7m^2} \times 374 = 1068 \text{ Watt} \)

The amount of power intake has increased by 2.85 leading to a cooling power at peak load of

\[ \text{Cooling power} = 3,33 \times 374 \text{ Watt} = 1086 \text{ Watt cooling} \]

The Stirling solar cooling system can generate 1,1 kW of cooling power by the use of a coupled Stirling engine to Stirling cooler on peak solar irradiance using a 2,0m\(^2\) of Fresnel lens.

---

**Design A**

<table>
<thead>
<tr>
<th></th>
<th>Cool power</th>
<th>374 Watt</th>
<th>Panel</th>
<th>33%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool load</td>
<td>1,134 Watt</td>
<td>Panel</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

**Annual**

<table>
<thead>
<tr>
<th></th>
<th>Cool power</th>
<th>224348 Watt</th>
<th>Panel</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool load</td>
<td>450,000 Watt</td>
<td>Panel</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

electricity 1,13 kWhe 67%

electricity 675,80 kWhe 50%

---

Figure 4.27: Values per panel for design Alpha.
Figures 4.27 and 4.28 show the performance per design to the cooling load occurring. Design A can achieve a reduction of 33% of the cool load at peak solar power and gain a 50% reduction on annual base. The maximum performance by design Beta can almost take peak load reducing the load by 94%. In the annual calculation it is clear not all the power has to be transferred to cooling power while a significant part can be used in creating electricity. The amount is hard to estimate, but when all the solar power is generated to electricity as much as 3,22 kWe per hour can be created at peak, covering an average household usage.

To compare it with similar systems is hard, as there are not direct comparable systems. For the comparison I take pv-cells connected to a cooler with the same performance as the Stirling cooler.

A good photo voltaic system has an efficiency of about 20% -25% given the surface of 2m² it can generate about 1000 * 0.75 * 2 *0.25 = 375 Watts of electricity. This could barely drive the cooler to
about 150 Watts of cooling. Pv-cells have the advantage that the angle of the solar inclination has less effect on the system, while there doesn’t have to be a focus on a conductor. The focus of the Stirling solar system is harder to keep on the conductor. The daily and therefore annual cooling capacity might therefore be higher than with the alpha design.

<table>
<thead>
<tr>
<th>Engine / System</th>
<th>Investment in € / kWe</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas engine</td>
<td>350</td>
<td>100 kWe to 1500 kWe</td>
</tr>
<tr>
<td>Micro gas turbine</td>
<td>1000</td>
<td>100 kWe to 1500 kWe</td>
</tr>
<tr>
<td>ORC</td>
<td>2500</td>
<td>Probably goes to €700 - 1000 / kWe when series produced</td>
</tr>
<tr>
<td>Stirling engine</td>
<td>500</td>
<td>A decrease in costs towards €370/ kWe is expected</td>
</tr>
<tr>
<td>Fuel cell system</td>
<td>1000</td>
<td>Probably lower when series produced</td>
</tr>
<tr>
<td>Pv cells</td>
<td>1800</td>
<td>Fuel is free, low maintenance. 20 years life span. No funds considered</td>
</tr>
</tbody>
</table>

Figure 4.29: Estimated costs (PolySMART, 2008).

The costs are hard to estimate there is a cautious estimation by PolySMART of about €500/kW and an expected reduction to €370/kW when the engine is manufactured in series. As figure 5.6 shows this has a potential economic advantage towards other engines and systems. The PV cell system has relatively high price of 1800 €/kW as government funds vary and are not considered in this calculation.

However, according to figure 5.6, the cost of the Stirling engine is likely to be commercially attractive.

**4.10 Design drawings**

For the all the design drawings on scale see attachment D.

The following drawings represent the result of the described parameters a facade should meet when the Stirling solar system is integrated. The prefab panel can be installed using common unitized system techniques. The concrete floor should contain a gap which embraces the Stirling system and can be done in situ by regular used casting methods.
Figure 4.30: Technical manufacturing of the panel.

Figure 4.31: Exploded view of the unitized panel.

The exploded view of the panel shows all elements in the different layers used to construct each panel.
Here the building sequence is shown starting with the specially designed concrete floor in the first image. The system is put in place connected to the radiator in the parapet, the cooling ceiling of the room beneath and the electrical grid.

Then the window frame is placed and fixed by adjusting bolts on the top and bottom. The next step is putting the collector in place with the mirroring container leading all the solar power to the (red) conductor of the Stirling engine.
The last phase is putting the Fresnel lens in, which is already set to the right distance and angle at the factory.
Facade elevation
Figure 4.35: Section V1 of the design.
Figure 4.36: Detail of the system in the façade.

The thickness of the floor is maintained at 200mm to prevent fire transfer and keep enough body to connect the panels to. The duplex system can be installed as one package in the space and connected to the radiator, cooling ceiling and electricity net.
The collector and Stirling engine are carefully wrapped in 55mm of fire resistant insulation and lowered into the floor so a computer floor can cover the equipment and give an elegant finish. The jump in the floor is at the point of a column so the force flow can be taken downwards. The cooling ceiling connects to the floor making it continuous. The open view has been maintained and a solar blind has been integrated in the panel.
5. Discussion

The Fresnel lens, the Stirling engine, the Stirling cooler and a combination of these have never been used in a facade before, therefore estimating performances are hard. However there is a potential for the appliance in the facade for each individual element and only extensive research and testing can confirm real results. The global energy situation can’t hold on forever and at some point some drastic measurements have to be taken, researching the Stirling solar system could be it.

The use of a Fresnel lens in the facade to create high temperature can get dangerous and give unwanted or unforeseen results. Therefore the design of this concentrating system should be researched further. The use of an inside tracking device as second concentrator should be considered optimizing power and minimizing malfunction.

The Stirling solar system could work on natural gas. A combination of the duplex Stirling system as standard operating climate system with the addition of the solar power when available should be given more thought. The costs of two climate systems will be prevented and the heat recovery options in the system could be fully exploited leading to high efficiencies.
6. Conclusion

The continuing global energy problems remain ongoing without the prospect of a real breakthrough. However it has to come a point that the awareness is growing to such proportions that breakthroughs are to be forced. Because it runs on a variety of fuels, it is durable, maintenance free and has high efficiency, the development of the Stirling engine could be of great importance for the improvement of the global energy related problems.

A system powered by solar power harvested from an office facade and put into cooling power is considered likely to work. It is feasible that this system can contribute to the reduction of the annual cooling load of an office building. For an office building this system will need an additional climate system and therefore additional costs. Even though the exact price of a Stirling engine or duplex engine is not yet known, the implementation of this system in coming office buildings is considered feasible according to the available information.

Because the Stirling engine needs a temperature around 600 °C, precautions should be made in an early design stage in the form of good insulation and safe integration. A system using a Fresnel lens with the grooves in has low maintenance and has the potential to create very high temperatures, therefore a good source to power a Stirling engine in a facade. Such a system should be carefully tested as the implementation of a Fresnel powering a Stirling engine hasn’t been done yet. The cooling water of the engine has potential to be used as room heater, while get rid of the unnecessary heat which will increase the efficiency of the total system. The combination of a Stirling to Stirling cooler is called a duplex Stirling and has great potential due to the few conversions of energy and the small number of moving parts. Performance and dimensions are an estimation made on the information presently available and therefore an educated guess, nevertheless they are set within reasonable doubt.

At maximum configuration the system can be designed in a way that it can take peak cooling loads when the Fresnel lens is taken big enough so covering the total annual cooling load of an office building. The system can be integrated well in an office building with the present building standards and construction methods. A computer system should regulate the needs of cooling, heating and electrical power.

Because of the simple design, the few moving parts, no need for expensive materials and the expected investments of companies and/or governments the Stirling engine has big potentials to be applied in many applications in the near future. Because the Stirling solar cooling system embraces all aspects of a climate system the biggest potential seems to lie in the decentralized stand alone system or micro DHCP with a constant fuel source to power it like gas. This could be very well combined with the harvest of solar power and this way all of the facets in the system are optimally (re)used. Real clarity on this matter should be investigated in further study.
7. Bibliography

Journals


Books


**Other Sources**


**Images**


Internet sources and useful links:

Stirling engine:

Wood pallets driven Micro CHP machine with Alpha Stirling engine. Producing heat and 3 KWh, 1kg pallets /h (for 50 cents/kg)
http://www.tibri.be/beelden/sm-2.wmv
http://www.tibri.be/beelden/sunmachine/sm-6.wmv

Whispergen CHP

Automobile

Computer processor cooling.


Animated engines:

Fresnel:

http://www.seao2.com/solarsphere/csp.htm


http://www.rexresearch.com/solrfurn/solfrnpat.htm
Attachments

Attachment A

Nomenclature

Thermodynamics:
Mechanics:
FPSE = Free Piston Stirling Engine
Carnot efficiency = Efficiency determined by the theory of Carnot
IC engine = Internal Combustion Engine

Symbols
Qh = Applied heat
Qc = Rejected heat
Ekin = Kinetic energy
M = Mass (kg)
V = Volume (m³)
R = Radius (m)
H = Height (m)
D = Diameter (m)
F = Force (N)
A = Surface (m²)
We = electrical Watt
kWe = electrical kilo Watt
eP = eW
cW = Cooling Watts
p = pressure (bar,pa)
W = work (N/m)
**Peak cooling load formulas.**

The cool load is calculated by the ISSO-8 (Instituut voor Studie en Stimulering van Onderzoek) and will give a global indication of the load to the study office.

**The global cool load (Φc) is given by:**

\[ Φc = Φi + Φe \]

- **Φi** = internal heat load (W)
- **Φe** = external heat load (W)

The **internal** heat load is given by:

\[ Φi = Φp + Φl + Φa \]

- **Φp** = heat load by persons (W)
- **Φl** = heat load by Lighting (W)
- **Φa** = heat load by apparatus (W)

The heat load by persons is given by:

\[ Φp = p \times q_p \]

- **P** = number of persons in the room
- **q_p** = heat exchange per persons (W)

\[ Φl = q_l \times A \]

- **q_l** = convection heat lighting (W/m²)
- **A** = floor surface (m²)

\[ Φa = q_a \times A \]

- **q_a** = convection heat apparatus (W/m²)
- **A** = floor surface (m²)

The **external** heat load (Φe) is given by:

\[ Φe = Φs, gl + Φtr, gl \]

- **Φs, gl** = the solar load through the glass surface (W)
- **Φtr, gl** = heat transmittance through the glass surface

The solar load through the glass surface is given by:
\( \Phi_{s, gl} = Z \times A \times ZTA \times q_{\text{conv}} \)

- **Z** = solar protection factor of the solar blinds
- **A** = Surface of the glass
- **ZTA** = Solar transmittance factor
- **q_{\text{conv}}** = convection heat by solar through the glass with outside solar blinds (W/m\(^2\))

The heat transmittance through the glass is given by:

\[ \Phi_{tr, gl} = U \times A \times (\theta_e - \theta_i) \]

- **U** = heat transmittance coefficient (W/m\(^2\)*K)
- **A** = surface of the glass
- **\theta_i** = interior temperature
- **\theta_e** = exterior temperature
Attachment C

Design Alpha and Beta system performance.
# Design A  
**page 1 of 2**

## Peak

<table>
<thead>
<tr>
<th>Solar Power (Watt/m²)</th>
<th>Angle (degrees)</th>
<th>Area (m²)</th>
<th>Dust (%)</th>
<th>Refraction</th>
<th>Focus</th>
<th>transmission loss</th>
<th>Temperature (°C)</th>
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<tbody>
<tr>
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<td>y = 300</td>
<td>0,7</td>
<td>Western Europa</td>
<td>95%</td>
<td>90%</td>
<td>15%</td>
<td>Hot side</td>
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<tr>
<td>25</td>
<td>17,3 - 38,5 %</td>
<td>2%</td>
<td>in 1 hour</td>
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<td></td>
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*number of division in lens: 1.0*

## Annual

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<th>Focus</th>
<th>transmission loss</th>
<th>Temperature (°C)</th>
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<td>y = 600</td>
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<td>95%</td>
<td>90%</td>
<td>15%</td>
<td>Hot side</td>
</tr>
<tr>
<td>25</td>
<td>17,3 - 38,5 %</td>
<td>2%</td>
<td>in 1 hour</td>
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<th>Watt</th>
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<tr>
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<td>60%</td>
<td>COP</td>
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<tr>
<td>Carnot</td>
<td>1,2</td>
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</tr>
<tr>
<td>50 C</td>
<td>264 Watt</td>
<td>211 W</td>
<td>374 Watt</td>
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</table>

**Peak cooling power**

Peak electricity generation

1,1 kW

1 hour of full solar power

when no cooling is used

<table>
<thead>
<tr>
<th>Engine</th>
<th>Shaft Power (Watt)</th>
<th>Cool Water (C)</th>
<th>COP</th>
<th>COP</th>
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<td>Carnot</td>
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**Annual cooling power**

Annual electricity generation

675,8 kW

224348 Watt

1000 sun hours per year

when no cooling is used
## Design B page 1 of 2

### Peak

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<tr>
<th>Solar Power (Watt/m²)</th>
<th>Angle (degrees)</th>
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<tbody>
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<td>Western Europa</td>
<td>95%</td>
<td>90%</td>
<td>15%</td>
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<td></td>
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<td></td>
<td>25%</td>
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- Hot side in 1 hour
- Western Europa:
  - Number of division in lens: 2,9

### Annual

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<th>Solar Power (Watt/m²)</th>
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<td>15%</td>
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<tr>
<td></td>
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<td></td>
<td>25%</td>
<td></td>
<td></td>
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</table>

- Hot side in 1 hour
- Western Europa:
  - Number of division in lens: 1,76

- Western Europa in 1 hour:
  - Number of division in lens: 1,76

---

Number of division in lens:
- Western Europa: 2,9
- Western Europa in 1 hour: 1,76
Design B  page 2 of 2

<table>
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<tr>
<th>Shahep power (Watt)</th>
<th>Cool water (C)</th>
<th>Shaft power (Watt)</th>
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<td>Carnot 1.0 COP</td>
<td>50 C 754 Watt 603 W 1068 Watt</td>
<td>50 C 452 Watt 362 W 641 Watt</td>
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</table>

Peak cooling power 1068 Watt 1 hour of full solar power

Peak electricity generation 3 kW when no cooling is used

Annual cooling power 1871701 Watt 1000 sun hours per year

Peak electricity generation 1931 kW when no cooling is used
Attachment D

Design drawings
Solar power coming in

Window sill

radiates heat from Stirling engine
duplex Stirling machine
electricity output

fresnel lens focuses sun

hot spot, 600 degrees Celsius

cooling ceiling
piping for cooling water

Section V3
Double glazed window
2500 x 1800 x 257
tilted 2600 x 1800 x 25

Frame with fresnel lens
Focus depending on the lens design, for now its 300mm