<table>
<thead>
<tr>
<th><strong>Treball Final de Grau/Carrera</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Realitzat i defensat a Lodz University of Technology (nom universitat) de Polònia (país)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Estudi:</strong></th>
<th>Grau en Eng. en Tecnologies Industrials Pla 2010</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th><strong>Títol:</strong></th>
<th>SOLAR COOLING</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th><strong>Document:</strong></th>
<th>Treball Final de Grau (TFG)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th><strong>Alumne:</strong></th>
<th>Álvaro Royes Moreno</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th><strong>Director/Tutor:</strong></th>
<th>Josep Xargayó</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Departament:</strong></td>
<td>Enginyeria Elèctrica, Electrònica i Automàtica</td>
</tr>
</tbody>
</table>

| **Convocatòria (mes/any):** | Juny/2015 |
Solar Cooling

Final Project Report

Authors:
Michael Leinen,
Magdalena Banasiak,
Miquel Gabaldà,
Álvaro Royes,
Pierre Mahé

Supervisors:
Witold Marańda,
Maciej Piotrowicz
Abstract

The global air conditioning (AC) market is still a rapidly growing one. People in countries like India and China also want the luxury of living and working in air conditioned rooms, which will create a huge energy demand. With the limited resources of fossil energy left, there is a need for a different approach for cooling. Due to the limited time and resources it is not possible to focus on the project in a general way; thus it is approached in a practical fashion, exploring the possibility of cooling a building of the Technical University of Lodz by only using green energy taken from the sun to power an AC device. In detail, the task was to first compute the actual cooling needs of the building. After that, a proper technique that could provide these amounts of cooling needs was found, as well as the appropriate device that could be implemented in the building. Finally, a business part of the project was done and the project was evaluated on a financial basis.

For the calculation of the cooling needs, some research was done to all the data and formulas that contribute to a building heat gains and losses. After acquiring the ones the team had access to, MATLAB was used to program a thermal model of the building, in reverse engineering was applied to estimate missing values and finally calculate the actual cooling needs of the building. This was then used to choose a suitable air conditioning device based on research and inquiries with the manufacturers. The final part, the business plan, consists of Microsoft Excel calculations based on Polish energy costs, prices of acquiring and installing solar panels and the solar irradiation in the area.

It was possible to show that the project, even when calculated with the worst case scenario, will turn a profit within 20 years after installation of the solar panels, most likely even earlier. Considering the longevity of modern panels, which exceeds 25 years, and a number of additional benefits coming from a self-energy generating building, the realisation of this project is strongly recommended. Furthermore, it is meant to encourage anyone to think about whether private solar panels would make sense in their situation and provide a small tool for that purpose on the team’s website as well.
Table of contents

Abstract ......................................................................................................................... II
Table of contents .......................................................................................................... III
Table of figures ............................................................................................................. VI
Abbreviations ............................................................................................................... VIII

1. Introduction .............................................................................................................. 1
   1.1 Motivation ............................................................................................................ 1
   1.1.1 World energy crisis ......................................................................................... 1
   1.1.2 Potential markets ............................................................................................ 2
   1.1.3 Conclusion ....................................................................................................... 5
   1.2 Project ................................................................................................................ 5
   1.2.1 Definition ....................................................................................................... 5
   1.2.2 Approach ........................................................................................................ 5
   1.2.3 Scope ............................................................................................................... 6

2. SCOOL Team ........................................................................................................... 8
   2.1 Team Logo and Name ........................................................................................ 8
   2.2 Team Members ................................................................................................... 9
   2.3 Team Roles ......................................................................................................... 10
   2.3.1 Leader .......................................................................................................... 10
   2.3.2 Specialist (Business) .................................................................................... 10
   2.3.3 Implementer .................................................................................................. 10
   2.3.4 Coordinator .................................................................................................. 11
   2.3.5 Plant ............................................................................................................. 11
   2.4 Communication tools ....................................................................................... 11
   2.4.1 Team Meetings ............................................................................................. 11
   2.4.2 Supervisor meetings ..................................................................................... 12
   2.4.3 Email services .............................................................................................. 12
   2.4.4 WhatsApp .................................................................................................... 12
   2.4.5 Dropbox ....................................................................................................... 12
   2.4.6 Skype ........................................................................................................... 13

3. Physical Foundation ................................................................................................. 14
   3.1 Heat transfer mechanisms ............................................................................... 14
   3.1.1 Conduction ................................................................................................... 15
3.1.2 Convection

3.1.3 Radiation

3.2 Standard AC design

3.2.1 Carnot cycle

3.2.2 AC unit

3.3 Solar Cooling Systems

3.3.1 Photovoltaic Systems

3.3.3 Thermal System

4. System Modelling

4.1 Equations

4.2 Thermal properties of the building

4.2.1 Calculated values

4.2.2 Estimated values

4.3 Methodology

4.4 Data collection and analysis

4.5 Thermal modelling

4.5.1 Reverse engineering of estimated variables

4.5.2 Cooling needs calculation program

4.6 Results

4.6.1 Charts

4.6.2 Calculations for Photovoltaic Systems

4.6.3 Calculations for Thermal System

4.6.4 Additional outputs

5. Economic Evaluation

5.1 General Overview of the PV Solution

5.1.1 The cooling system

5.1.2 The PV system

5.1.3 Other costs

5.1.3.1 Installation cost

5.1.3.2 Maintenance cost

5.1.4 Amortization of the project

5.2 Overview of the Thermal Solution

5.2.1 The thermal system

5.2.2 Additional costs

5.2.3 Amortization of the project
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.</td>
<td>Project Management</td>
<td>88</td>
</tr>
<tr>
<td>6.1</td>
<td>Project’s Gantt chart</td>
<td>88</td>
</tr>
<tr>
<td>6.2</td>
<td>Project’s course</td>
<td>89</td>
</tr>
<tr>
<td>6.2.1</td>
<td>Team’s Identity</td>
<td>89</td>
</tr>
<tr>
<td>6.2.2</td>
<td>Research</td>
<td>89</td>
</tr>
<tr>
<td>6.2.3</td>
<td>Program</td>
<td>89</td>
</tr>
<tr>
<td>6.2.4</td>
<td>Website</td>
<td>89</td>
</tr>
<tr>
<td>6.2.5</td>
<td>Midterm evaluation</td>
<td>90</td>
</tr>
<tr>
<td>6.2.6</td>
<td>Business plan</td>
<td>90</td>
</tr>
<tr>
<td>6.2.7</td>
<td>Final evaluation and further ideas</td>
<td>90</td>
</tr>
<tr>
<td>6.3</td>
<td>SWOT Analysis</td>
<td>90</td>
</tr>
<tr>
<td>6.4</td>
<td>Project’s Outcome</td>
<td>92</td>
</tr>
<tr>
<td>7.</td>
<td>Conclusions</td>
<td>93</td>
</tr>
<tr>
<td>7.1</td>
<td>Results</td>
<td>93</td>
</tr>
<tr>
<td>7.2</td>
<td>Summary</td>
<td>93</td>
</tr>
<tr>
<td>7.3</td>
<td>Recommendations</td>
<td>94</td>
</tr>
<tr>
<td>7.4</td>
<td>Closing thoughts of the team members</td>
<td>95</td>
</tr>
<tr>
<td>7.4.1</td>
<td>Michael</td>
<td>95</td>
</tr>
<tr>
<td>7.4.2</td>
<td>Pierre</td>
<td>96</td>
</tr>
<tr>
<td>7.4.3</td>
<td>Álvaro</td>
<td>98</td>
</tr>
<tr>
<td>7.4.4</td>
<td>Miquel</td>
<td>100</td>
</tr>
<tr>
<td>7.4.5</td>
<td>Magdalena</td>
<td>101</td>
</tr>
<tr>
<td>Appendix A</td>
<td></td>
<td>102</td>
</tr>
<tr>
<td>Appendix B</td>
<td></td>
<td>103</td>
</tr>
<tr>
<td>Appendix C</td>
<td></td>
<td>105</td>
</tr>
<tr>
<td>Appendix D</td>
<td></td>
<td>108</td>
</tr>
<tr>
<td>Appendix E</td>
<td></td>
<td>110</td>
</tr>
<tr>
<td>Bibliography</td>
<td></td>
<td>112</td>
</tr>
</tbody>
</table>
# Table of figures

Figure 2-1: Team Logo .................................................................................................................................................. 8
Figure 2-2: Michael Leinen Belbin ............................................................................................................................. 10
Figure 2-3: Pierre Mahé Belbin .................................................................................................................................. 10
Figure 2-4: Miquel Gabaldà Belbin ........................................................................................................................... 10
Figure 2-5: Álvaro Royes Belbin .................................................................................................................................. 11
Figure 2-6: Magdalena Banasiak Belbin .................................................................................................................... 11
Figure 3-1: Heat transfer mechanisms ....................................................................................................................... 14
Figure 3-2: Conduction heat transfer though a simple wall ...................................................................................... 15
Figure 3-3: Simple picture for circular air flow impacts ........................................................................................... 17
Figure 3-4: P-V diagram of the Carnot cycle ............................................................................................................. 19
Figure 3-5: T-S diagram of the Carnot cycle ............................................................................................................. 19
Figure 3-6: Realistic conversion vs. Carnot cycle ....................................................................................................... 21
Figure 3-7: Isothermal expansion from a to b along PV=nRT ................................................................................ 21
Figure 3-8: Basic refrigeration cycle ......................................................................................................................... 23
Figure 3-9: Solar cooling system classification ......................................................................................................... 24
Figure 3-10: Panels of a photovoltaic power field .................................................................................................. 24
Figure 3-11: Basic PV system components ............................................................................................................... 25
Figure 3-12: The residential demand vs. PV energy generation ............................................................................. 26
Figure 3-13: Swanson effect chart ............................................................................................................................ 27
Figure 3-14: Basic scheme of thermal system ......................................................................................................... 28
Figure 3-15: Flat plate collector ................................................................................................................................... 29
Figure 3-16: Glass tubes ............................................................................................................................................. 29
Figure 3-17: Mechanism of a heat exchanger ........................................................................................................... 30
Figure 3-18: Scheme of a thermally driven single-effect absorption chiller ............................................................ 31
Figure 3-19: Scheme of an adsorption chiller ........................................................................................................... 32
Figure 3-20: Comparison of the two different types of chillers ............................................................................. 33
Figure 4-1: The different surface types visible as windows and red-brick walls ................................................................. 39
Figure 4-2: Calculation of the value for the wall (compare to Fig. 3-1) ................................................................. 40
Figure 4-3: Heat losses (and some gains) of all parts .............................................................................................. 41
Figure 4-4 Excel worksheet of the weather data (extract) ...................................................................................... 45
Figure 4-5: Steps to create the model ....................................................................................................................... 46
Figure 4-6: Final variables used in the program ..................................................................................................... 47
Figure 4-7: Final heating calculation and error ........................................................................................................ 48
Figure 4-8 Part of the loop section of the heat calculation program ........................................................................... 49
Figure 4-9: The thermal model at work..........................................................50
Figure 4-10: Variables of cooling needs, taken from heat calculation.........50
Figure 4-11: Reading of Excel files in MATLAB code ...............................51
Figure 4-12: Initialization of Arrays and Matrices .....................................51
Figure 4-13: Sum up of electrical energy consumed .................................52
Figure 4-14: Iteration part and calculations of the program .......................53
Figure 4-15: Output lines ...........................................................................54
Figure 4-16: Monthly results; 1 = heating, 2 = cooling, 3 = total .............55
Figure 4-17: March 15th 2014 ...................................................................56
Figure 4-18: June 8th 2014 .......................................................................57
Figure 4-19: November 10th 2014 .................................................................58
Figure 4-20: Monthly electric energy needs and production ...................59
Figure 4-21: Azimuth angle ........................................................................63
Figure 4-22: Roof satellite view of the B18 building ....................................65
Figure 4-23: Estimating the area of the roof ................................................66
Figure 4-24 Panels configuration no.1 ..........................................................71
Figure 4-25 Panels configuration no.2 ..........................................................71
Figure 4-26: Roof satellite view with drawing of panels .............................72
Figure 4-27 The model of the B18 building ..................................................73
Figure 4-28 Heating program with increased ventilation (0.4→0.5) ..........78
Figure 6-1: Gantt chart of the project ...........................................................88
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Air conditioning</td>
</tr>
<tr>
<td>Q</td>
<td>Energy</td>
</tr>
<tr>
<td>COP</td>
<td>Coefficient of Performance</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>ESEER</td>
<td>European Seasonal Energy Efficiency Ratio</td>
</tr>
</tbody>
</table>
1. Introduction

1.1 Motivation

This project is a part of the European Project Semester (EPS) at the Technical University of Lodz. As such, from all the different project possibilities, this was chosen by all the members of the team.

Everyone wants to work in a pleasant and comfortable environment. Furthermore, this value is also an important part of the working conditions that many developed countries regulate by law. What is more, not only developed countries like European ones and the USA, but also developing countries have a huge cooling demand.

While this is a good development for office workers, providing the cooling and heating comfort requires quite a big amount of energy. Actually, finding the right balance between those two standards is a problem for many companies that struggle with paying the energy bills.

1.1.1 World energy crisis

All of this has to be seen in the context of the world’s huge increase in demand for energy. If the current path continues, the following graph shows the growth over the next years:

![Fig 1-1: World energy consumption forecast](image)

As everyone can see, the need is rising exponentially. With a limited supply of oil and coal, which are our main energy suppliers, this will become a bigger issue every year it is not solved.
1.1.2 Potential markets

As you could already see in the energy consumption chart exposed in Fig. 1-1, the importance of the Asian market is growing steadily.

Fig 1-2: Importance of Asian market

This is confirmed by almost all sources, but where does this trend come from? Well, the main buyers of AC units are persons and companies living in countries that have a) a strong need for cooling, mainly tropical or subtropical regions and b) can afford to spend money on the ‘luxury’ of air conditioning. As it is shown on the next page, this is particularly the case in India and China, which together house about one third of the world population. Looking back to the energy consumption, those are also the main consumers or electrical energy.
Figure 3: Satellite-derived solar resource map

Fig 1-3: World solar irradiation
Fig 1-4: Estimated world cooling needs standardized to USA
1.1.3 Conclusion

Given this context, there is a real need for clean and renewable energy usage. This project focused on the air conditioning since there is an opportunity to show the feasibility on a real project in a country not known for its particularly strong sun. If Solar Cooling is not only possible, but also economically viable in Poland, it can also be realized in the countries better suited for it (see Fig 1-3).

1.2 Project

1.2.1 Definition

The project is very well defined by its name: SCOOL, which stands for solar cooling. It tries to give an example of a comfortable working environment made possible by green solar energy.

It is aimed to deliver the Technical University of Lodz (TUL) the planning of a fully functional air conditioning unit running on solar power for one of their buildings, the Department of Microelectronics and Computer Science (shortened DMCS), with the building number B18.

1.2.2 Approach

How is this tried to be achieved? First of all, it is clear that, in the course of this EPS project, these problems cannot be approached on a large scale.

But can be shown that it is possible to achieve one’s cooling needs without taking any energy from the grid in a country that is not optimal for gaining solar power. It is not claimed that this is, in any way, a solution the energy crisis described before, but it is shown that the possibility for change exists.

The goal of this project is to evaluate an optimal cooling system for the building B18. Two main factors have to be taken in consideration:

- Cost effectiveness

  For the cooling system to become solar powered, the switch has to make sense economically. It must have a reasonable ratio con-
sidering the money the university may spend on it and the saving it is going to get from it.

➢ Energy efficiency

The developed system should make the best use possible out of the electrical energy it takes. Technically speaking, this is reflected in a high the ‘European Seasonal Energy Efficiency Ratio’ (ESEER) coefficient, which is the amount of cooling supplied per unit of electrical energy used. But this will be covered in detail in the results section when using this coefficient.

1.2.3 Scope

While guided by the broad goals set before, it is followed a practical approach by designing an actual AC unit under clear, precise conditions.

➢ Main work

In order to be able to deliver the project on time, certain steps had to be followed, as you can see in the Gantt-Chart (Fig.6-1). All the steps were necessary to successfully finish this project and are explained below.

The research part was necessary to give an understanding of the physical and technical challenges that were being faced. While some of the members had an engineering background and thus have a basic understanding of physics and thermodynamics, none of them have worked on a project like this before. This meant that gaining some knowledge about quite a few things was needed, such as:

1. What factors influence the temperature in the building?
2. What is the exchange rate with the outside temperature?
3. What kinds of air conditioning units exist today, how are they working and which ones are viable for the building this project was dealing with?
4. How can solar energy be effectively used in those units?

The technical planning started when the research part was finished. Then different problems were faced, foremost the question of how the data analysis and calculations found necessary based on the research could
be implemented. This step also included calculating the factors and building properties necessary for the implementation.

The final part of the technical work had to be the actual implementation of a thermal model (see Chapter 4.4 for details) in a program and verifying the results. With these, the data needed for developing the actual scope of the air conditioning unit needed for the building could be obtained, which was crucial knowledge for the design.

As the last step of our work, the business side of the project was evaluated. While the question if it was possible to power the whole unit just with solar energy was trying to be answered, also wanted to know if it was economic to do so.

While working on these main steps, a website for our project was being developed. The main aim of the webpage is to show and share the work done in this project. Bonus feature: As an additional output of this project, an open web-based calculator that everyone can use to get an estimation of the costs of getting a solar-based AC unit.
2. SCOOL Team

It is a great pleasure to introduce the team members, team name and the logo. The team members are a group of people that have been working together with devotion for the past few months under the supervision of PhD Witold Marańda and PhD Maciej Piotrowicz to achieve the goal of providing a finished project work that, hopefully, will be a source of knowledge to both laymen and professionals.

2.1 Team Logo and Name

Name: SCOOL. The name of the team is a simple abbreviation of the project’s title – solar cooling. The idea for this name came from the team’s supervisors right at the beginning. It refers not only to the project’s purpose, but also to the learning and researching part of it, by sounding similar to the word ‘school’.

![Team Logo](image)

Figure 2-1: Team Logo

The logo of the team in its simplicity refers to the two factors of our project. The yellow sun and the air conditioning cooling effect connected often with the blue colour. It may also reflect the attractive side of the idea. Its simplicity is aimed at the ability to print logo on products, posters, leaflets, making it highly recognizable within the society. The logo is a visual representation of the name and structures more detail to the aspects of the project.
2.2 Team Members

Magdalena Banasiak

E-mail: 181406@edu.p.lodz.pl

Third year student of Information Technology at the Technical University of Lodz. Web technologies passionate, creative mind of the team.

Michael Leinen

E-mail: 901445@edu.p.lodz.pl

Third year student of Industrial Engineering at the Hochschule für Technik und Wirtschaft des Saarlandes. Born team leader, perfect work organizer.

Miquel Gabaldà

E-mail: 901318@edu.p.lodz.pl

Sixth year student of Industrial Engineering at the Universitat Politècnica de Catalunya : Escuela de Ingeniería de Terrassa. Technical mind, fluent in the field of ideas implementation.

Álvaro Royes

E-mail: 901451@edu.p.lodz.pl

Fourth year student of Industrial Engineering at the Universitat de Girona. Technical work organizer and a very good researcher. Helps the team in the direction definition and goal realization.

Pierre Mahé

E-mail: …@edu.p.lodz.pl

Third year student of International Business at the Ecole Supérieure de Commerce de la Rochelle. Team’s marketing specialist. Takes care of the business plan and costs evaluation.
2.3 Team Roles

2.3.1 Leader

In the Fig. 2-7 there is presented a Belbin diagram [1] of Michael Leinen. There it can be seen that he has very well developed senses of shaper and monitor evaluator. This has confirmed our team choice of a strong, motivated leader, who will help us to conduct the project in a proper way.

2.3.2 Specialist (Business)

In the Fig. 2-8 there is presented the Belbin diagram of Pierre Mahé. It shows that Pierre is of course a Team Worker, but also a very good Specialist. He takes care of his field in the project. Therefore he was chosen to be our devoted business specialist for which role he is the best suited person among all the members.

2.3.3 Implementer

In the Fig. 2-9 there is the Belbin Diagram of Miquel Gabaldà. It proves that Miquel is an inborn implementer, resource investigator and plant. It places him in the role of a very independent developer and a true engineer. For our team he has become a person responsible for implementing the projects goal.
2.3.4 Coordinator

In the Fig. 2-10 there is presented the Belbin diagram of Álvaro Royes. It shows that he is a perfect coordinator, and he has proven that during the Project work. He handles all the team activities, organizes our time and tasks. For our team he is very important due to the fact he is responsible for making team meeting minutes.

2.3.5 Plant

In the Fig. 2-11 there is presented the Belbin diagram of Magdalena Banasiak. It shows that she is a very good plant and team worker. She has contributed to generating as many solution ideas as possible and being creative engine of the team during the project work and presentations.

2.4 Communication tools

For working properly and efficiently on the project as a group, many tools and applications were used to communicate within the members. Taking in consideration that everyone got an internet connection and is theoretically always reachable, all of the different tools, except for the meetings, of course, were digital and free-to-use, such as email services, WhatsApp, Dropbox and Skype.

2.4.1 Team Meetings

The main and vital communication method within the team throughout the whole project were definitely the organized team meetings, usually two to three times a week. In the private room at IFE, the
team has been meeting in order to organize work, prepare the agenda together, talk, motivate and of course realise tasks. The meeting’s durations varied, depending on the period of the semester and the amount of work that had to be done. As a team, these meetings really helped us develop a project in its final shape, putting an altogether effort.

2.4.2 Supervisor meetings

The meetings with the supervisors were held at least weekly throughout the whole project scope. These have been very useful mainly because of the knowledge and experience that our supervisors have shared with the team while leading it to the final project’s solution. Their guidance was a priceless contribution to the project’s final shape and to the goal realization.

2.4.3 Email services

The email services have been used to reach the supervisors and fix the meetings with them. Furthermore e-mails were used to contact any of the project’s stakeholders – for example companies producing air conditioning devices or photovoltaic solar panels. The very important advantage of e-mails is the ease at which the team could keep track of all the exchanged messages during the whole semester.

2.4.4 WhatsApp

WhatsApp [2] was used daily, used to chat with the different members of the team. A SCOOL group of WhatsApp was created and was used to set up meetings, discuss any news or unexpected events as well as share pictures of the meetings and minutes. This app took a really important role in the team’s communication methods.

2.4.5 Dropbox

Just as WhatsApp was the most important for chatting with all members of the team, Dropbox [3] was the main cloud hard-drive where all the documents, programs and the other images were saved. With 2GB of free space and its back-up ability restore deleted files, the
project team could share the work done in a really easy and simple way.

2.4.6 Skype

Last but not least, Skype [4] calls were used during some team meetings. This program was helpful when one of the members of the team could not make it to a meeting but it was necessary to discuss important aspects of the project as a whole team.
3. Physical Foundation

In order to be able to develop the best system possible, the team had to understand how the world of air conditioning works on the physical level.

3.1 Heat transfer mechanisms

Everyone who has ever accidentally touched a hot plate can confirm that heat in general ‘flows’ from a hot object or environment or a colder one when they are in contact. It follows a basic law of nature to get to equilibrium. But how exactly is it possible to ‘move the heat’ or better ‘energy’ from one system to another?

There are three ways how heat can move from or to one system. In our case, the most important system to take into consideration is, of course, a building. The transfer mechanisms are called Conduction, Convection and Radiation. All of these are important to take into consideration when analysing the energy needs of an air conditioning device for a given building [5]:

![Figure 3-1: Heat transfer mechanisms](image)

Here is explained how each of them works in detail and how they have to be taken into account:
3.1.1 Conduction

This is the first and probably most basic principle. When two systems of different temperature are in direct physical contact (remember the hand on the hot plate!), heat is transferred from the hotter to the colder system. Keep in mind that the second system does not have to be another object, but may very well be the outside air! This is why in the actual case this principle is used to calculate energy losses through the buildings’ walls, windows and roof.

In its most basic form, the calculation for heat transfer [6] though conduction at a building wall looks like this:

\[ Q = k \cdot A \cdot \Delta T \cdot t \]

With

- \( Q \) = Energy [J]
- \( A \) = Surface area \([m^2]\)
- \( \Delta T \) = Temperature difference \([K]\)
- \( t \) = Time \([s]\)
- \( d \) = Diameter of the wall \([m]\)
- \( k \) (=U) = Heat transfer factor of the wall \([J/m^2\cdot K]\)

In graphical form [7]:

![Conduction heat transfer through a simple wall](image)

Figure 3-2: Conduction heat transfer though a simple wall

This means that the amount of energy transferred though the wall is dependent on the exposed area and time, the temperature difference and
a wall factor $k$ (or for a multi-layer wall: the $u$-value), which depends on the materials and structure of the wall (e.g. isolation materials).

3.1.2 Convection

This type of heat transfer is based on moving particles, for example water or air flow. It is the reason why fish can survive in an apparently frozen lake and radiators heat an entire room.

In the case of B18 building, convection is responsible for taking heat faster from the walls. But far more important is the impact it has by moving through open doors/windows into and out of the building (Eq. 2 and 3). While this is important for hygienic reasons, on hot days it also carries a lot of energy into the building if the air is hot, or provides free cooling!

\[
Q = h \cdot S \cdot \Delta T \cdot t
\]  

(2)

Circular air flow effect (see Fig. 3-3)

\[
Q = \text{Energy} \ [\text{J}]
\]

\[
S = \text{Surface area} \ [\text{m}^2]
\]

\[
\Delta T = \text{Temperature difference} \ [\text{K}]
\]

\[
t = \text{Time} \ [\text{s}]
\]

\[
h = \text{Air convection constant} \ 1.77 \cdot T^{0.25} \ [\text{J/(s} \cdot \text{m}^2 \cdot \text{K})]
\]

\[
Q = V_c \cdot A \cdot h \cdot t
\]  

(3)

Natural ventilation and free cooling impact.

\[
Q = \text{Energy} \ [\text{J}]
\]

\[
V_c = \text{Cooling Ventilation} \ [\text{L/s/m}^2]
\]

\[
h = \text{Room height} \ [\text{m}]
\]

\[
A = \text{Building size} \ [\text{m}^2]
\]

\[
t = \text{Time} \ [\text{s}]
\]
3.1.3 Radiation

Last but not least, in a project concerned itself with solar energy, radiation plays a major role. In contrast to both other forms, radiation does not need a medium to transfer energy. All that is taken into account (except for constants) is the size of the body and the temperature:

$$ Q = \sigma \cdot e \cdot A \cdot T^4 \cdot t $$

General radiation equation.

- $Q$ = Energy [J]
- $A$ = Surface area [$m^2$]
- $T$ = Temperature [K]
- $t$ = Time [s]
- $\sigma$ = Constant [W/m²·K⁴]
- $e$ = emissivity of material (0-1)

Solar radiation is measured as energy per square meter over time, and is important for this project for two reasons:

First of all, since the project is using photovoltaic (PV) arrays to transform solar into electrical energy, knowledge of the irradiation allows us to calculate the square area that has to be covered by solar arrays to fit the energy demand. (more on this in the results subchapter)
Secondly solar irradiation actually heats up the building, especially when much of its surface is covered by windows, as it is the case of B18 one. Though this aspect may be easily forgotten, it has a huge impact on the energy balance calculated in the project’s model!

Calculating the second impact is quite tricky. The calculations were based on a paper [8], whose formula was used with the radiation data from a sensor and the estimation for the u-value of the building.

### 3.2 Standard AC design

How these basic principles are applied in the AC devices of the modern world?

#### 3.2.1 Carnot cycle

To explain how the system can cool down a building, some basic knowledge of thermodynamics may be needed. It is therefore necessary to explain the physics involved in the so called ‘Carnot cycle’ [9].

The Carnot cycle is a theoretical thermodynamic model proposed by Nicolas Léonard Sadi Carnot in 1824. It is the most efficient method for converting a given thermal energy to mechanical or electrical energy and, conversely, creating a temperature difference given a certain amount of power. This cycle is reversible, which means that can operate both ways; extracting or introducing heat.

To explain the different stages of the Carnot cycle, a heat pump configuration will be used. It should be remembered that a Carnot cycle can be reversed and work as an extractor of heat (cooling configuration) instead of supplying heat to the desired area. As the cycle is theoretically reversible, the assumption that it is working with ideal gases must be done. The four stages of the refrigerant gas in the Carnot cycle are the ones shown in Fig. 3-4 and 3-5:
Figure 3-4: P-V diagram of the Carnot cycle

Figure 3-5: T-S diagram of the Carnot cycle
The Carnot cycle shown in the Pressure – Volume diagram shows two isothermal lines (temperature doesn’t change) and two adiabatic processes. The second diagram shows the same cycle from the perspective of Temperature – Entropy. The explanation of these four steps is the one following:

1→2 A→B. **Isothermal expansion.** The gas is expanded without changing its temperature. As the gas is expanding, you would expect the pressure to drop and the gas to cool down. However, to keep on the same temperature as before expanding, the gas absorbs heat from the outside. This step also causes an increase of the entropy.

2→3 B→C. **Isentropic and adiabatic expansion.** At this point the system is in thermal isolation so the gas doesn’t gain or lose energy. This adiabatic expansion forces the gas to cool down to the lower temperature level. In this process the entropy remains unaffected.

3→4 C→D. **Isothermal compression.** The fluid is compressed and would usually gain temperature (reverse back to 2). Instead, this thermal energy is taken out of the cycle to cool something on the outside, making this step isothermal. As its internal temperature doesn’t change, but the gas is compressed, the system loses energy. The entropy of the system needs to drop.

4→1 D→A. **Isentropic and adiabatic compression.** Again in thermal isolation, this step is compressing the gas even further. This time gets its temperature raised but, since no energy can escape, the entropy unchanged. At this point in the idealized process the gas is back to the same state as at the start of step 1, making it possible to start over.

The Carnot cycle is the ideally efficient. However, in reality there are a few changes; as the entropy of a material changes with temperature, losses of heat because the system is not always totally isolated and there also exist losses due to friction. In Fig. 3-6 one can see the differences between a real and an ideal Carnot cycle.
It is useful to know that the maximum amount of heat that the cycle is able to deal with (which also can be expressed as work) is the area contained of the 4 steps of the P-V diagram. The bigger the compression and the expansion of the gas, and the larger the range of temperatures, the more work is done by the gas.

$$W = \int_{V_a}^{V_b} P \cdot dV = \int_{V_a}^{V_b} \frac{nRT}{V} dV = nRT \ln \frac{V_a}{V_b}$$  \hspace{1cm} (5)

Focusing the theory in one isothermal line the graph is like shown in Fig. 3-7:

Figure 3-7: Isothermal expansion from a to b along $PV=nRT$
3.2.2 AC unit.

The three basic components of any AC unit system are the compressor, the condenser coil and the evaporator coil (also known as cooler).

The compressor and the condenser coil are situated outside the building, while the cooler is inside, as this is the area desired to cool.

This process follows the same principles as the ideal cycle, but with inverted signs. This means, compared to the cycle presented in 3.2.1, it starts and ends in state 3.

The refrigerant fluid (3) flows inside the pipes of the system extracting heat at the cooler from the surroundings, changing from the liquid to the gaseous state (4) by expanding (Carnot 3→4). The gas flows then to the compressor, where no heat exchange takes place, but the temperature of the gas increases due to the volume reduction (Carnot 4→1). At that point, after the compressor, the gas is saturated (1). Following the compressor the condenser is found, which allows the gas to give away the heat to the outside environment (Carnot 1→2) and turn into saturated liquid (2) due to heat loses. Finally, the refrigerator runs to the expansion valve that lets the fluid gain volume again and drop the pressure (Carnot 2→3). Before entering the evaporator again, the refrigerant is found partially in a liquid and the rest in a gaseous state (3). See Fig. 3-8:
It is important to note the refrigerator state in each step. When the fluid enters one component, physical changes connected to thermodynamics occur. As commented before, the refrigerator keeps changing state from liquid to gas and vice versa and that is the basic operating principle behind the refrigeration cycle.

3.3 Solar Cooling Systems

As the main goal of this project is cooling a building using the sun’s energy, as photovoltaic (PV) or thermal systems, consisting of arrays of solar panels or collectors are the systems that may come first to mind. In fact, these both systems are only two of the different ways of using solar energy, although there are also other different options; concentrated solar power (CSP) and passive solar techniques that use the solar energy without any electrical appliances in the process also exist.

Focusing the research for most common systems, the electrical and thermal, it is possible to find the follow classification [10]:

![Basic Refrigeration Cycle Diagram](image-url)
As it is shown, there are many different options but not all of them are accessible in the market. That is why the team’s study was about the electric processes by solar panels and closed cycles for the thermal process.

3.3.1 Photovoltaic Systems

After doing research and evaluating the different range of techniques that could be used, the PV system was chosen as one of the possibilities of getting the electrical energy needed to power a conventional AC system, economically evaluated it in chapter 5.

![Figure 3-10: Panels of a photovoltaic power field](image)

To understand what is happening, an explanation of how a PV system works can be read in the following paragraphs.
First it is important to understand the general structure of the PV installation. The PV system is composed of solar panels, an inverter and a main fuse box that allows the system to be connected to the grid and to the building/appliances which need electricity to operate [11].

![PV System Components](image)

**Figure 3-11: Basic PV system components**

The solar modules are covered by solar cells and they produce electricity from the radiation given by the sun. These solar cells are made of different materials depending on its generation. Cells can be classified into first, second and third generation cells. The first generation cells — also called conventional, traditional or wafer-based cells — are made of crystalline silicon, the commercially predominant PV technology, that includes materials such as polysilicon and monocrystalline silicon. Second generation cells are thin film solar cells that include amorphous silicon, CdTe and CIGS cells and are commercially significant in utility-scale photovoltaic power stations, building integrated photovoltaic or in small stand-alone power system. The third generation of solar cells includes a number of thin-film technologies often described as emerging photovoltaic — most of them have not yet been commercially applied and are still in the research or development phase. The basic physics behind are that those materials are semiconductor materials, which means that they are able to conduct electricity depending of the situation they are found.

As the panel arrays produces direct current (D/C), for better use or transportation the alternating current (A/C) is necessary since the whole Eu-
European electrical energy system operates with A/C. To convert D/C to A/C current the system needs an inverter.

Later on, the main fuse can be found in the system. It is important as it plays the role of switching the electricity flow depending on the demand and production and the time of the day. Taking a residential system as an example, at 7 a.m. many people are waking up to go to work and they use kitchen appliances, shower with hot water and put the laundry on. That requires a certain amount of electricity that cannot be obtained from solar energy due to the lacking of solar irradiation in the morning. To cover those electricity needs, energy is bought from the grid. On the other hand, at 2 p.m. when there is nobody at home but the radiation is pretty high, the PV system provides much more energy than needed by the building. This electricity is then sold to the grid to take profit from it and helping to cover someone else’s demands [12].

![Diagram showing residential demand vs. PV energy generation](image)

Figure 3-12: The residential demand vs. PV energy generation

While aware of this problem, buying energy from the grid during times of high demand and selling to it at other times is almost completely balanced. This is why the final PV solution based was designed based on the yearly consumption and also covering the overall needs instead of focusing on peak times (see Results).
In this way it is important to remark the PV systems evolution in recent years. It is obvious that the renewable energies’ market is a potential market around the world and it is being developed really quickly. A clear and simple example is the prices evolution of PV panels during the last 10 years [13]:

![Swanson effect chart](image)

Figure 3-13: Swanson effect chart

It is possible to see that the recent prices have become almost 90% smaller than 15 years ago while having much higher efficiency and overall quality.

3.3.3 Thermal System

Talking about thermal methods for air conditioning systems, it makes reference to thermodinamical systems based in water heating through the collection of solar energy.

As it has been mentioned at the beginning of the chapter, the thermal system was focused in closed systems based in the next scheme [14]:
Figure 3-14: Basic scheme of thermal system

In the scheme, it is possible to distinguish clearly the different parts of the system and the most important, the solar collectors and the chiller that are going to be explained:

a) Solar thermal collector

The solar collectors’ target is to transfer the heat kept from the solar radiation to the water that’s driving through them.

It’s possible to find two different types of collectors:

- Flat Plate

  The usual flat-plate collector is a metal box with a glass or plastic cover, called glazing, on the top and a dark-coloured absorber plate on the bottom. The bottom and sides are usually insulated to minimize the heat losses.

  Sunlight through the glazing and strikes the absorber plate, which heats up, changing solar energy into heat energy. The heat is transferred to liquid passing through pipes attached to the absorber plate. Absorber plates are commonly painted with "selective coatings," which absorb and retain heat better than ordinary black paint [15].
Furthermore, they are usually made of metal, typically copper or aluminium. Copper is more expensive, but is a better conductor and less prone to corrosion than aluminium. In locations with average available solar energy, flat plate collectors are sized approximately one-half- to one-square foot per gallon of one-day's hot water use.

- Evacuated tubes

  It is known that convection heat losses due to air movements inside the flat-plate collectors are a real problem. These losses could be reduced by maintaining a vacuum between the front cover and the absorber of a flat-plate collector. The flaw factor is the difficulty to maintain the vacuum over a long period of time, due the ambient air will always find a way to get into the collector. These disadvantages can be avoided with evacuated-tube collectors.

  The high (almost complete) vacuum inside the closed glass tube of the evacuated-tube collector [16] is more stable over a long period of time than in an evacuated flat-plate collector. Due to their shape, glass tubes can better resist the ambient air pressure, and therefore no supports are needed between the back and front sides.
An evacuated-tube collector comprises a closed glass tube, inside which is a metal absorber sheet with a heat pipe in the middle, containing a temperature-sensitive medium such as methanol. The sun heats up and vaporizes this heat pipe fluid, and the vapour then rises to the condenser and heat exchanger at the end of the pipe. There, the vapour condenses, and transfers heat to the heat carrier of the solar cycle, water with antifreeze agent [17].

![Figure 3-17: Mechanism of a heat exchanger](image)

The condensed fluid flows back to the bottom of the heat pipe where the sun begins heating it up again. A cross-section of the evacuated-tube collector and the principle of its operation it is shown in Figure 3-15.

b) Chiller

The chiller, which is used in thermodynamic solar systems like in this project, is a mechanical device used to facilitate heat exchange from water to a refrigerant in a closed loop system.

- Absorption

The basic physical process consists of two chemical components, the refrigerant and the sorbent. The majority of absorption chillers use water as refrigerant and liquid lithium-bromide as sorbent. The required heat source temperature is usually above 85ºC and typical COP values are between 0.6 and 0.8.
Currently, the chillers are designed to be operated with low driving temperatures and thus applicable for stationary solar thermal collectors. In addition to the traditional working fluids H₂O/LiBr, also H₂O/LiCl and NH₃/H₂O are applied [18].

![Diagram of a thermally driven single-effect absorption chiller](image)

**Figure 3-18:** Scheme of a thermally driven single-effect absorption chiller

Compared to a conventional electrically driven compression chiller, the mechanical compression unit is replaced by a “thermal compression” unit with absorber and generator. The cooling effect is based on the evaporation of the refrigerant in the evaporator at low pressure. Due to the properties of the phase change, high amounts of energy can be transferred. The vaporised refrigerant is absorbed in the absorber, thereby diluting the refrigerant/sorbent solution. Cooling is necessary to run the solution is achieved by applying driving heat. The refrigerant leaving the generator by this process condenses through the application of cooling water in the condenser and circulates by means of an expansion valve again into evaporator.

- Adsorption

Beside processes using a liquid sorbent, also machines using solid sorption materials are available. This material adsorbs the refrigerant, while it releases the refrigerant under heat input. Market available systems use water
as refrigerant and silica gel as sorbent, but at the moment, there already are systems using zeolithes as sorption material.

Typical COP values of adsorption chillers are between 0.5 and 0.6. Advantages are the low driving temperatures (since 60°C), the absence of solution pump and the comparatively noiseless operation.

![Diagram](image)

Figure 3-19: Scheme of an adsorption chiller

The adsorption chillers consist basically of two sorbent compartments 1 and 2, as it’s shown in the Figure 3-19, and the evaporator and condenser. While the sorbent in the first compartment is desorbing (removal of adsorbed water) using hot water from the external heat source, as solar collectors, the sorbent in the second compartment adsorbs the refrigerant vapour entering from the evaporator; this compartment has to be cooled in order to increase the process efficiency. The refrigerant, condensed in the cooled condenser and transferred into the evaporator, is vaporised under low pressure in the evaporator. Here, the useful cooling is produced. Periodically, the sorbent compartment are switched over in their functions from adsorption to desorption. This is usually done through a switch control of external located valves.

The next chart shows a resume of both chillers:
<table>
<thead>
<tr>
<th>Type of refrigerant cycle</th>
<th>Closed Refrigerant flows in closed cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principle</td>
<td>Chilled water</td>
</tr>
<tr>
<td>Phase of sorbent</td>
<td>Solid</td>
</tr>
<tr>
<td>Typical material duo</td>
<td>Water - silica gel</td>
</tr>
<tr>
<td></td>
<td>Water - water/lithium bromide, ammonia- water</td>
</tr>
<tr>
<td>Available technology</td>
<td>Adsorption chiller</td>
</tr>
<tr>
<td>Typical cooling capacity</td>
<td>5.5 - 500 kW</td>
</tr>
<tr>
<td>Typical coefficient of performance</td>
<td>0.5 - 0.7</td>
</tr>
<tr>
<td></td>
<td>(single effect)</td>
</tr>
<tr>
<td>Typical driving temperature</td>
<td>65 - 90 ºC</td>
</tr>
<tr>
<td>Solar collectors</td>
<td>tubes, flat plate</td>
</tr>
</tbody>
</table>

Figure 3-20: Comparison of the two different types of chillers
4. System Modelling

Doing research of the market size after evaluating the current problem and studying the multiple possibilities was just the clean job. The key point of this project is to actually develop the system itself. In this chapter will be explained how the project evolved step-by-step.

4.1 Equations

However, before explaining how the system was developed, a basic thermodynamics level is required. The purpose of this subchapter is to get you familiar with the equations and further methods used. If you are already acquainted with thermodynamics you should skip to next chapter 4.2.

**Transmission heat losses (based on Eq. 3.1)***

\[ q_t(t) = U \cdot S \cdot (T_{out}(t) - T_{int}) \]  

Where:

- **U** is the average thermal transmittance of the building envelope (W/m\(^2\)K)
- **S** is the overall surface of the building envelope (m\(^2\))
- **T\(_{out}\)(t)** is the instantaneous outdoor air temperature (ºC)
- **T\(_{int}\)** is the fixed indoor air temperature (ºC)

The **T\(_{out}\)** is provided in a Weather file.

**Ventilation heat losses (based on Eq. 3.2 and 3.3)**

- Sanitary ventilation

\[ q_{vSa}(t) = V_c \cdot A \cdot \frac{(\rho \cdot C_P)_{a}}{1000} \cdot (T_{out}(t) - T_{int}) \]  

Where:

- **V\(_c\)** is the sanitary ventilation rate (l/s/m\(^2\))
- **c\(_{P a}\)** is the density of the air (1,2 kg/m\(^3\) at 20ºC and 30% relative humidity (Hageboft, 2005)
- **A** is the heated floor area in a building (m\(^2\))
- **T\(_{out}\)** is the ventilation temperature, which in this case correspond with outdoor temperature
- Natural ventilation

\[
q_{\text{Nat}}(t) = V_{cn} \cdot A \cdot (\rho \cdot C_p) \cdot (T_{out}(t) - T_{int}) \tag{8}
\]

Where \( V_{cn} \) is the airflow rate for natural ventilation (l/s/m\(^2\))

Total heat loss/gain due to the ventilation is then:

\[
q_v(t) = q_v{Sa}(t) + q_v{Nat}(t) \tag{9}
\]

**Solar Gains (based on Eq. 3.4)**

\[
q_r(t) = T_s \cdot W_c \cdot W_f \cdot S_w \cdot \text{Insolation}(t) \cdot 0.65 \tag{10}
\]

Where:

- \( T_s \) is the coefficient of solar transmission of the window (0-1)
- \( W_c \) is the shading coefficient of the window (0-1)
- \( W_f \) is the frame coefficient of the window (0-1)
- \( S_w \) is the total surface of windows of the building (m\(^2\))
- Insolation (t) is the global irradiation on horizontal surface (W/m\(^2\))

The values for Irradiation are provided in the Weather file.

The 0.65 is a coefficient to compensate the radiation on horizontal surface instead of vertical.

**Internal heat gains**

\[
q_{\text{int}}(f) = (\text{Elect}(f) + q_{occ} + q_{buis}) \cdot \frac{10^6}{30 \cdot 24 \cdot 60} \tag{11}
\]

Where:

- \( q_{\text{int}}(f) \) is the Internal heat gains for each temporal unit, (W)
- \( \text{Elect}(f) \) is the heat generation by electrical consumption from Lighting and Appliances, (W)
- \( q_{occ} \) is the heat generation by occupants, (W)
- \( q_{buis} \) is the heat generation by ventilation fans, (W)
For qocc, is considered 150 W/person and 100 people/day, 6h/day and 20 days/month, that means is 1.8MWh/month

**Total Heat Balance**

\[ q(t) = q_t(t) + q_v(t) + q_r(t) + q_{int}(t) \]  \hspace{0.5cm} (12)

If \( q(t) < 0 \) means it's heat demand \((q_{heat})\).
If \( q(t) > 0 \) means it's cooling demand \((q_{cool})\).

**Total Results**

**Total Transmission Losses**

\[ Q_T = \frac{1}{C} \int_{t_1}^{t_2} q_t(t) dt \hspace{0.5cm} [\text{MWh}] \]  \hspace{0.5cm} (13)

Where:

\( Q_I \) is the annual Transmission losses, \((\text{MWh})\)

\( C \) is the conversion factor from \( \text{Wmin} \) to MWh

**Total Ventilation Losses**

\[ Q_V = \frac{1}{C} \int_{t_1}^{t_2} q_v(t) dt \hspace{0.5cm} [\text{MWh}] \]  \hspace{0.5cm} (14)

Where \( Q_V \) is the annual Ventilation losses, \((\text{MWh})\)

**Total Solar Gains**

\[ Q_R = \frac{1}{C} \int_{t_1}^{t_2} q_r(t) dt \hspace{0.5cm} [\text{MWh}] \]  \hspace{0.5cm} (15)

Where \( Q_R \) is the annual solar gains, \((\text{MWh})\)
Total Internal Heat Gains

\[ Q_I = \frac{1}{D} \int_{1}^{12} q_{\text{int}}(t) df \text{ [MWh]} \]  

Where:

\( Q_I \) is the annual internal heats, (MWh)

\( D \) is the conversion factor from Wmin different month to MWh

Total Heat Demand

\[ Q_{\text{heat}} = \frac{1}{C} \int_{t_1}^{t_2} q_{\text{heat}}(t) dt \text{ [MWh]} \]  

Where \( Q_{\text{heat}} \) is the annual heat demand, (MWh)

Total Cooling Demand

\[ Q_{\text{cool}} = \frac{1}{C} \int_{t_1}^{t_2} q_{\text{cool}}(t) dt \text{ [MWh]} \]  

Where \( Q_{\text{cool}} \) is the annual Cooling demand, (MWh)

Total Demand

\[ Q_{\text{total}} = |Q_{\text{heat}}| + |Q_{\text{cool}}| \text{ [MWh]} \]  

Where \( Q_{\text{total}} \) is the total annual demand
4.2 Thermal properties of the building

In order to be able to use the equations in our program, the team obviously needed more than just the weather data. As it can be seen in chapter 4.1, the variables used required some knowledge about the building itself. This meant it had to be measured or, if this was not possible for any reason, estimated properties of the building B18 of the TUL.

4.2.1 Calculated values

These values are based on calculations or measurements. We are relatively confident that they are very close to the real values and thus do not lead to any measuring mistake.

a) The building surface and area (S, A)

Using the plans of the building that can be found in the Appendix section, the team was able to measure the ground and the outside area. The team also gained access to the roof to measure the height and the roof area.

Additionally, a distinction was made between actual walls consisting of bricks and glass surfaces like windows, doors and aesthetic features of the building. The reason here is a difference in the calculations: First of all, there is a distinction in the amount of heat that can leave the building through these surfaces, called the u-value (see next point). Additionally, the class area was needed to be able to calculate the solar irradiance going into the building and the heat resulting from it.

b) Overall Heat Transfer Coefficient (u-value)

This value is defined as “the quantity of heat transmitted through a unit thickness of a material - in a direction normal to a surface of unit area - due to a unit temperature gradient under steady state conditions”[1]. This obviously is an important value to know when calculating heat losses in a building. That is why the team tried to calculate it as correctly as possible using a free online tool [19]. First, the individual values for the different surfaces that are in contact with the outside air were calculated.
These are:

- Wall (thick)
- Wall with Glass
- Windows/Roof

Figure 4-1: The different surface types visible as windows and red-brick walls

For each of these surfaces, the thickness of the different parts they consist of had to be measured. For example, in Fig 4-2 you see the wall consisting of four different parts that combined result in the final value.
Figure 4-2: Calculation of the value for the wall (compare to Fig. 3-1)

The same calculations for the other two areas were done as well. But since it was poorly probable to know the exact parts the walls consisted of or the exact type of windows that were used, the team had to come at it from another angle as well. The exact energy consumption the building was using for heating in one month was provided by the supervisors. This value offered the possibility to do a kind of reverse engineering: from knowing how much the energy was used to heat the building, the calculated values, which already were close to the real ones, to fit the value given by the supervisors could be adjusted.
With the updated values, a precise combined u-value for the whole building could be computed, which was then used in the thermal model. This was simply done by calculating a weighted average:

\[
U_{\text{comb}} = \frac{U_{\text{wall}} \cdot A_{\text{wall}} + U_{\text{roof}} \cdot A_{\text{roof}} + U_{\text{window}} \cdot A_{\text{window}}}{A_{\text{total}}}
\]  
(20)

c) Heat produced by electrical devices and occupants \((q_{\text{elec}} + q_{\text{occ}})\)

Another aspect that can be easily overlooked is the amount of heat produced by electrical devices and humans. While this may seem strange to you to think of humans or computers as sources of heat, their impact should not be underestimated. Even modern light bulbs, which are installed in this building, do not have a good efficiency in terms of lumen per watt. In fact, the installed compact fluorescent lamps, which are with LEDs praised as the most efficient light sources, still produce only 7-10% of light with the used electricity; the remaining 90% are wasted as heat! With computers it is safe to assume that a similar value of the electrical energy ends up as waste heat. With
this knowledge, the electrical energy consumption of the building was provided by the supervisors and corrected it with a value of 0.9 to get the heating gained through these means.

For humans the calculations were a bit trickier. First, the average heat production of a person had to be found out. Luckily there are several researchers who were already interested in this phenomenon and provided their data to the public. [19]

According to these publications, an average human person emits about 50 Watts per square meter surface when resting up to a value of 250 W/m² for heavy work. Since office workers were not expected to do heavy lifting, a value of 100 W/m² was assumed as an average, which is the value emitted when reading or walking slowly.

4.2.2 Estimated values

For the following values it was impossible to get real data. Either the information was quite inaccessible (window properties) or barely impossible to measure (air flow in the building.) For these values, reasonable assumptions based on our sources were done.

a) Air flow ($V_c$ and $V_{cn}$)

Any house where people are staying for extended periods requires a certain degree of sanitary ventilation $V_c$. This is not only to keep the air fresh, but also because of humidity. The minimum value found for sanitary ventilation was 0.35 [8], going up to 0.5 [20]. Since the building is rather modern, which makes humidity less of an issue, but houses many people; a factor of 0.4 was chosen.

The natural ventilation, $V_{cn}$, describes the aspect of ‘free cooling’ due to air moving though the building. This, of course, requires a certain level of heat in the building, which is why it is a separated value from the sanitary ventilation. Here was assumed a rather high value of 0.8 (for the impact see results) while the conditions are met. The reasons are that the building has many windows and it was observed that the doors were often left open on warmer days. Even on colder ones they often were open for longer periods of time due to the fact that many people entered and exited the building.
b) Window properties \((T_s, W_c)\)

For these values, finding useful data was completely impossible to be found. Although knowing the manufacturer of the windows in the structure, these variables were neither described on the internet or any sources with access to. This is why standard values for both were assumed (after talking with the supervisors, who have more experience in these matters).

### 4.3 Methodology

To design the optimal cooling system, the cooling demand was the main factor to analyse. Obviously, this demand was not written anywhere nor there were studies that already predicted the cooling needs, so estimating these needs was an extensive work load in this project. To get the result, a program was written.

However, to code that program, some ‘reverse engineering’ had to be done. After acquiring the heating needs of the building, a program that estimated the same heat demand as the heating system readout was written. With the many parameters shown in 4.2.1 it was able to adjust the other ones in 4.2.2 and finish the program that estimated the heating demand (details follow in 4.5.1).

From the heating demand program to the cooling demand program the changes are rather small, as basically have the same structure, only changing the direction of the heat transfer.

### 4.4 Data collection and analysis

As commented before, to develop the programs, a real reference, a real reading of the building demand was needed. The weather data of the building's location were needed as well. The supervisors provided SCOOL with the heating data for the building for the whole March of 2015 and the weather information for the same month. The weather data spreadsheet contained the temperature, the insolation, the atmosphere pressure, the wind speed, the wind direction and the humidity in intervals of one minute. Having all this records in one document, a filter was needed.
To analyse the weather data, a second spreadsheet was built where only the environmental temperature and insolation details were considered. This document was done to make it easier for the future program to read the weather data. As the units where in SI and already fit the equation units, no changes had to be done in order to proceed with the calculations.

Once the program calculating the heating demand was done and fitted the real demand, the supervisors handed the team the weather information for the full year 2014. With the data in this new spreadsheet the cooling needs of the building should be estimated for the whole year. This data was treated like the March 2015 spreadsheet and it was separated by columns with the correct format for the program to read.

Fig 4-4 shows a part of a screenshot of the weather data. This data is from the 08/06/2014 and around 18:30h. It shows how the first column (A) is the day column, followed by the temperature (B), the insolation (C), the wind direction (C, in an angular degree indicator, being 0 and 360 North and 180 South), the wind speed (D), the air humidity (E), the time of the day in intervals of one minute (F) and the digit that indicates which month is it (G). This digit was just added to simplify the work when programing the code in MATLAB; later on is explained why.
<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>288307</td>
<td>08/06/2014</td>
<td>30.6</td>
<td>317.9</td>
<td>105</td>
<td>1,2</td>
<td>33,6</td>
<td>18:21:00</td>
</tr>
<tr>
<td>288308</td>
<td>08/06/2014</td>
<td>30.6</td>
<td>314.6</td>
<td>82</td>
<td>0,2</td>
<td>33,5</td>
<td>18:22:00</td>
</tr>
<tr>
<td>288309</td>
<td>08/06/2014</td>
<td>30.6</td>
<td>310.6</td>
<td>65</td>
<td>0,7</td>
<td>33,3</td>
<td>18:23:00</td>
</tr>
<tr>
<td>288310</td>
<td>08/06/2014</td>
<td>30.6</td>
<td>307.9</td>
<td>91</td>
<td>0,4</td>
<td>33,7</td>
<td>18:24:00</td>
</tr>
<tr>
<td>288311</td>
<td>08/06/2014</td>
<td>30.5</td>
<td>306.4</td>
<td>24</td>
<td>0,5</td>
<td>33,7</td>
<td>18:25:00</td>
</tr>
<tr>
<td>288312</td>
<td>08/06/2014</td>
<td>30.5</td>
<td>304.1</td>
<td>347</td>
<td>0,7</td>
<td>34,3</td>
<td>18:26:00</td>
</tr>
<tr>
<td>288313</td>
<td>08/06/2014</td>
<td>30.5</td>
<td>301.5</td>
<td>7</td>
<td>0,4</td>
<td>33,5</td>
<td>18:27:00</td>
</tr>
<tr>
<td>288314</td>
<td>08/06/2014</td>
<td>30.5</td>
<td>297.5</td>
<td>13</td>
<td>0,8</td>
<td>33,6</td>
<td>18:28:00</td>
</tr>
<tr>
<td>288315</td>
<td>08/06/2014</td>
<td>30.5</td>
<td>294.3</td>
<td>54</td>
<td>0</td>
<td>33,5</td>
<td>18:29:00</td>
</tr>
<tr>
<td>288316</td>
<td>08/06/2014</td>
<td>30.5</td>
<td>291.1</td>
<td>137</td>
<td>0,8</td>
<td>33,3</td>
<td>18:30:00</td>
</tr>
<tr>
<td>288317</td>
<td>08/06/2014</td>
<td>30.4</td>
<td>288.3</td>
<td>28</td>
<td>2</td>
<td>34,1</td>
<td>18:31:00</td>
</tr>
<tr>
<td>288318</td>
<td>08/06/2014</td>
<td>30.4</td>
<td>285.8</td>
<td>39</td>
<td>0</td>
<td>33,9</td>
<td>18:32:00</td>
</tr>
<tr>
<td>288319</td>
<td>08/06/2014</td>
<td>30.4</td>
<td>282.4</td>
<td>356</td>
<td>0</td>
<td>33,8</td>
<td>18:33:00</td>
</tr>
<tr>
<td>288320</td>
<td>08/06/2014</td>
<td>30.4</td>
<td>280.2</td>
<td>105</td>
<td>0</td>
<td>33,9</td>
<td>18:34:00</td>
</tr>
<tr>
<td>288321</td>
<td>08/06/2014</td>
<td>30.5</td>
<td>278.6</td>
<td>122</td>
<td>1</td>
<td>33,7</td>
<td>18:35:00</td>
</tr>
<tr>
<td>288322</td>
<td>08/06/2014</td>
<td>30.5</td>
<td>274.6</td>
<td>176</td>
<td>0</td>
<td>33,4</td>
<td>18:36:00</td>
</tr>
<tr>
<td>288323</td>
<td>08/06/2014</td>
<td>30.5</td>
<td>272.8</td>
<td>38</td>
<td>2,2</td>
<td>33,9</td>
<td>18:37:00</td>
</tr>
<tr>
<td>288324</td>
<td>08/06/2014</td>
<td>30.4</td>
<td>268</td>
<td>114</td>
<td>0</td>
<td>33,3</td>
<td>18:38:00</td>
</tr>
<tr>
<td>288325</td>
<td>08/06/2014</td>
<td>30.4</td>
<td>265.3</td>
<td>107</td>
<td>2,3</td>
<td>33,5</td>
<td>18:39:00</td>
</tr>
<tr>
<td>288326</td>
<td>08/06/2014</td>
<td>30.4</td>
<td>261.8</td>
<td>6</td>
<td>0</td>
<td>34</td>
<td>18:40:00</td>
</tr>
<tr>
<td>288327</td>
<td>08/06/2014</td>
<td>30.4</td>
<td>259.6</td>
<td>98</td>
<td>0</td>
<td>34</td>
<td>18:41:00</td>
</tr>
<tr>
<td>288328</td>
<td>08/06/2014</td>
<td>30.3</td>
<td>258.2</td>
<td>40</td>
<td>0,4</td>
<td>34,6</td>
<td>18:42:00</td>
</tr>
<tr>
<td>288329</td>
<td>08/06/2014</td>
<td>30.3</td>
<td>255.3</td>
<td>64</td>
<td>0</td>
<td>34,7</td>
<td>18:43:00</td>
</tr>
<tr>
<td>288330</td>
<td>08/06/2014</td>
<td>30.3</td>
<td>251.6</td>
<td>138</td>
<td>0,8</td>
<td>34,5</td>
<td>18:44:00</td>
</tr>
<tr>
<td>288331</td>
<td>08/06/2014</td>
<td>30.2</td>
<td>245.7</td>
<td>147</td>
<td>0,4</td>
<td>34,2</td>
<td>18:45:00</td>
</tr>
</tbody>
</table>

Figure 4-4 Excel worksheet of the weather data (extract).
4.5 Thermal modelling

In order to calculate the amount of energy needed for cooling during the year, a virtual model of the building in MATLAB was coded. In fact, as explained before, first a program calculating the heating demand of March 2015 was created and then modified to discover the cooling needs of the whole year. Code found in the reference [1] was used as a basis, but changed to fit the team’s needs.

![Diagram of thermal modelling process]

Figure 4-5: Steps to create the model

4.5.1 Reverse engineering of estimated variables

As previously stated, the first program written did not actually work for calculating cooling needs. Instead, a similar method as explained in the calculation of the u-value was used. The program was used to verify or, if needed, correct the variables that were just possible to estimate.

The big advantage was the knowledge of the actual heating demand of the building in March of 2015 and the fact that our supervisors provided SCOOL with the irradiation and temperature data of this month. Together with the variables explained in 4.2, the team was able to write program that made use of the equations shown in 4.1.
Since the weather data were divided into minutes, the program looped over the list, calculating the energy value for each type (whether gain or loss), and summing them up for the final result.

Figure 4-6: Final variables used in the program
As presented in fig. 4-7, the error made by the program was calculated as a percentage of diversion from the actual number in the data. Obviously the first attempts were not that close. Some estimations proved to be wrong in the first tries, which allowed correction of the values to be made and minimization of the error via iteration. This meant correcting the values based on the information gained and retry. As you can see in figure 4-4, the team was able to get within 0.3% of the real result. This allowed for quite some confidence in the final variables, which were used in the second program, which now calculated heating and cooling needs for the building for one whole year.
Figure 4-8 Part of the loop section of the heat calculation program

The total of the code can be seen in the Appendix B. Now that the first program and the programming style has been introduced, the main operating process will be explained.
4.5.2 Cooling needs calculation program

Regarding the code that estimated the cooling needs, there were some things that changed, but the main idea was still the same. This time the program worked with the data of the weather of the whole year 2014. The program read the data file, did calculations and showed the results. While sounding simple, there was plenty of work behind the software that is explained in the following pages.

```
1 - format shortG
2 - C=60*1000000; % conversion Wain->MWh
3 - D=1000000/(30*24*60); % conversion Wain for each month to MWh
4 - Tint=23;
5 - U=0.65; % weighted average
6 - s=9000;
7 - A=3240;
8 - Vc=0.4; &Vc=0.35
9 - Vcn=0.8;
10 - Is=0.6; % estimation
11 - Wc=0.66; %estimation
12 - Wf=0.9; %estimation
13 - Sw=1800;
14 - qocc=1.800; % average 100 people 150 W/person 6h/day 20days 1.8MWh/month
15 - qbuil=0.025; &q fans
16 - i=1;
```

Figure 4-10: Variables of cooling needs, taken from heat calculation

The program followed the structure as the program used to fit the variables with the heating data of March 2015.
As seen in Fig. 4-11 the program calls for two Excel sheets (see Fig. 4-4) where all the weather data are. The data extracted are the external temperature and insolation of the year 2014. The other data sheet contains the monthly electric consumption, the spreadsheet also given by the supervisors. Two matrices are made that contain the important values from the work-sheets, dimensions as big as the files they are reading.

```matlab
17 - Weather=xlsread('Weather.xlsx');
18 - ElectCons=xlsread('ECons.xls');
```

**Figure 4-11: Reading of Excel files in MATLAB code**

Before the calculations, all the matrices that will be used later, are also defined (to be technically correct, some of them are vectors). The whole definitions of those tables are shown in Fig. 4-12:

```matlab
19 - Insolation=Weather(:,2);
20 - qr=zeros(1,length(Weather));
21 - qvSo=zeros(1,length(Weather));
22 - qvNet=zeros(1,length(Weather));
23 - qv=zeros(1,length(Weather));
24 - qg=zeros(1,length(Weather));
25 - q=zeros(1,length(Weather));
26 - qheat=zeros(1,length(Weather));
27 - qcool=zeros(1,length(Weather));
28 - Elect=ElectCons(:,1);
29 - Tout=Weather(:,1);
30 - qint=zeros(1,12);
31 - month=Weather(:,7);
32 - monthly_needs=zeros(3,12);
```

**Figure 4-12: Initialization of Arrays and Matrices**

Basically two ways have been used to define a table. When the command zeros is used, a vector is created and all values set to ‘0’. The dimensions of that vector are based on the size of the Excel files, so ‘zeros(1, length(Weather))’ means that the new vector is one row wide and n columns long, n standing the length of the Weather. The other technique to create a vector that is used is similar to the one before, but still different. For instance, ‘Tout=Weather(:,1)’ creates a vector with the data of the first column of the existing Weather table. The big difference between these two ways of creating a file is that in the first case a vector/matrix is created, with some specified dimensions and full of zeros. With the second method, also a vector/matrix is created, but the data is read from the given file and wrote into MATLAB.
The next step was first to include the electric consumption and adapt it for further calculations (explanation in 4.2.1). As can be seen in Fig. 4-13, the electrical energy consumed is added up with the heat emission of occupants and the heat generated by the ventilations fans. It is also converted into units that fit the later calculations, so from megawatt per month to watt per minute.

```
34    for f=1:12
35        qint(f)=[Elect(f)+qocc+qbus]*1000000/(30*24*60);
36        %Internal heat gains for month to W and min
37    end
```

Figure 4-13: Sum up of electrical energy consumed

Coming up next, the main loop of the program can be seen. The ‘while’ structure allows the team to do all the calculations needed for getting the cooling demand. The reference of this loop can be seen in figure 4.13 below. It iterates, and ergo calculates, the different heat balances for intervals of one minute because reads every row for a length of the Weather matrix.

Those equations are explained in chapter 4.1. As said before, the program calculates the heat balance in intervals of one minute but take in consideration the following lines. Where the ‘if’ loop begins, a set of combinations are set: for the whole year, due to some reasons (the building is never 100% full, cooling needs are lower during holidays and weekends…) the cooling needs are halved. On July, the cooling demand is reduced to a quarter part of its first estimation because of lack of classes and activity in the building. It is not reduced more because the weather data shows how July temperatures and radiation are the highest ones. On August, the cooling needs taken into account are just a 10% of the original estimated. This conclusion is made due to the fact that there is almost no activity in the building, which means that just a small part has to be cooled.

Another reason for this inclusion is the fact that the program does calculates the needs for 24 hours every day, even when there is no actual need. Furthermore, the heat capacity of the building is only partially taken into account, further leading to a reduction of the actual needs.
These are reasons for these correction factors:

**Calculation correction factors**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>0.7</td>
</tr>
<tr>
<td>Cooling July</td>
<td>0.25</td>
</tr>
<tr>
<td>Cooling August</td>
<td>0.1</td>
</tr>
<tr>
<td>Cooling rest</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The ‘monthly needs’ table of figure 4-14 shows the format of the output of the program as the different needs of the building B18. Notice that the table is 3x12, which means that is 3 rows long and 12 columns wide, so will report the monthly information. The first row will save the sum of the heating demand, the second one the sum of the cooling demand and the last one the total balance of the heat.

**Figure 4-14: Iteration part and calculations of the program**

Last but not least, the program outputs are presented. Actually, it was the main reason to build up a program out of nothing. Following, as seen on
the figure 4-15, there are some modifications of the ‘monthly needs’ table just explained. Can also be seen how some simple final calculations are being made, without ‘;’ to give an output at the command window of MATLAB. First, the modifications of the monthly needs table is basically done to change the units of the results of the previous table. As it is seen during the definition of the variables and constants, ‘C’ is just a constant that helps to convert from Wmin to MWh. It does nothing more. It was included because people are used in dealing with energy in kWh or MWh. Next, the collection of final calculations provides the desired output of the program. They show the cooling needs (heating gains) because of transmission, ventilation, radiation and the heat generated inside due to internal activity. Also the global heating needs, cooling needs and the very total balance is given by these calculations.

```matlab
69 -   j=1; %just to convert units (Wmin--> MWh)
70 -   while j<18
71 -       monthly_needs(1,j)=monthly_needs(1,j)/C;
72 -       monthly_needs(2,j)=monthly_needs(2,j)/C;
73 -       monthly_needs(3,j)=monthly_needs(3,j)/C;
74 -       j=j+1;
75 -   end
76 -   OT=sum(qt)/C
77 -   OV=sum(qv)/C
78 -   OR=sum(qr)/C
79 -   OL=sum(qint)/D
80 -   %Every year we have this demand of heating and cooling
81 -   Qheat=sum(qheat)/C
82 -   Qcool=sum(qcool)/C
83 -   %The total Q to add and subtract of the building
84 -   Qtotal=abs(Qheat)+abs(Qcool)
```

Figure 4-15: Output lines
4.6 Results

Running the cooling program provided us with numerous different outputs. Obviously, the most important ones were the total and monthly cooling loads needed by the building. These are the most important figures to design the air conditioning unit, since the total amount shows the amount of cooling the unit has to provide to the building.

![Table]

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>85.0068</td>
<td>56.1532</td>
<td>59.9296</td>
<td>63.1575</td>
<td>40.0391</td>
<td>40.4702</td>
<td>22.2152</td>
<td>17.1250</td>
<td>32.0623</td>
<td>41.4046</td>
<td>57.6797</td>
<td>77.7488</td>
</tr>
</tbody>
</table>

Figure 4-16: Monthly results; 1 = heating, 2 = cooling, 3 = total

The results verify further our assumptions, since the cooling loads are, as it was expected highest in July and August (before correction for inactivity, see [4.5.2]) while reaching almost zero during the winter months. The heating values presented in column 1 are also in line with the actual heating data.

The total cooling load obtained from our program is 96 MWh, load that our solar cooling system has to cover with the air conditioning system.

The next values that had to be extracted were the peaks of cooling power needs, since the units have to be able to provide adequate cooling even on the hottest days.

To that end, analysis of the weather data obtained was performed. In the following graphs the average temperature and insolation curves of each month are plotted. They show you quite nicely that peaks in temperature not necessarily mean peaks in irradiation. And while the temperature is the highest in July and August, the irradiation corresponds more to the inclination of the solar rays, which is closest to 90 degrees on the 21st of June.

4.6.1 Charts

Following can be seen some charts plotted with actual data and calculations plus some explanations regarding them. The purpose of them is to sum up many descriptions done in this chapter and justify in a graphic way our results. The following days are March 15th, June 8th, and November 10th of 2014. These days were chosen with the intention to give three different
year scenarios. These charts display power needs and power production, which is the power the cooling system needs/produces before the AC unit device. Briefly speaking, the power needs are 5.89 times lower than the cooling needs of the building (because of the ESEER of the AC device). Just remark that the energy produced is the area compressed between the Electric power lines and the desired interval of time to evaluate.

![Image of charts showing power needs, PV production, and temperature over a day.]

**Figure 4-17: March 15th 2014**

The first of them is the March 15th. This day was quite instable regarding the insolation and the temperature. As can be seen easily, the temperature keeps alternating between 3 and almost 9ºC. The power needs are drastically changing and so the PV production. The day might have been cloudy and cold, and although there are some power needs, these have a peak of around 13kW. The total electric power needs were 459.6 kW while the PV production would have been about 1757 kW. While the day was, bluntly speaking, ugly, the panels would have managed to over-produce more than 1200 kW, so it would have been a nice day for the PV system.
Figure 4-18: June 8th 2014

The next day plotted is June 8th. Many differences can be seen on the chart. If the temperature and the insolation is compared, this day was clearly sunny (so solar radiation was strong) and stable during the whole day. Even the patterns of temperature and power needs follow almost the same pattern. The power needs were really high, with more than 33 kW peak. In this case, the PV system wouldn’t have been able to cover the power needs of the building and although receiving a great source of insolation, which means buying some electricity from the grid would have been needed. The only time of the day where there is more production than needs is between 5 and 7 am, when there is sunlight and enough radiation to deal with the “low” temperatures of the sunrise welcoming the summer day. The total power production of the panels would have been of 8995 kW while the power needs of the building were twice as big, 17373 kW.
The last day contrasted is the November 10\textsuperscript{th}. This autumn day was cool but still quite stable compared to March 15\textsuperscript{th}. The temperature was above 10ºC and the day registered some cooling needs. The insolation was quite uniform during the whole day taking in consideration that it was already November. In this case, the PV system would have covered all the power needs and also over produced some spare power, with 1314.7 kW produced and a demand of just 328kW.

Now that some chosen days have been explained, let us consider a year overview of the electrical needs and production. As explained before, the aim of this cooling system was to cover the year demand, not covering the monthly needs if these were higher than the average. For instance, in June the system would not have covered the cooling needs but sure it would have done it yearly as can be seen in the figure 4-20. The chart is displaying energy [kWh] instead of power as it could be seen in other pictures.
Figure 4-20: Monthly electric energy needs and production

As seen in the figure, monthly cooling needs grow following the season cycle of the northern at the northern hemisphere; during May, June, July and August cooling needs are higher because of the summer climate, while are low or zero during winter months. The cooling needs have the peak on June, with almost 5000 kWh though it is important to remember that the cooling needs of July are estimated as a quarter of the real ones and on August is just 10% of the real ones. Also, the PV production is proportional to the radiation which grows gradually with more hours of sun and more direct impact of it because of the inclination of the Earth. This phenomenon gives the peak of insolation during July (ergo peak of PV production) although the production between July and June is quite similar. An overproduction of electrical energy is seen from October to March while the insufficiency is found from April to September (excluding August). Note that even in the hottest month, the PV production is almost 2/3 of the total needs of that month.

To verify the system, the total needs of the year 2014 were 20540 kWh while the PV production would have been 20937 kWh. That means that if the panels would have been installed before 2014, a total of 397 kWh would have been saved (around 2% of the electrical energy produced), meaning that the system has a small margin.
4.6.2 Calculations for Photovoltaic Systems

Electrical Energy needed by AC Unit (MWh)

\[
EE_{\text{InAC}} = \frac{\text{CoolingLoad}}{ESEER}
\]  

(21)

Where:

- \( EE_{\text{InAC}} \) is the Electrical Energy needed by AC Unit, (MWh)
- \( \text{CoolingLoad} \) is the Cooling demand value got by our program, (MWh)
- \( \text{ESEER} \) is the European Seasonal Energy Efficiency Ratio

It is interesting to talk about the ESEER and its meaning. This parameter, called in North America IPLV (Integrated Part Load Value), is the seasonal efficiency of refrigeration equipment, which is calculated using the energy efficiency ratio for partial loads (100%, 75%, 50% and 25%).

The ESEER is calculated as:

\[
ESEER = \left( \frac{\text{EER}[100\% \text{ Load}]}{0.03} \right) + \left( \frac{\text{EER}[75\% \text{ Load}]}{0.33} \right)
+ \left( \frac{\text{EER}[50\% \text{ Load}]}{0.41} \right) + \left( \frac{\text{EER}[25\% \text{ Load}]}{0.23} \right)
\]  

(22)
Where,

<table>
<thead>
<tr>
<th>Partial Load Ratio</th>
<th>Air temperature (°C)</th>
<th>Water temperature (°C)</th>
<th>Weighting coefficients (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>35</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>75</td>
<td>30</td>
<td>26</td>
<td>33</td>
</tr>
<tr>
<td>50</td>
<td>25</td>
<td>22</td>
<td>41</td>
</tr>
<tr>
<td>25</td>
<td>20</td>
<td>18</td>
<td>23</td>
</tr>
</tbody>
</table>

The value obtained is more realistic than EER (Energy Efficiency Ratio) or COP (Coefficient Of Performance) due they consider only full load working state.

**Electrical Energy needed by Inverter (MWh)**

\[ EE_{\text{inINV}} = \frac{EE_{\text{inAC}}}{\eta_{\text{inv}} \cdot (1 - \frac{\%\text{losses}}{100})} \]  

Where:

- \( EE_{\text{inINV}} \) is the Electrical Energy provided to Inverter, (MWh)
- \( EE_{\text{inAC}} \) is the Electrical Energy needed by AC Unit, (MWh)
- \( \eta_{\text{inv}} \) is the efficiency of the inverter, (%)
- \( \%\text{losses} \) is the estimated losses, (%)

**Number of Panels**

\[ N_{p} = \frac{EE_{\text{inINV}} \cdot 1000}{W_{p}} \]  

Where:

- \( N_{p} \) is the Number of panels needed
- \( EE_{\text{inINV}} \) is the Electrical Energy needed by Inverter, (MWh) (kWp)
- \( W_{p} \) is the power peak of each panel, (W)
The electrical energy needed for the inverter has to be the energy produced by the solar panels. From the “PV Polska” sheet [Appendix E] provided by our supervisors, it’s known that for each kWp of solar panels installed, it’s produced around 1MWh/year. Therefore, the follow equivalence will be used to calculate the electrical power needed:

$$1 \text{kWp} = 1 \text{MWh}$$

**Total Area Panels**

$$A = \frac{N \cdot A_p \cdot \cos(\beta)}{\eta_{A-\text{Used}}}$$

(25)

Where:

- $A$ is the total area occupied by panels, ($m^2$)
- $N$ is the number of panels
- $A_p$ is the area of each panel ($m^2$)
- $\beta$ is the inclination of the panels ($^\circ$)
- $\eta_{A-\text{Used}}$ is the percentage of the area used for the panels, which is considered 90%

**Percentage of installation used**

$$\%_{\text{used}} = \frac{EE_{\text{inINV}} \cdot 1000}{N_{p\text{Max}} \cdot W_p} \cdot 100$$

(26)

Where:

- $\%_{\text{used}}$ is the percentage of losses estimated, ($\%$)
- $EE_{\text{inINV}}$ is the Electrical Energy provided to Inverter, (MWh) (kWp)
- $N_{p\text{Max}}$ is the maximum number of panels
- $W_p$ is the power peak of each panel, (W)
Inclination

This is an important point due the dependence of the solar irradiation incidence about the inclination of the panels. The angle depends on the situation of the region studied and its Latitude and Azimuth.

Maximal inclination

\[ \beta_{\text{max}} = 60^\circ - (41^\circ - \text{Latitude}) \]  

(27)

Minimum inclination

\[ \beta_{\text{min}} = 5^\circ - (41^\circ - \text{Latitude}) \]  

(28)

Figure 4-21: Azimuth angle

Using the azimuth angle in the graphic it is possible get the region that corresponds to the studied building. To choose the inclination is interesting: One takes an angle that includes the point operating in the high absorption region (white region), which will favour for the region studied, Poland, where the irradiation is not so high.
For this reason, the inclination angle of 35º was chosen:

<table>
<thead>
<tr>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitud (°)</td>
</tr>
<tr>
<td>Longitude (°)</td>
</tr>
<tr>
<td>Azimuth (°)</td>
</tr>
<tr>
<td>Azimuth (°)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inclination</th>
</tr>
</thead>
<tbody>
<tr>
<td>βmin (°)</td>
</tr>
<tr>
<td>βmax (°)</td>
</tr>
<tr>
<td>β (°)</td>
</tr>
</tbody>
</table>

Results

Now, using the equations and the parameters found in the data sheets of all products that compose the system, the following results are obtained:

<table>
<thead>
<tr>
<th>Electrical Energy needed by AC Unit (MWh)</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Energy needed by Inverter (MWh)</td>
<td>21</td>
</tr>
<tr>
<td>Losses Estimation (%)</td>
<td>10</td>
</tr>
<tr>
<td>Power Peak of each Panel (Wp)</td>
<td>290</td>
</tr>
<tr>
<td>Nº Panels</td>
<td>73</td>
</tr>
<tr>
<td>Area panels (m2)</td>
<td>121.1</td>
</tr>
</tbody>
</table>

After calculations, the number of solar panels required to cover the cooling demand is 73. Knowing that the provider sells the panels in packs of 20, the final number of panels in this installation will be 80.

<table>
<thead>
<tr>
<th>Final Nº Panels</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Area Panels</td>
<td>121.11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Max Electrical Energy Production (MWh)</th>
<th>23</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Installation demand</td>
<td>90.52</td>
</tr>
</tbody>
</table>
Summing up, the AirCon unit takes 90.52% of the yearly production of the PV installation, having still a small margin for punctual peaks or sell to the grid. Therefore, the cooling system designed overproduces around 2MWh.

**Full Capacity**

This also enables a calculation of the maximal electrical energy producible with the photovoltaic system using whole area available to place solar panels.

This is an appliance from a website daftlogic.com, which using Google maps, allows you to calculate areas, distances …

**Area (m²)**

In the next pictures it is possible to see the actual procedure to get the value of the area. This was done using the actual google maps as a free satellite map and some tools that measured distances based on a legend.

![Figure 4-22. Roof satellite view of the B18 building](image-url)
As it’s shown in the results, the current area ($A_{\text{Full}}$) is around 360 m$^2$.

Knowing that, it’s possible to estimate what would be the maximum number of panels could be implemented on the building’s roof, and consequently, the max energy produced in full capacity.
Max Number of panels

\[ N_{\text{FullMax}} = \frac{A_{\text{Full}} \cdot \eta_{\text{A-Used}}}{A_p \cdot \cos \beta} \]  

(29)

Where:

- \( N_{\text{FullMax}} \) is the maximum number of panels in full capacity
- \( A_{\text{Full}} \) is the total area useful to install solar panels. It’s the roof part situated on the South, (m\(^2\))
- \( A_p \) is the area of each panel (m\(^2\))
- \( \beta \) is the inclination of the panels (°)
- \( \eta_{\text{A-Used}} \) is the percentage of the area used for the panels, (%)

Total Power

\[ EE_{\text{MaxFull}} = \frac{N_{\text{FullMax}} \cdot W_p}{1000} \]  

(30)

Where:

- \( EE_{\text{FullMax}} \) is the total Electrical Power/Energy obtained by solar panels at Full Capacity, (kWp) (MWh)
- \( A_p \) is the area of each panel (m\(^2\))
- \( W_p \) is the power peak of each panel, (W)

Percentage Capacity used vs. Full Capacity

\[ \%_{\text{Full}} = \frac{EE_{\text{inINV}}}{EE_{\text{MaxFull}}} \cdot 100 \]  

(31)

\( \%_{\text{Full}} \) is the percentage of the system used compared by Full capacity system, (%)

- \( EE_{\text{inINV}} \) is the Electrical Energy/Power provided to Inverter, (MWh) (kWp)
- \( EE_{\text{FullMax}} \) is the total Electrical Power/Energy obtained by solar panels at Full Capacity, (kWp) (MWh)
Therefore,

<table>
<thead>
<tr>
<th>Total Area (m²)</th>
<th>360</th>
</tr>
</thead>
<tbody>
<tr>
<td>Useful Area (m²)</td>
<td>324</td>
</tr>
<tr>
<td>Total Panels</td>
<td>238</td>
</tr>
<tr>
<td>Total Power/Energy (kWp) (MWh)</td>
<td>69</td>
</tr>
<tr>
<td>% Capacity vs. Full Capacity</td>
<td>30.45</td>
</tr>
</tbody>
</table>

Distribution of Panels

The panels' distribution is an important point worth discussing, which will depend on the solar panels and inverter's parameters given by the manufacturers in the data sheets. Following are the different estimations of numbers of panels.

**Maximum Number**

\[
N_{\text{max, panels-serial}} = \frac{V_{\text{MaxINV}}}{V_{oc(\text{panel}-10^\circ C)}}
\]  

(32)

Where:

- \(N_{\text{max, panels-serial}}\) is the maximum solar panels number in serial connexion
- \(V_{\text{MaxINV}}\) is the maximum voltage monitoring of the inverter, (V)
- \(V_{oc(\text{panel at } -10^\circ C)}\) is the Module load voltage at -10°C, (V)

\[
V_{oc(\text{panel at } -10^\circ C)} = V_{oc,STC} - 35^\circ C \cdot \Delta V
\]  

(33)

Where:

- \(V_{oc,STC}\) is the load voltage in standard conditions (STC), (V)
- \(\Delta V\) is the voltage constant variation of the module in function of temperature. Given by manufacturer, (%/°C)
Minimal Number

\[ N_{\text{Min,panels-serial}} = \frac{V_{\text{Mpp, min INV}}}{V_{\text{Mpp (panel at 70ºC)}}} \]  \hspace{1cm} (34)

Where:

- \( N_{\text{min,panels-serial}} \) is the minimal solar panels number in serial connexion
- \( V_{\text{Mpp, min INV}} \) is the minimal voltage monitoring of the inverter at max Power, (V)
- \( V_{\text{Mpp (panel at 70ºC)}} \) is the Module max Power voltage at 70ºC, (V)

\[ V_{\text{Mpp (panel at 70ºC)}} = V_{\text{Mpp,STC}} + 45ºC \cdot \Delta V \]  \hspace{1cm} (35)

Where:

- \( V_{\text{Mpp,STC}} \) is the load voltage at standard conditions (STC), (V)
- \( \Delta V \) is the voltage constant variation of the module in function of temperature. Given by manufacturer, (%/ºC)

Maximum Parallel brands

\[ N^{\circ}_{\text{Max brands}} = \frac{I_{\text{Max INV}}}{I_{\text{Mpp (panel at 70ºC)}}} \]  \hspace{1cm} (36)

Where:

- \( N^{\circ}_{\text{Max brands}} \) is the maximum number of parallel branches
- \( I_{\text{Max INV}} \) is the Maximum admissible current by inverter, (A)
- \( I_{\text{Mpp (panel at 70ºC)}} \) is the module maximum power current at 70ºC (STC), (A)

\[ I_{\text{Mpp (panel at 70ºC)}} = I_{\text{Mpp,STC}} + 45ºC \cdot \Delta I \]  \hspace{1cm} (37)

Where:

- \( I_{\text{Mpp,STC}} \) is the maximum power current at standard conditions (STC), (A)
- \( \Delta I \) is the current constant variation of the module in function of temperature. Given by manufacturer, (%/ºC)
With these equations, the following results were obtained:

<table>
<thead>
<tr>
<th>Serial</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Voc(panel -10°C)</td>
<td>49.659</td>
</tr>
<tr>
<td>Voc(panel 70°C)</td>
<td>18.237</td>
</tr>
<tr>
<td>Max Number/branch</td>
<td>20</td>
</tr>
<tr>
<td>Min Number/branch</td>
<td>14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parallel</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I (70°C)</td>
<td>6.933</td>
</tr>
<tr>
<td>Max branches</td>
<td>5</td>
</tr>
</tbody>
</table>

Therefore, it’s possible to say that number of panels selected for the chosen inverter is:

| Max number Panels | 100 |
| Min number Panels | 14  |

Finally, the best distribution has to be chosen depending of electrical requirements established by:

- Options between maximum and minimum number of serial panels, 14-20
- Maximum number of branch, 5
- Branches with more than minimum number of panels, 14

In the next table one can see all possible configurations which the team has to choose the best one.

The red boxes mean that they don’t satisfy the requirement, so these configurations won’t be allowed to implement. However, the green boxes mean that they satisfy the requirement to be used.
At the end, there are two possible configurations:

- 1st configuration
  
  4 branches of 20 serial panels

![Figure 4-24 Panels configuration no.1](image1)

- 2nd configuration
  
  5 branches of 16 serial panels

![Figure 4-25 Panels configuration no.2](image2)

To choose between these options one has to consider two factors

1- Width of roof area available

Knowing that the width is around 5 m, which only 3.5 m available to place the solar panels.

Knowing the length of each panel (1.665m) and the inclination (35º)

the length occupied per panel will be:

$$1.665 \cdot \cos 35 = 1.37 \text{ m}$$

Therefore, the number of panels placed in cascade will be:

<table>
<thead>
<tr>
<th>Number Panels</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>1.37</td>
<td>2.74</td>
<td>4.11</td>
</tr>
</tbody>
</table>
2- Complete branches

The advantage of having complete branches is the possibility to install more panels in case of extending the system.

Considering both factors, the best configuration for the design system is the first option, 4 branches of 20 panels. Furthermore, in this case better aesthetic result is obtained due to that two pairs of branches will exist, and there is enough space.

Figure 4-26. Roof satellite view with drawing of panels

A model of the building was done as well to show how the installation would look. On the right is the existing installation, on the left the new one:
Figure 4-27 The model of the B18 building
4.6.3 Calculations for Thermal System

This next step is to calculate the thermal system properties and study if it is viable. In case it can be implemented, may need to be compared with the PV system studied before.

Conversion factor

This a needed factor to convert the cooling load in MWh to kW.

\[ \text{April} - \text{Oct} = 183 \text{ days} \]

\[ h = 184 \text{ days} \cdot 11 \frac{h}{\text{day}} = 2013 \text{ h} \]  

(39)

Where \( h \) is the working hours during the evaluated period.

Cooling Load

\[ Q_{\text{Cool}} = \frac{\text{CoolingLoad} \cdot 1000}{h} \]  

(40)

Where:

- \( Q_{\text{Cool}} \) is the Cooling load obtained from the designed program, (kW)
- \( \text{CoolingLoad} \) is the Cooling load obtained from the designed program, (MWh)
- \( h \) is the conversion factor from MWh to kW, (h)

Net Cooling Load

\[ Q_{\text{NCool}} = \frac{Q_{\text{Cool}}}{1 - \frac{\%_{\text{tanklosses}}}{100}} \]  

(41)

Where:

- \( Q_{\text{NCool}} \) is the cooling load of chilled water required by the chiller, (kW)
- \( Q_{\text{Cool}} \) is the Cooling load obtained by the designed program, (kW)
- \( \%_{\text{tanklosses}} \) is percentage of losses of cold water storage tank, (%)
Heat Needed from Hot Water

\[ Q_{HW} = \frac{Q_{NCool}}{COP \cdot \left(1 - \frac{\%_{tanklosses}}{100}\right)} \quad (42) \]

Where:

- \( Q_{HW} \) is the equivalent heat needed from hot water, (kW)
- \( Q_{NCool} \) is the cooling load of chilled water required by the chiller, (kW)
- \( COP \) is the coefficient of performance of the chiller given by the producer
- \( \%_{tanklosses} \) is percentage of losses of hot water storage tank, (%)

Solar Heat Required (kW)

\[ Q_S = \frac{Q_{HW}}{\eta_{Exchan.} / 100} \quad (43) \]

Where:

- \( Q_S \) is the solar heat required by the system, (kW)
- \( Q_{HW} \) is the equivalent heat needed from hot water, (kW)
- \( \eta_{Exchan.} \) is the heat exchanger efficiency, (%)

Number of Panels

\[ N = \frac{Q_S}{\eta_p / 100 \cdot P_{peak}} \quad (44) \]

Where:

- \( N \) is the required number of collectors
- \( Q_S \) is the solar heat required by the system, (kW)
- \( \eta_p \) is the conversion efficiency of each collector, (%)
- \( P_{peak} \) is the power peak for each collector, (kW)
Area Occupied

\[ A_{occ} = N \cdot A_p \cdot \cos \beta \]  \hspace{1cm} (45)

Where:

- \( A_{occ} \) is the total occupied area for panels, \( (m^2) \)
- \( N \) is the required number of collectors
- \( A_p \) is the total panels area, \( (m^2) \)
- \( \beta \) is the panels inclination. Taken from PV System calculations, \( (^\circ) \)

Using the above equations and the data sheet parameters the results obtained are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Load (MWh)</td>
<td>96</td>
</tr>
<tr>
<td>Cooling Load (kW)</td>
<td>48</td>
</tr>
</tbody>
</table>

**Chilled Water System**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold water Storage (m3)</td>
<td>4</td>
</tr>
<tr>
<td>Losses Cold Water Storage Tank (%)</td>
<td>5</td>
</tr>
<tr>
<td>Q cooling water needed (kW)</td>
<td>50</td>
</tr>
</tbody>
</table>

**Chiller**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Load (kW)</td>
<td>50</td>
</tr>
<tr>
<td>Cooling Capacity (kW)</td>
<td>64</td>
</tr>
<tr>
<td>% Capacity</td>
<td>75</td>
</tr>
</tbody>
</table>

**Hot Water System**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Water Storage (m3)</td>
<td>7</td>
</tr>
<tr>
<td>Losses Hot Water Storage Tank (%)</td>
<td>5</td>
</tr>
<tr>
<td>Q hot Water required by Chiller kW)</td>
<td>81</td>
</tr>
<tr>
<td>Q Solar to heat Hot Water</td>
<td></td>
</tr>
<tr>
<td>Efficiency Exchanger (%)</td>
<td>85</td>
</tr>
<tr>
<td>Q Solar Required (kW)</td>
<td>96</td>
</tr>
<tr>
<td>Number of Panels</td>
<td></td>
</tr>
<tr>
<td>Power Peak (kW)</td>
<td>1.91</td>
</tr>
<tr>
<td>Conversion Efficiency Panels (%)</td>
<td>50</td>
</tr>
<tr>
<td>Number of Panels</td>
<td>101</td>
</tr>
</tbody>
</table>
Finally, the factor that will decide if it’s possible to implement the thermal system is the area occupied by the panels. This area will depend on the total collectors' area and the inclination calculated in the photovoltaic system.

<table>
<thead>
<tr>
<th>Inclination (°)</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available Area (m²)</td>
<td>324</td>
</tr>
<tr>
<td>Occupied Area (m²)</td>
<td>365</td>
</tr>
</tbody>
</table>

Comparing the available area to place collectors and the occupied area, it's easy to see that the necessary area is bigger than the available. Therefore, it is safe to say that the thermal system can NOT be implemented.
4.6.4 Additional outputs

While the cooling outputs described above were expected, the program gave additional insights not expected:

- The impact of airflow ($V_c$)

No one on the team realized this before, but just small changes in this value already lead to an explosion in the heating demand. This shows crystal clear why it is important to keep windows closed and fix any cracks or openings, however small they may be, as fast as possible to keep the air from flowing through your building. In summer, this may only cause a slight increase in the cooling costs when the outside air is really hot, but in winter the costs for heating skyrocketed immediately.

Figure 4-28 Heating program with increased ventilation (0.4→0.5)

If compared it to fig. 4.6, the only thing changed is the increased ventilation, by only 0.1 l/sec*m³, which is very likely to happen in even slightly leaky buildings. For comparison, some calculators give ranges in the ventilation for very old buildings going up to 2 l/sec*m³. And the 0.1 already caused an increase of heating by 13.5%, which would mean an increase in heating needed by about 3.75 MWh for one month only!
Amount of energy produced locally

After calculating the actual electrical energy delivered by the solar panels, it was also possible to calculate the percentage of energy the building will have to take less from the grid.

As it turns out, with the building’s energy consumption of about 300MWh, the amount saved is about 10%. While this is not a significant amount taken by itself, but if one imagines a world where every building can supply 10% of its own energy needs, this would help with the stabilization of the grid, especially during peaks, a lot.
5. Economic Evaluation

For any project, an important part of the work to achieve is to make an evaluation of the cost that will have to be cover in order to achieve this project. In this case the team evaluated many components to have a business plan closer as possible to the reality.

5.1 General Overview of the PV Solution

The main objective of this business plan is to know if the project will be profitable or not and in how many time. Depending of the cost of the conventional electricity the PV solution is a profitable solution quite quickly.

The installation of a cooling system in a building requires a certain amount of electricity (in our case 28 MW between May and October). The main reason to choose a PV solution lies in taking a long term perspective. The cost of installation will be higher but the university will not pay any electricity in the future. The profitability of the project depends on this balance between cost of the project, efficiency, needs and production of electricity. In our case the amount saved between no panels and the PV solution will be between 2000 – 3000 € annually.

In the Excel sheet presented in fig. 5-1 one is be able to find the different elements selected by the team with the different prices and final costs. The maintenance cost and the installation cost of the system are approximate but they can give a close idea of what this project will cost.
## System Elements

<table>
<thead>
<tr>
<th>Elements</th>
<th>Product</th>
<th>Supplier</th>
<th>Qty</th>
<th>Price ATI</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cooling system</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC Unit</td>
<td>AC Daikin Units RYYQ40T</td>
<td>Daikin</td>
<td>1</td>
<td>39 799,00 €</td>
<td>39 799,00 €</td>
</tr>
<tr>
<td>Unit for multi module combinaison</td>
<td>Daikin RYMQ10T</td>
<td>Daikin</td>
<td>1</td>
<td>9 601,00 €</td>
<td>9 601,00 €</td>
</tr>
<tr>
<td>Multi-module connection kit</td>
<td>Daikin BHFQ22P1517</td>
<td>Daikin</td>
<td>1</td>
<td>295,00 €</td>
<td>295,00 €</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td></td>
<td>49 695,00 €</td>
<td></td>
</tr>
<tr>
<td><strong>PV system</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Panel</td>
<td>Winaico WSP-285M6 (290Wp) Mono (pack of 20)</td>
<td>Pvshop</td>
<td>4</td>
<td>5 092,20 €</td>
<td>20 368,80 €</td>
</tr>
<tr>
<td>Inversor</td>
<td>ABB PRO-33.0-TV-OUTD</td>
<td>Pvshop</td>
<td>1</td>
<td>3 800,00 €</td>
<td>3 800,00 €</td>
</tr>
<tr>
<td>Mounting system (2 solar panels)</td>
<td>Product number 998760</td>
<td>Pvshop</td>
<td>40</td>
<td>157,00 €</td>
<td>6 280,00 €</td>
</tr>
<tr>
<td>Cables (2m per PV panel)</td>
<td>WattUNeed 2x4mm² 10m</td>
<td>Wattuneed</td>
<td>16</td>
<td>38,90 €</td>
<td>622,40 €</td>
</tr>
<tr>
<td>DC Combiner Box</td>
<td>ENWI - S-1000-4Sx-X-Y-PC-4.0</td>
<td>Pvshop</td>
<td>1</td>
<td>186,00 €</td>
<td>186,00 €</td>
</tr>
<tr>
<td>Other electrical elements</td>
<td>little cables, connectors, etc…</td>
<td>-</td>
<td>1</td>
<td>1 000,00 €</td>
<td>1 000,00 €</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td></td>
<td>32 257,20 €</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td>81 952,20 €</td>
<td></td>
</tr>
</tbody>
</table>

### System Components
The engineers of the team calculated the cooling demand of the building and also the electrical consumption that will have to be provided by the PV system in order to completely cover it.

With these data it was time to look for a real solution to realize the project. The team searched for a complete system which will include all the different components needed to get an effective and profitable cooling system.

The different elements of the system were carefully selected in order to fill the needs of the building in cooling in every situation. This system is able to cover, based on the weather data, the yearly cooling needs easily.

5.1.1 The cooling system

It was decided to choose the elements described in the Excel sheet up to build the cooling system because of the great characteristics that they have. For the AC Unit part, the most important parameter which made the choice this Daikin Unit is that the Nominal Cooling Capacity is superior to the Cooling Load. Moreover, the ESEER of the system is really high. This system can provide to the building all the cooling needed for a reasonable price.

5.1.2 The PV system

The Solar Panels possess a high Power Peak (Wp) in order to reduce considerably the number of panels needed and have also a high efficiency.

The invertor was selected for the following features:

- The DC input Voltage and Current are important for distribution (improvement of number of branches and maximize the number of serial panels)
- The kind of Output voltage needed by AC unit (AC 3 phase)
- The output AC Power > Power input AC unit
- The output max current > AC Unit Input Current

All the different elements of our system were selected in order to provide the best efficiency and the best profitability as possible.
5.1.3 Other costs

Some additional costs have to be taken in consideration in order to create a business plan as completed as possible and to get a more accurate idea of the cost that it will engender. The installation and maintenance costs are the most relevant costs to take in consideration because they are those that cannot be avoided. It was decided not to take into account some extra costs like more little materials (more cables, connectors, tools, etc...) because it was already planned in the budget to have some extra quantities of those just in case.

5.1.3.1 Installation cost

The majority of these components require certain skills to be installed. In order to install all the system properly, hiring a specialized company would be necessary. Magdalena contacted many of them in the area of Lodz to get some prices and costs of installation. This charge should not be neglected because it can be a high component of the final cost of the project and it can have a high impact on the system.

Below you find the average of the cost of the installation of such system provided by the companies around. These costs are obviously not definitive but they can give an idea of what it would cost.

5.1.3.2 Maintenance cost

The system does not demand a lot of maintenance. Once the system is installed it works by itself without needing any special cares. Because the cost of maintenance is not significant it can be assumed that it would be close to zero so it is not relevant to count it in our project. In case of one intervention have to be performed in case of one issue an estimation of the cost is around 100 € (≈ 400 PLN).
5.1.4 Amortization of the project

When realizing a project it is really important to know the amortization and/or the profitability of it. No one wants to have a project that will not be efficient or profitable.

<table>
<thead>
<tr>
<th>Cost of the conventional electricity</th>
<th>0.34 PLN per kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumption of the building</td>
<td>21000 kWh</td>
</tr>
<tr>
<td>Consumption saved annually</td>
<td>7140.00 PLN</td>
</tr>
<tr>
<td><strong>Total saved</strong></td>
<td><strong>1721.93 €</strong></td>
</tr>
</tbody>
</table>

Based on the cost of the conventional electricity one can calculate which amount of money can be saved annually. Knowing that in Poland the kWh conventional costs around 0.34 PLN and the amount of electricity needed per year by our cooling system is 21000 kWh, so the saved amount of money will be around 7140 PLN a year (1721.93€ based on the currency exchange of the 14/06/15).

The electricity overproduced by the PV system was not taken into consideration. It will be sold to the grid, so it will reduce the amortization time of this project.

During the period of utilization of the cooling system, it happens that the PV system does not deliver enough energy to allow the cooling system to work at the capacity levels needed (see 4.6.1). In that case power from the grid has to be bought. On a yearly basis, which is our period of evaluation, the PV system allows for more energy to be sold to the grid than has to be taken from it.

The amortization time of the PV system will be about 18 years with the pessimistic estimations. Since this is the worst case, it may mean that our PV system will be amortized several years earlier in the reality than this estimation.
Some of the criteria which were not taken in consideration are:

- The sale of the overproduced electricity
- The decreased demand of energy of the building
- The price of the electricity in the next years

All of these factors would have a positive influence on the amortization period, but since it was the goal to show that even a worst-case scenario would still be profitable, their impact was disregarded. Considering just the energy prices, which have been rising constantly over the years, the project will be profitable rather in 10-15 years than in 18.

### 5.2 Overview of the Thermal Solution

In order to find the best solution for the project, it was decided to explore the other option, the thermal solution. It was already disregarded (see 4.6.3) for its technical problems, but the economical evaluation was done nevertheless to see if a partial solution should even be explored. Unfortunately, as you will be able to see below, this solution is not relevant for this type of project due to the following facts listed in the budget plan.

In this case the amount saved between conventional solution and thermal solution will be between 2000 – 3000 € annually as the PV solution.

As for the PV / Cooling system solution, the Excel sheet presented below shows the different elements selected by the team with the different prices and final costs. The maintenance cost and the installation cost of this system are omitted because only for the material part it is already cost-prohibitive.
5.2.1 The thermal system

<table>
<thead>
<tr>
<th>System</th>
<th>Elements</th>
<th>Product</th>
<th>Qty</th>
<th>Price ATI</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal system</td>
<td>Chiller</td>
<td>SorTech Adsorption Chiller Aggregate eCoo 2.0 40IPS</td>
<td>1</td>
<td>22 000,00 €</td>
<td>22 000,00 €</td>
</tr>
<tr>
<td></td>
<td>Recooler</td>
<td>SorTech ReCooler - eRec 40</td>
<td>1</td>
<td>4 500,00 €</td>
<td>4 500,00 €</td>
</tr>
<tr>
<td></td>
<td>Hot Water Storage Tank</td>
<td>Ezinc G-2001</td>
<td>2</td>
<td>3 500,00 €</td>
<td>7 000,00 €</td>
</tr>
<tr>
<td></td>
<td>Cold Water Storage Tank</td>
<td></td>
<td>3</td>
<td>2 000,00 €</td>
<td>6 000,00 €</td>
</tr>
<tr>
<td></td>
<td>Collectors kit</td>
<td>APRICUS APSE-30 Solar Collector</td>
<td>90</td>
<td>2 040,00 €</td>
<td>183 600,00 €</td>
</tr>
<tr>
<td></td>
<td>Accessories</td>
<td>pumps, controllers, extra mounting kits, connectors, tubes, liquid….</td>
<td>1</td>
<td>8 000,00 €</td>
<td>8 000,00 €</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>231 100,00 €</strong></td>
<td></td>
</tr>
</tbody>
</table>

In the previous Excel sheet the elements of the thermal system needed to cool down the B18 building have the same efficiency than the PV / Cooling system studied previously. However as it can be seen, the cost of the different elements are much more expensive than a PV solution. In the Excel sheet is it only estimation but it is quite close to the reality. A thermal system will cost more than two times the cost of the PV / Cooling system.

Moreover, as stated in chapter 4.6.3, the thermal system needs 365 m² to be implemented. On the B18 building however, the available area is only 324 m².

5.2.2 Additional costs

Some additional costs have to be included for the thermal system as well, such as the installation, maintenance cost and also the small materials needed during the installation. All of these costs were not studied due to the fact that even on the material side it is not relevant to prefer the thermal solution to the PV solution in our case.
5.2.3 Amortization of the project

The amortization for the thermal solution is a huge amount of years that confirm the fact that choosing the thermal is irrelevant. The cost of the electricity stayed the same as for the PV, the saving cost is still 1721.93 € annually.

<table>
<thead>
<tr>
<th>Cost of the conventional electricity</th>
<th>0,34 PLN per kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumption of the building</td>
<td>21000 kWh</td>
</tr>
<tr>
<td>Consumption saved annually</td>
<td>7140,00 PLN</td>
</tr>
</tbody>
</table>

Total saved 1721.93 €

1€ = 4.1465 PLN (14/06/15 - www.xe.com Currency Converter)

Below is the estimation in years for the amortization of the thermal system, calling back equations (46) and (47).

\[
\frac{231100}{1721.93} = 134.21 \text{ years}
\]
6. Project Management

6.1 Project's Gantt chart

This is the project’s Gantt chart that allowed the tram to progress properly.

The project’s Gantt chart has been created in order to properly manage milestones and tasks’ of separate categories in time. The technical planning has been divided in two parts in order to have time for checking the ideas we have planned then evaluate and make them better.
6.2 Project's course

6.2.1 Team's Identity

The team logo and name were not the most important issues for our team at the beginning, though the team has had a strong will to feel identified. That is why on one of the meetings it was decided that each team member should prepare an individual project of the team name and logo and present it on the upcoming meeting, where they will be graded and we will choose the best alternative. It was done as it was planned and as a result the most suitable project was chosen that everyone was satisfied with.

6.2.2 Research

The team has been learning about various technologies, techniques of cooling, heating, physical foundations and connected topics. By reading specified literature, forums and webpages of companies or sometimes even governments our knowledge was extended to an extent, which allowed to perform own experiments. The whole list of sources, which is considered important, is available in the bibliography section of the report.

6.2.3 Program

Right after the team started to self-educate and do research it begun to technically plan further actions. With huge help of the supervisors it was realised that it will be needed to write a program that will help is in calculations. Therefore it has been decided to use MATLAB, in which a few members of the team had some experience, and which seemed the very suited for our situation.

6.2.4 Website

The idea of creating a website for the project has come to the members’ minds in order to boast about the project among other students and EPS participants. By this website it was aimed to present the project ideas. In order to introduce the topic a simplified version of our program embedded into the website was created. Technologies
used on the website are: php framework Symfony2, jquery, javascript and of course standard html and css. The website can be found under address: www.scool.dmcs.pl.

6.2.5 Midterm evaluation

The midterm evaluation session was held on the 30th April and has been a significant milestone in our project. It was organised by the EPS responsible in order to give feedback to the teams after almost a half of their work. The team has presented the goals of work, plans and direction. It was confirmed by showing parts of the research to the audience in a form of a Pecha-Kucha presentation.

6.2.6 Business plan

In the final weeks of project’s development the team has moved toward detailed business planning. A complex business data and analysis under the supervision of Pierre has been prepared. Although it was not easy to gather all the important data, this part of the project has confirmed the team’s impression of the project’s overall success.

6.2.7 Final evaluation and further ideas

At the end of the project a final presentation to all the EPS students and supervisors is going to be given. This is going to happen on the 29th June 2015. The project is going to be evaluated as a whole, but also all the members of the team will get feedback from the EPS supervisors and coordinators.

The project is expected to be developed in the university later on. It would be a great gratification for the Project team to have developed the basis for such an important investment.

6.3 SWOT Analysis

The group is composed of 1 Polish student, 1 German student, 1 French student and 2 Spanish students. This fact enhances the diversity in the group since the members have different ways of thinking and manners influenced by their own cultural heritage. Due to that it is possible for each member to broaden their horizons, by experiencing
new things about other culture and taking the better features of each one. Furthermore, the members have to speak in English so it is a good chance to improve the communication skills in this language, which recently has become the universal language of the job market. On the other hand, the diversity issue may seem to be a weakness, since the communication among the members is not so fluid as it would be in their mother tongues.

All the team members are under 27 years old. This youth implies that the team has plenty of innovative ideas, is looking forward to do creative things and prove themselves that young people are capable of positive contribution to the society in the near future. Moreover, the youth factor also means that all members were born and grown up surrounded by the technology so they are keen on new technologies and learning new tools is something logical. This is a huge strength in the world where we live nowadays.

Contrary to the above and due to this, the team does not have much experience in this kind of project so it is a challenge.

The members of the team have different profiles and whereas some of them have fine experience in engineering and others have experience with programming, business and in management tasks, all of them describe themselves as inexperienced. This fact makes the team more competitive since this way it can face more complex projects by working together instead of a very specific one. At the same time the members can broaden their professional profiles somehow by learning from their teammates' knowledge.

On the other hand, different profiles may be a trouble, while planning strategies to face the project since each member may tend to go through his speciality. In addition to this and due to the fact that all the members are students, the team has to reach agreements, about meetings because of different courses and handle difference timetables.

At last but not least, it should be noticed that within the team there is a very good working environment so there is no tension
among members. This enables the information exchange in a smooth way.

6.4 Project's Outcome

We would describe our project work, as one of the most demanding tasks during our study. It stimulates our abilities because it is very challenging. It has taught us a lot of valuable issues. We have gained priceless experiences that for sure will stimulate our personal development and will berry in the future.

The project itself is of course a very important achievement, which will possibly develop on our eyes in hands of more experienced people, hopefully modifying also the opinions about solar cooling as such.
7. Conclusions

7.1 Results

After all research and calculations done during the project, the final solution to cover the 96MWh of cooling load from the building B18, is the implementation of a Photovoltaic system.

Technically, the system design would produce around 23MWh of electrical energy when the demand is 21 MWh, so it still has a margin for peaks. Besides, the area occupied for the panels would be 121 of 324 m² available.

Economically, it’s also feasible with an investment of 32.000€ and a payback period of 19 years as the most pessimistic.

On the other hand, the thermal system has been discarded due unfeasibility, both physically and economically. The results obtained say that the area needed is around 365 m² when the available is 324, and the investment is 230.000€ with around 100 years payback period. That’s why this option is completely unfeasible.

7.2 Summary

While working on the project, especially when analysing the results, we learned quite a few things:

- For solar panels, even in the climate of Poland, the amortization period can be seen as rather short. The panels we chose were very modern and with their guarantee to still produce 82% of their original output after 25 years, implementing the ideas presented the report makes a lot of sense economically. This is why we recommend anyone planning to implement a new system to look into the possibility to use Solar Cooling to their advantage!
- Additionally, the solar panels can work independent from the AC unit, should the University ever decide to replace it, and just continue to produce energy for other usage in the building, making it less demanding from the grid.
### 7.3 Recommendations

Considering the PV solution to provide the electricity needs of a cooling system is highly recommended. This solution is economically profitable and green. Based on our researches, it is possible to implement PV solution to a new AC system or an existing one.

Depending on the location of the building (solar radiation, weather data), the amortization time of the system will vary but will ever be finally profitable. If you want to implement a cooling system powered by a PV solution, a tool on our website allows you to calculate, depending on your building your cooling needs (SCOOL’s Website: [scool.dmcs.pl](http://scool.dmcs.pl)).
7.4 Closing thoughts of the team members

As the last part of our report, we would like to give you the personal impressions of every one of us. This project has been a big part of our life during the last four months, and we would like to share with you what we have learned, not only about the work, but about each other.

7.4.1 Michael

For me, this has been a very different, but great experience. Not only have I never worked on a big team project before, nor have I left Germany for anything but vacation. So I really did not know what I would have to expect from the EPS. How well would the communication work? Are people from other countries behaving different than my fellow German students? Do I have the knowledge required to contribute to our project? Questions like these were quickly answered: Communicating in English seemed strange at first, but worked well from the beginning and got even better over time. And while there are of course cultural differences we got to experience first-hand (the long Spanish lunch during which you could not expect a response met short German lunch break), most stereotypes proved false and we actually had a lot in common. The work went well and while we all were not familiar with the thermodynamics of air conditioning at first, we caught up pretty quick and everyone pulled his weight. In my managing role, I could actually see the benefit of the modern leadership and motivation styles I was taught in my lectures at home and the problems that arose when they were not applied properly.

Summing up, I will leave the EPS with more technical knowledge, but I value mostly the experience of working in an international team that grew together over time.
7.4.2 Pierre

When I started the project in the beginning of the semester I did not really know what it can give me in terms of personal development. I saw this project as a team work which will permit us to begin from one point and to build something together. I think before this project I did not realized the important of the impact of the habits of the people depending on their country of origin on the work. And this is an interesting part. I think the project that we build together with my team was more than only a project for the university but it permitted me to learn more about the team work. I ever liked to work in team and more with coworkers or colleagues from different countries. But inside this project it was the first time that I had to work with people whose are from many nationalities.

The EPS project is not only the work with your team and the goals that you want to achieve even if it is an important component of the EPS semester. The other main component of EPS is to be in a group which is diversifed by the different individuals that composed it but also by the context of the semester. The fact to be in a class of twenty, thirty people from many nationalities and working for many different project brings so many features to the EPS semester.

First of all there is a kind of friendship inside all the class. We share the same experience, we are living in a different country for most of us, we discover a lot about the other nationalities, habits etc.

On the other hand there is a kind of competition between us due to the fact that we are in different project / group and that we want to achieve something, have to best mark or the best work.

The result of these features is, as we can imagine, a friendly competition between all the individuals that we are. We “fight” to get the best project and on the other hands we make friendships and have fun.

I think the EPS cannot be resumed by the work that we tempt to achieve at the university. There are many experiences which composed the EPS experience (as we can call it like this). All the experi-
ences that we lived here, the people that we met take a part to the EPS experience as much at least than the work itself I think.

I think that the EPS semester and the project gave me the opportunity to work with people that I did not met before, from different nationalities, with different personalities with who without this semester project I would probably never met. But also it gave me an opportunity to discover what I was capable of in an area and subject which I do not have a lot of knowledge and understanding before.
Surprised, fulfilled and challenged. This is how I feel now of the EPS now that the semester is practically finished.

Surprised because at first I thought that my stay in Łódź would be much different; I didn’t expect having such a great time here in Poland, especially with my colleagues and teammates. I remember landing in Warsaw afraid of the unknown, but anxious about the first meeting on the February 27th. After meeting people from other countries, I realized that some were even more frightened than me. This was such an indescribable experience. Surprised, because I never worked in such a multicultural group before or dealt with the cultural barriers while we were united and faced the inconveniences of speaking in English, language which was not native for any of us.

Fulfilled because in the end we accomplished our set goals, we got various results and we were also capable of working with them. As said before, when French, German, Polish and Catalan culture are mixed in one single boat it is not easy to sail to desired land, but we did it! Fulfilled, because this project has just been a part of my stay in Łódź but still has been an important aspiration to me. I am handling this project as my final degree project at my university so it meant much more than a simple report to me.

Challenged because I have hunger of much more. The EPS has woken up some ideas and dreams inside me that I have the will to accomplish. On the personal life, being an Erasmus student has awakened the desire of meeting even more cultures and beliefs around the globe. On the professional prospective, I have discovered that being away from home and dealing with the language barriers don’t have to stop my potential and my yearnings.

As my final remark to the EPS, I would like to quote an inspirational sentence from the American writer Marianne Williamson that particularly resumes my feeling after the EPS:
“Our deepest fear is not that we are inadequate. Our deepest fear is that we are powerful beyond measure. It is our light, not our darkness, that most frightens us.”
7.4.4 Miquel

Challenge. Yes, probably, this is the word that could describe what the EPS was for me. Actually, it wasn’t something new for me, due that during the first semester, when I was already studying in this university, I was close and connected with other students who were in the EPS. However, it has left me surprised.

First of all, I couldn’t imagine finding a project as close as SCOOL. My next course I will start new studies about energy efficiency and renewable energies. This is the reason why I’ve been extra motivated in this project.

Another important point has been the multidisciplinary and multicultural work, with people from different countries and different cultures and habits. This experience gives me practice and self-confidence to feel comfortable in future works.

About my personal skills, the experience has been incredible. I have got a good background about AC world, programing in basic software for my future as MATLAB, or even discover new uses of a so common software as Excel.

Therefore, my personal EPS balance is completely positive and satisfactory, personally and professionally. Sure, I would and will recommend everyone this experience.
7.4.5 Magdalena

The European Project Semester has been an almost life changing experience for me. Although the project’s topic was not particularly relevant to my original course of study, it has fortunately broadened my horizons in engineering. I have learned another approach to project management, an international insight into the team working methods and a lot of patience in problem solving.

Personally, at the beginning I had to give up the position of a leader to another member of my group. For my character that was a great challenge because leading position is the one I feel really good in. Although it was hard I must admit that it was a great experience to look at team working form a position of a usual team member.

During the semester I have realized that even having the best attitude and eagerness you are still vulnerable to have problems, which are of course possible to be solved. Due to that fact from now on I feel much more comfortable in problem solving and communication skills and I will have even more courage in using English in my everyday professional life.

As an information technology student I have developed also in my field, by being responsible for creating the website. I have also provided support in all the activities connected with programming and data analysis in Matlab and Excel. These actions have given me an opportunity to experience the supportive side of IT skills.

On the other hand the EPS let me meet wonderful people in an international environment to develop lifelong friendships and to above all have some fun. All of my new acquaintances are priceless and unforgettable.

To sum it up I would like to say that this multidisciplinary, intercultural project gave me a great experience an invaluable opportunity. I suppose this may in the future skyrocket my career. I can sincerely recommend that course to everyone.
Appendix A

Model Program

Real=-27777; %kW
C=60*1000; %conversion wmin->kWh
Tint=23;
U=0.65; %weighted average
S=4000;
A=3240;
Vc=0.4; % Vc=0.35
Vcn=0.8;
Ts=0.6; %estimation
Wc=0.66; %estimation
Wf=0.9; %estimation
Sw=1600;
Weather=xlsread('WeatherMarch.xlsx');
Tout=Weather(:,1);
Insolation=Weather(:,2);
i=1;
qlig=20000; % 18MWh/March
qApp=7000; % 7MW/month
qocc=1800; % average 100 people 150 W/person 6h/day 20days
1.8MWh/month
qbuis=25; %q fans
qint=(qlig+qApp+qocc+qbuis); % Internal heat gains
qt=zeros(1,length(Weather));
qvSa=zeros(1,length(Weather));
qvNat=zeros(1,length(Weather));
qv=0.4; % Total
qr=0.6; % Total
while (i<length(Weather))
    qt(i)=U*S*(Tout(i)-Tint);
    qvSa(i)=Vc*A*1200/1000*(Tout(i)-Tint);
    qvNat(i)=Vcn*A*1200/1000*(Tout(i)-Tint);
    qv(i)=qvSa(i)+qvNat(i);
end

QT=sum(qt)/C
QV=sum(qv)/C
QR=sum(qr)/C
qint
Total=(((sum(qt)+sum(qv)+sum(qr))/C)+qint)*0.7
Real
error= (Real-Total)/Real
Appendix B

Final Program

```matlab
format shortG
%Real=-27777; % kW
C=60*1000000; % conversion Wmin->MWh
D=1000000/(30*24*60); % conversion Wmin for each month to MWh
Tint=23;
U=0.65; % weighted average
S=4000;
A=3240;
Vc=0.4; % Vc=0.35
Vcn=0.8; % ??
Ts=0.6; % estimation
Wc=0.6; % estimation, do research
Wf=0.9; % estimation
Sw=1600;
Weather=xlsread('Weather.xlsx');
ElectCons=xlsread('ElCons.xls');
Elect=ElectCons(2,:);
Tout=Weather(:,1);
Insolation=Weather(:,2);
i=1;
qocc=1.800; % average 100 people 150 W/person 6h/day 20 days 1.8MWh/month
qbuis=0.025; % q fans
qt=zeros(1,length(Weather));
qvSa=zeros(1,length(Weather));
qvNat=zeros(1,length(Weather));
qv=zeros(1,length(Weather));
qr=zeros(1,length(Weather));
q=zeros(1,length(Weather));
qheat=zeros(1,length(Weather));
qcool=zeros(1,length(Weather));
qint=zeros(1,12);
month=Weather(:,7);
monthly_needs=zeros(3,12);
for f=1:12
    qint(f)=(Elect(f)+qocc+qbuis)*1000000/(30*24*60); % Internal heat gains for month in W
end
%while (i<25)
while (i<length(Weather))
    %Transmission
    qt(i)=U*S*(Tout(i)-Tint);
    % Ventilation
    % Sanitary
    qvSa(i)=Vc*A*1.2*(Tout(i)-Tint);
    % Natural
    qvNat(i)=Vcn*A*1.2*(Tout(i)-Tint);
    % Tot Vent.
    qv(i)=qvSa(i)+qvNat(i);
    % Fin Ventilation%
```
\[
qr(i) = Ts \times Wc \times Wf \times Sw \times \text{Insolation}(i) \times 0.65; \quad \%\text{Solar radiation}
\]

\[
\text{%Calculus}
q(i) = (qt(i) + qv(i) + qr(i) + q\text{int(month}(i)));
\]

\[
\text{if} \quad (q(i) < 0);
\quad q\text{heat}(i) = q(i) \times 0.7;
\quad \text{else}
\quad \text{if} (\text{month}(i) == 7);
\quad q\text{cool}(i) = q(i) \times 0.25;
\quad \text{elseif} (\text{month}(i) == 8);
\quad q\text{cool}(i) = q(i) \times 0.1;
\quad \text{else}
\quad q\text{cool}(i) = q(i) \times 0.5;
\quad \text{end}
\quad \text{end}
\]

\[
\text{month}\_\text{ly}_\text{needs}(1, \text{month}(i)) = q\text{heat}(i) + \text{monthly\_needs}(1, \text{month}(i));
\]

\[
\text{month}\_\text{ly}_\text{needs}(2, \text{month}(i)) = q\text{cool}(i) + \text{monthly\_needs}(2, \text{month}(i));
\]

\[
\text{month}\_\text{ly}_\text{needs}(3, \text{month}(i)) = \text{abs}(q\text{heat}(i)) + q\text{cool}(i) + \text{monthly\_needs}(3, \text{month}(i));
\]

\[
i = i + 1;
\]

\[
\text{end}
\]

\[
j = 1; \quad \%\text{just to convert units (Wmin--> MWh)}
\text{while} \quad j < 13
\quad \text{monthly\_needs}(1, j) = \text{monthly\_needs}(1, j) / C;
\quad \text{monthly\_needs}(2, j) = \text{monthly\_needs}(2, j) / C;
\quad \text{monthly\_needs}(3, j) = \text{monthly\_needs}(3, j) / C;
\quad j = j + 1;
\quad \text{end}
\]

\[
QT = \text{sum}(qt) / C
\]

\[
QV = \text{sum}(qv) / C
\]

\[
QR = \text{sum}(qr) / C
\]

\[
QI = \text{sum}(q\text{int}) / D
\]

\[
\%\text{Every year we have this demand of heating and cooling}
Q\text{heat} = \text{sum}(q\text{heat}) / C
\]

\[
Q\text{cool} = \text{sum}(q\text{cool}) / C
\]

\[
\%\text{The total Q to add and substract of the building}
Q\text{total} = (\text{abs}(Q\text{heat}) + \text{abs}(Q\text{cool}))
\]
Appendix C

Devices Data

SorTech Adsorption Chiller Aggregate eCoo 2.0 40IPS

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chiller</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling Capacity (kW)</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Heat Capacity (kW)</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>COP thermal (Max)</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td><strong>Chilled Water</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>m (m3/h)</td>
<td>8</td>
<td>11.6</td>
</tr>
<tr>
<td>T (ºC)</td>
<td>8</td>
<td>21</td>
</tr>
<tr>
<td><strong>Connection (DN)</strong></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td><strong>ReCooling Water</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>m (m3/h)</td>
<td>16.4</td>
<td>20.4</td>
</tr>
<tr>
<td>T (ºC)</td>
<td>22</td>
<td>44</td>
</tr>
<tr>
<td><strong>Connection (DN)</strong></td>
<td>65</td>
<td></td>
</tr>
<tr>
<td><strong>Hot Water</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>m (m3/h)</td>
<td>6.4</td>
<td>10</td>
</tr>
<tr>
<td>T (ºC)</td>
<td>50</td>
<td>95</td>
</tr>
<tr>
<td><strong>Connection (DN)</strong></td>
<td>40</td>
<td></td>
</tr>
<tr>
<td><strong>Power supply (V)</strong></td>
<td>230</td>
<td>AC</td>
</tr>
<tr>
<td><strong>Losses (W)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal losses (W)</td>
<td>480</td>
<td>1040</td>
</tr>
<tr>
<td>Pump losses (W)</td>
<td>2472</td>
<td>2736</td>
</tr>
</tbody>
</table>

SorTech ReCooler - eRec 40

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ReCooler</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ReCooler Capacity (kW)</td>
<td>116</td>
<td></td>
</tr>
<tr>
<td>Nominal Volume Flow m(m3/h)</td>
<td>19.2</td>
<td></td>
</tr>
</tbody>
</table>
### APRICUS APSE-30 Solar Collector

<table>
<thead>
<tr>
<th>Solar Thermal Collector</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Num. Tubes</td>
<td>30</td>
</tr>
<tr>
<td>Peak Power (kW)</td>
<td>1.91</td>
</tr>
<tr>
<td>Aperture Area (m²)</td>
<td>2.83</td>
</tr>
<tr>
<td>Gross Area (m²)</td>
<td>4.4</td>
</tr>
<tr>
<td>Absorptance (%)</td>
<td>&lt;92</td>
</tr>
<tr>
<td>Emittances (%)</td>
<td>&gt;8</td>
</tr>
<tr>
<td>Operating Angles (°)</td>
<td>Min</td>
</tr>
<tr>
<td></td>
<td>28</td>
</tr>
<tr>
<td>Flow Rate (L/min)</td>
<td>Max</td>
</tr>
<tr>
<td></td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Conversion eff.</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### Winaico WSP-285M6 (290Wp) Mono-crystalline

<table>
<thead>
<tr>
<th>Solar Panels</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Mono</td>
</tr>
<tr>
<td>Pmax (kW)</td>
<td></td>
</tr>
<tr>
<td>STD W/m²</td>
<td>1000</td>
</tr>
<tr>
<td>Nominal W/m²</td>
<td>800</td>
</tr>
<tr>
<td>Wp</td>
<td>290</td>
</tr>
<tr>
<td>214.39</td>
<td></td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td></td>
</tr>
<tr>
<td>Max (W/m²)</td>
<td>17.46</td>
</tr>
<tr>
<td>Used (W/m²)</td>
<td>12.89</td>
</tr>
<tr>
<td>Linear</td>
<td>14.42</td>
</tr>
<tr>
<td>11.43</td>
<td></td>
</tr>
<tr>
<td>Voltage DC (V)</td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>32.16</td>
</tr>
<tr>
<td>Pmax</td>
<td>29.32</td>
</tr>
<tr>
<td>No-Load</td>
<td>38.83</td>
</tr>
<tr>
<td>35.57</td>
<td></td>
</tr>
<tr>
<td>ΔV (%/°C)</td>
<td>-0.3094</td>
</tr>
<tr>
<td>ΔI (%/°C)</td>
<td>-0.0466</td>
</tr>
<tr>
<td>Current DC (A)</td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>9.03</td>
</tr>
<tr>
<td>Pmax</td>
<td>7.31</td>
</tr>
<tr>
<td>Short circuit</td>
<td>9.64</td>
</tr>
<tr>
<td>Return</td>
<td>7.74</td>
</tr>
<tr>
<td>Oper. T range (°C)</td>
<td>Min</td>
</tr>
<tr>
<td></td>
<td>-40</td>
</tr>
<tr>
<td>Area (m²)</td>
<td>Total (mm)</td>
</tr>
<tr>
<td></td>
<td>1665</td>
</tr>
<tr>
<td></td>
<td>999</td>
</tr>
<tr>
<td></td>
<td>1.66</td>
</tr>
</tbody>
</table>
### Growatt 33000TL3

**Inverter**

<table>
<thead>
<tr>
<th>Number of Individual MPPT</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC input Voltage (V)</td>
<td>Startup/Absolute</td>
</tr>
<tr>
<td></td>
<td>Min</td>
</tr>
<tr>
<td></td>
<td>250</td>
</tr>
<tr>
<td>DC input Power (W)</td>
<td>Rated</td>
</tr>
<tr>
<td>DC Input Current Max (A)</td>
<td>Individual</td>
</tr>
<tr>
<td></td>
<td>38</td>
</tr>
</tbody>
</table>

**Output AC**

<table>
<thead>
<tr>
<th>Rated AC Power (kW)</th>
<th>33</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Apparent Power (kVA)</td>
<td>33</td>
</tr>
<tr>
<td>AC grid Voltage (V)</td>
<td>Nominal</td>
</tr>
<tr>
<td></td>
<td>230</td>
</tr>
<tr>
<td>Max Current (A)</td>
<td>81</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>Max</td>
</tr>
<tr>
<td></td>
<td>98.2</td>
</tr>
</tbody>
</table>

### AC Daikin UNItS RYYQ40T

**HVAC Unit**

<table>
<thead>
<tr>
<th>INPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (V)</td>
</tr>
<tr>
<td>Power Input (kW)</td>
</tr>
<tr>
<td>Cooling (kW)</td>
</tr>
<tr>
<td>Heating (kW)</td>
</tr>
<tr>
<td>Performance</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Nominal Current (A)</td>
</tr>
</tbody>
</table>

**OUTPUT**

<table>
<thead>
<tr>
<th>Nominal Capacity</th>
<th>Cooling (kW)</th>
<th>Heating (kW)</th>
<th>Range (HP)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>112</td>
<td>125</td>
<td>40</td>
</tr>
</tbody>
</table>

Max indoor units | 64 |
Appendix D

B18 Building Drawing – Ground floor
Appendix E
### Estimation of energy yield of the PV system

<table>
<thead>
<tr>
<th>Miasto Location</th>
<th>Roczna produkcja energii</th>
<th>Oczekiwana roczna energia [kWh/kW]</th>
<th>Roczne napromieniowanie</th>
<th>Oczekiwane roczne napromieniowanie [kWh/m²]</th>
<th>Różnica</th>
<th>Oczekiwana roczna energia [kWh/kW]</th>
<th>Oczekiwane roczne napromieniowanie [kWh/m²]</th>
<th>Oczekiwana roczna energia [kWh/kW]</th>
<th>Oczekiwane roczne napromieniowanie [kWh/m²]</th>
<th>Różnica</th>
</tr>
</thead>
<tbody>
<tr>
<td>Białystok</td>
<td>913</td>
<td>1033</td>
<td>1132</td>
<td>1272</td>
<td>-12</td>
<td>998</td>
<td>1196</td>
<td>1337</td>
<td>-47</td>
<td></td>
</tr>
<tr>
<td>Bydgoszcz</td>
<td>950</td>
<td>1013</td>
<td>1132</td>
<td>1263</td>
<td>-14</td>
<td>1196</td>
<td>1337</td>
<td>1269</td>
<td>-14</td>
<td></td>
</tr>
<tr>
<td>Gdańsk</td>
<td>986</td>
<td>1059</td>
<td>1169</td>
<td>1308</td>
<td>14</td>
<td>1013</td>
<td>1196</td>
<td>1269</td>
<td>-14</td>
<td></td>
</tr>
<tr>
<td>Kalisz</td>
<td>950</td>
<td>1031</td>
<td>1132</td>
<td>1269</td>
<td>-14</td>
<td>1013</td>
<td>1196</td>
<td>1269</td>
<td>-14</td>
<td></td>
</tr>
<tr>
<td>Katowice</td>
<td>986</td>
<td>1059</td>
<td>1169</td>
<td>1299</td>
<td>14</td>
<td>1013</td>
<td>1196</td>
<td>1269</td>
<td>-14</td>
<td></td>
</tr>
<tr>
<td>Kielce</td>
<td>986</td>
<td>1059</td>
<td>1169</td>
<td>1299</td>
<td>14</td>
<td>1013</td>
<td>1196</td>
<td>1269</td>
<td>-14</td>
<td></td>
</tr>
<tr>
<td>Koszalin</td>
<td>913</td>
<td>1019</td>
<td>1132</td>
<td>1255</td>
<td>-26</td>
<td>1055</td>
<td>1169</td>
<td>1302</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Kraków</td>
<td>986</td>
<td>1055</td>
<td>1169</td>
<td>1302</td>
<td>10</td>
<td>1013</td>
<td>1196</td>
<td>1269</td>
<td>-14</td>
<td></td>
</tr>
<tr>
<td>Łódź</td>
<td>950</td>
<td>1023</td>
<td>1132</td>
<td>1267</td>
<td>-22</td>
<td>1010</td>
<td>1196</td>
<td>1269</td>
<td>-22</td>
<td></td>
</tr>
<tr>
<td>Lublin</td>
<td>1023</td>
<td>1684</td>
<td>1205</td>
<td>1557</td>
<td>39</td>
<td>1010</td>
<td>1196</td>
<td>1269</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>Olsztyn</td>
<td>913</td>
<td>1010</td>
<td>1132</td>
<td>1246</td>
<td>-35</td>
<td>1010</td>
<td>1196</td>
<td>1269</td>
<td>-35</td>
<td></td>
</tr>
<tr>
<td>Opole</td>
<td>986</td>
<td>1067</td>
<td>1169</td>
<td>1319</td>
<td>22</td>
<td>1037</td>
<td>1196</td>
<td>1269</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Płock</td>
<td>950</td>
<td>1037</td>
<td>1132</td>
<td>1278</td>
<td>-8</td>
<td>1025</td>
<td>1196</td>
<td>1269</td>
<td>-8</td>
<td></td>
</tr>
<tr>
<td>Poznań</td>
<td>950</td>
<td>1025</td>
<td>1132</td>
<td>1267</td>
<td>-20</td>
<td>1010</td>
<td>1196</td>
<td>1269</td>
<td>-20</td>
<td></td>
</tr>
<tr>
<td>Rzeszów</td>
<td>1023</td>
<td>1096</td>
<td>1242</td>
<td>1351</td>
<td>51</td>
<td>1084</td>
<td>1196</td>
<td>1269</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>Szczecin</td>
<td>913</td>
<td>986</td>
<td>1132</td>
<td>1230</td>
<td>-59</td>
<td>1035</td>
<td>1196</td>
<td>1269</td>
<td>-59</td>
<td></td>
</tr>
<tr>
<td>Tarnów</td>
<td>1023</td>
<td>1084</td>
<td>1205</td>
<td>1339</td>
<td>61</td>
<td>1049</td>
<td>1196</td>
<td>1269</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>Warszawa</td>
<td>950</td>
<td>1035</td>
<td>1132</td>
<td>1275</td>
<td>-10</td>
<td>1049</td>
<td>1196</td>
<td>1269</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td>Wrocław</td>
<td>950</td>
<td>1049</td>
<td>1169</td>
<td>1304</td>
<td>4</td>
<td>1010</td>
<td>1196</td>
<td>1269</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Zielona Góra</td>
<td>913</td>
<td>1010</td>
<td>1132</td>
<td>1247</td>
<td>-35</td>
<td>1045</td>
<td>1196</td>
<td>1269</td>
<td>-35</td>
<td></td>
</tr>
<tr>
<td><strong>Średnia/Average</strong></td>
<td><strong>959</strong></td>
<td><strong>1045</strong></td>
<td><strong>1171</strong></td>
<td><strong>1289</strong></td>
<td></td>
<td><strong>1010</strong></td>
<td><strong>1196</strong></td>
<td><strong>1269</strong></td>
<td><strong>1289</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Założenia/Acquisitions:**

- Roczne i oczekiwane roczne średnie: min. 1 max. –最小值和最大值 year.
- Różnica pomiędzy średnimi produkcją roczną dla danej lokalizacji a średnimi obliczonymi dla średnich z 60-letniej (1045 kWh) –年平均辐射量
difference between expected yearly energy yield for the given location and average of 60 locations (1045 kWh).
- Zainstalowano moc oznaczoną: 1 kW – installed rated PV power: 1 kW
- Type of PV modules: kryształowe (c-si) – Type of PV modules: crystalline (c-si)
- Degradeja sprawną modułu: 0% – PV module efficiency degradation: 0%
- System montażu: mocował stajni, wokół kotwiczącego PV system assembly: fixed, stand-alone

**Polskie Towarzystwo Fotowoltaiki**

pl. Przysieka 5/50, 03-310 Warszawa, tel. mob.: +48 60595781, tel./fax: +48-22-6789870

+48-22-6789870

e-mail: informacja@pv-polska.pl, www.pv-polska.pl, NIP: PL 5242898361, REGON 140355926

KRS 0000235799, Sąd Rejonowy m.st. Warszawy w Warszawie, XIII Wydział Gospodarczy Krajowego Rejestru Sądowego

111 | Page
Bibliography


