cordeel

UNIVERSITY
OF TWENTE.

ANALYSIS OF PHOTOVOLTAICS IMPLEMENTATION IN A COLD-STORAGE WAREHOUSE

THE EARTH IS WHAT WE ALL HAVE IN COMMON

INTERNAL SUPERVISOR: DR. KARINA VINK

EXTERNAL SUPERVISOR: ING. ROSSEN RAIKOV

AUTHOR: IVAN DIMITROV

Colophon

Title
Analysis of photovoltaics implementation in a cold-storage warehouse

Autor
Name: I. I. (Ivan) Dimitrov
S2274507
T: +359 88 9090810
E: i.dimitrov@student.utwente.nl

Internal supervisor
Name: Dr. K. (Karina) Vink
T: +31 534898682
E: k.vink@utwente.nl

External supervisor
Name: Ing. R. (Rossen) Raikov
T: +359 (2) 489 67 57
E: rossen.raikov@cordeel.eu

Internship period
18 April – 1 July

University of Twente
Faculty of Engineering Technology
De Horst, building 20
7500 AE
Enschede
Nederland
www.utwente.nl

Cordeel Bulgaria Inc.

36 Chelopeshko Shose
1839
Sofia
Bulgaria
cordeel.bg/en

Preface

My bachelor thesis "Analysis of photovoltaics implementation in a cold-storage warehouse" is on display in front of you, and it was prepared as my final individual project for my Bachelor of Science degree at the University of Twente's Faculty of Civil Engineering. This study is being carried out at Cordeel Bulgaria Inc., and it intends to contribute to our knowledge of implementing photovoltaics in a cold-storage warehouse (freezer).

Without the help and assistance of Rossen Raikov, my supervisor at Cordeel Bulgaria, who helped me through the process, this project would not have been feasible. His accessibility and direct help instilled in me the confidence and motivation to produce high-quality work. I would like to express my gratitude to the entire Cordeel Bulgaria team, who welcomed me as one of their own, presented me with project data and information, offered me with feedback, and demonstrated what it is like to work in a construction company.

My university supervisor, Karina Vink, deserves special recognition for guiding me through the thesis writing process and providing critical input that was important to the successful completion of my graduation thesis. Furthermore, his expertise in the field aided me in making the best selections possible.

Finally, I would like to express my gratitude to my family and friends for their unwavering support during my study and never let me down, despite the challenges and tense situations I faced.

I hope that the readers will find this research interesting and useful for future research.

Sofia, July 1, 2022

Ivan Dimitrov

Abstract

People require clean air to breathe, clear water to drink, and living situations that are free of toxic substances and dangers. Three-quarters of global greenhouse gas emissions come from the burning of fossil fuels for energy. To reduce CO_2 emissions and local air pollution, the world must move quickly to low-carbon energy sources like nuclear and renewables. It is crucial to look into cold-storage warehouses since they are used to store food supplies for society that must be kept in a cold environment to maintain quality. Additionally, the building continually consumes energy, contrarily to other type of warehouses, leading to exorbitant costs and environmental degradation and together with that, the limited amount of information that is currently available on the installation of solar panels on such a structure also suggests the necessity for more study. This thesis aims at analysing the impact of photovoltaics on the energy demand of a cold-storage warehouse from a social, economic, and environmental point of view, which provides us with a better understanding of the situation and leads us to a better solution.

The main question to be answered is to what extent PVs (photovoltaics) promote human well-being and the environment, improve the financial costs of a building related to energy expenditure, and assure independence from geopolitical crises and supply chain disruptions related to a cold storage warehouse. To answer that, a methodology is developed. The first step is to analyze the energy consumption of the building. After that, based on the useful area of the roof, the number of photovoltaic panels is determined, which leads to a specific amount of potentially produced energy. The production of electricity is compared to the consumption of the building, which leads to the next vital part of the report, the storage of the energy. The final findings showed that because photovoltaics are active all day, installing solar panels would be better suited for buildings that utilize the most energy during the day. A combination of solar batteries and the sale of power was shown to be the optimum choice by the energy storage study. The current study did not entirely meet all of its objectives, but it did give a discussion of its results and highlight the need for more research to fully understand the installation of solar panels atop a cold-storage warehouse. Finally, the study emphasized the significance of switching to renewable energy sources in order to enhance both human and environmental welfare.

Keywords: solar panels, renewable energy, cold-storage warehouse, energy storage, solar batteries, energy demands

Table of Contents

List of Figures

List of Tables

1. Introduction

Since the Industrial Revolution, fossil fuels have dominated the energy mix of most countries on the planet. This has far-reaching ramifications for the global climate as well as human well-being, which is inextricably tied to environmental health. According to the World Health Organization, 24 percent of fatalities worldwide on annual basis can be attributed to preventable environmental conditions (Team, 2021). People need clean air to breathe, pure water to drink, and environments free of hazardous chemicals and risks to live in. The combustion of fossil fuels for energy accounts for three-quarters of worldwide greenhouse gas emissions. Furthermore, fossil fuels are responsible for a significant quantity of local air pollution, which causes at least 5 million premature deaths each year (Ritchie & Roser, 2020).

To minimize CO_2 emissions and local air pollution, the world must swiftly transition to low-carbon energy sources such as nuclear and renewable technology. Understanding the present role of renewables in the decarbonization of numerous industries is critical to maintaining a smooth route to net zero emissions (Ritchie & Roser, 2020).

Green energy is beneficial to the environment because it replaces the negative consequences of fossil fuels with less harmful alternatives. In this study, green energy is defined as energy derived from natural resources, renewable, and clean, which means it emits no or little greenhouse gases and is often easily available. Even when the whole life cycle of a green energy source is considered, it emits significantly less greenhouse gases than fossil fuels and emits little or low levels of air pollutants. This is not only excellent for the environment, but it is also healthier for the wellbeing of humans and animals that must breathe the air (Cambridge, 2019). The difference between green and renewable energy is as follows. Green energy is the generation of energy from infinite sources that does not produce carbon emissions or negatively impacts the environment. Renewable energy is the generation of energy from infinite sources. Solar panels are considered to be green energy, which also means that the energy is renewable. Therefore, both terms will be used as synonyms further in the thesis (Smoot, 2021).

Renewable energy can contribute to stable energy costs since it is frequently generated locally and is less susceptible to geopolitical crises, price spikes, and supply chain interruptions. The economic advantages also include the development of jobs in the construction of structures that frequently serve the areas where the employees are working. In 2018, renewable energy created 11 million jobs worldwide, a figure that is expected to rise as we attempt to fulfil goals such as net zero emissions (Cambridge, 2019).

Renewable energy is more cost-effective solution for many sections of the world's power demands compared to fossil energy. Sustainable sources are becoming less costly whereas fossil fuels grow more expensive. Other variables, such as the capacity to build very affordable localised energy solutions, such as solar farms, also work in favour. The attention, investment, and development of renewable energy solutions is incurring expenses, and it may become not only economically feasible, but also the preferred alternative over any energy which is transformed from fossil fuels (Y. Abdelilah, 2021).

Due to the increased amount of greenhouse gas emission and the increased demand of electricity from the society, the need to switch to more renewable and sustainable energy sources is something that applies to Bulgaria as well. By 2030, the installed photovoltaic capacity will have tripled, which on the other hand draws a lot of investors into the country because of the favourable circumstances and location, the low tax rates, and the affordable land costs (Teneva, 2021). Since food industry has a vital role in country's development and growth, the amount of energy utilized is of significant importance. Therefore, the examined warehouse in this thesis is chosen to be equipped with solar panels on top of the roof. Due to the fact that the cold storage warehouse uses energy continuously, it is important to look at its energy requirements. Considering the inside temperature must remain consistent to maintain the great quality of the food, it never stops operating, which implies the high levels of energy needs, emissions, and expenses, that will be discussed further in more details. The remaining structure of the report is as follows. First, some context is given such as study area, involved parties, more information on the concept of renewable energy and details about the problem. Then, the research objective is formulated, followed by the development of research questions. The methodology is developed to answer those questions, which includes the used formulas and approaches. After that follows the" Results" chapter, where all of the outcomes are presented. Towards the end of the report, there is a "Conclusion and Discussion" chapters that summarize the study's significant results and examines the research as a whole. Last but not least, future study can be conducted to compare the work of solar panels and their efficiency in various cold-storage warehouses and identify any potential variations in results.

2. Context

2.1. Study Area

The exact location of the building which is closely examined in this project is Podbalkanski Pat (E871), 4th km, 2139 Village, Musachevo, Sofia District with coordinates 42.7043, 23.5558. It has total built area of $8689.90\ m^2$. An image taken from Google Earth is shown in Figure 1. The private area of the building has one entrance and one exit which is connected to a main road leading directly to the inner side of Sofia. The location is crucial for the wellbeing of the business. The main purpose of the building is related to the logistics business. It functions as a freezer where grocery companies such as BILLA, METRO and LIDL store their food, transport it to different parts of the country and check the quality of the products. Therefore, the functionality of the building is of great importance for the reputation of the users. The average consumption of electricity per month is 257,5 MW. In addition, the warehouse consists of 8 cooling cells.

Figure 1. Top view of the project building

2.2. Involved parties

2.2.1. Cordeel Bulgaria Inc.

Cordeel Group has been found in 1934, Belgium. Since then, it has expanded across Europe in countries such as Netherlands, Germany, France and Bulgaria. Cordeel Bulgaria, with headquarters in Sofia, Bulgaria, is the project's host and appears to be the most prominent stakeholder. The company is active in construction across the logistics, manufacturing, office, public, petrochemical and residential real estate sectors. With a main focus on industrial projects, they have become a market leader in design and build solutions for logistics centres and manufacturing plants. For the current project, Cordeel Bulgaria is the owner of the building that needs to be redesigned and optimised in such way that becomes more energy neutral. In addition, the building has been rented to other companies in the food business as a storage warehouse. Therefore, other stakeholders appear to be of an importance.

2.2.2. Other Actors

As mentioned before, the building is rented to other clients, so they would be one of the stakeholders. All potential stakeholders will be listed below.

- Companies (clients) which would rent the building for their food storage business. Such companies are BILLA, METRO and LIDL. They are currently one of the clients that use the building as storage warehouse.
- The municipality appears to be one of the important stakeholders as well. Depending on the redesign of the building, the host company needs to deliver to the municipality specific documents and plans which need to be approved, in order to let Cordeel Bulgaria to implement the new changes.
- The authorities which are responsible for the delivery of electricity through the power grid. Due to the nature of the project, some legal requirements need to be fulfilled and approved. In order to make the transition from traditional electricity supply to renewable self-produced power, changes in the connection of the building with the central power grid need to be made.
- The involved reconstruction work may emit noise pollution and dust. In addition, the road leading towards the study area could be interrupted in specific times of the day. Therefore, the other industrial buildings, workers and clients around the project area may be influenced. Some consultation with them could be necessary to keep them satisfied.

2.2.3. Possible conflicts

Some of the possible conflicts that may arise during the project will be listed below. In case some other problems appear in later phases of the project, they will be added and discussed separately.

- Current clients vs Cordeel Bulgaria: the company wants to implement new technologies such as solar panels to produce some of the required energy by themselves. However, this involves initial investment which may lead to increased month rent. The companies that use the building could argue about that.

2.3. My contribution

My overall role in this project is to analyse the efficiency of the potential solar panels that will be installed on the roof of the building and give alternatives of different photovoltaic technologies. Then, alternatives will be provided and analysed of how the energy will be stored in a way to be most cost effective and efficient. One of the most important parameters for my research would be the amount of energy the building consumes. After that, the benefits and drawbacks of having renewable energy sources will be presented. In the end recommendations will be given. The used methods and solutions could be employed in similar situations where the client wants to turn his building into more energy neutral system using renewable energy sources. With the increased prices of fossil fuels and the regulations towards more sustainable environment, more companies will look towards renewable sources which is why the research would be valuable for future projects.

2.4. Studies conducted in the past

There are many articles, books, and websites which represent similar situation where a specific building needs to become more sustainable and efficient, in order to minimize the impact on the environment and improve the financial aspects. Articles were searched in Web of Science (2022) using the keywords "renewable energy AND solar panels AND buildings" (8849 results were found in total). Here we show the development of the number of the results over the past 12 years. The outcome for the period 2010-2021 is shown in Figure 2. This result indicates the rising interest and popularity among the population for using renewable energy sources such as solar panels on buildings. However, we are more interested in demonstrating how many articles emerge not only for any type of structure, but for buildings comparable to those in our project. Therefore, the keywords were changed to "renewable energy AND solar panels AND warehouse". In total 19 results appeared. Out of these results, just 3 of them were related to cold-storage warehouse (the articles were from 2013, 2018 and 2021). This demonstrates that the idea of putting solar panels on a cold-storage facility has received little attention. There is a shortage of knowledge, which is why this research might be highly beneficial and valuable for future initiatives, providing essential information and insight that has not previously been studied.

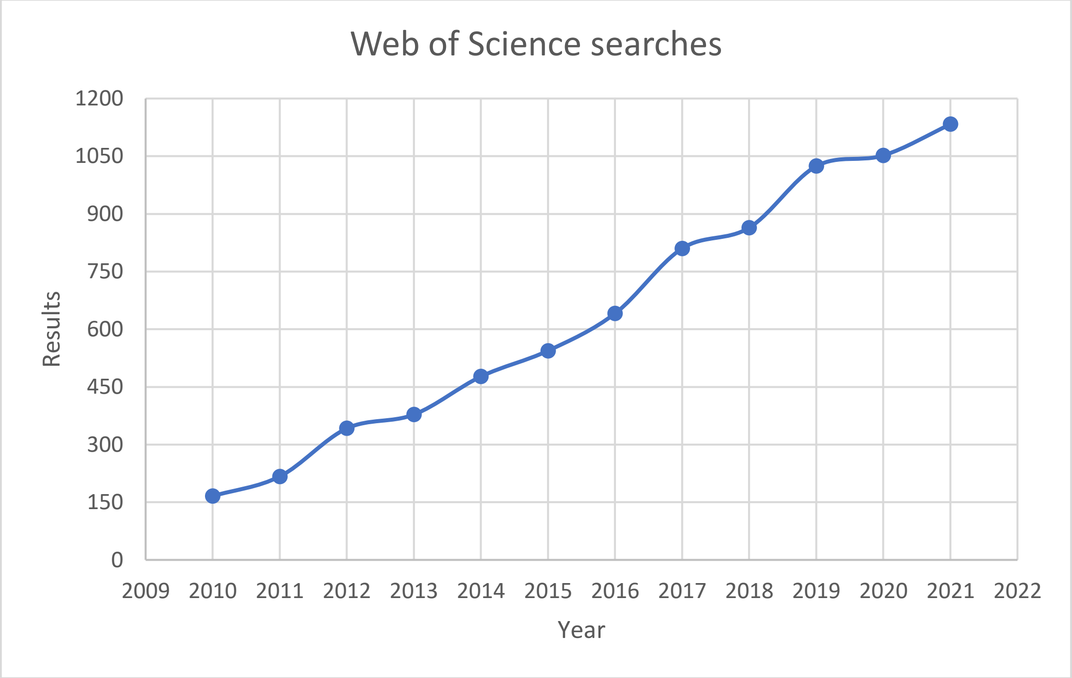


Figure 2. The development of the number of related articles during 2010-2021 (Web of Science,2022)

Some examples of similar warehouses (in terms of structure and size) as in the project are Coach House located in United Kingdom, which saves 177 tons of CO_2 and 100 000£ annually with the help of solar panels, Soper of Lincoln BMW car dealership, located in South Hykeham, which saves 65 tons of CO_2 each year with the help of solar panels system. Other buildings are Bradleys Engineering warehouse, M&I Materials warehouse, Computacenter, etc (Low Carbon Energy, 2022). All of the buildings listed above employ solar panels as an energy source, which saves tons of CO_2 and thousands of dollars each year. More examples are provided further in depth below.

One study evaluates the generation of solar energy using photovoltaics on governmental office building in Portland. As a result, the study concludes that the cost of PV panels and related equipment is predicted to fall dramatically. Abu Dhabi-headquartered International Renewable Energy Agency (IRENA) predicts 59% cost reduction for electricity produced with PV by 2025 (Clover, 2016). In addition, by 2030 the efficiency will approach 25-30% compared to the 15-18% today (Solar PV powering through to 2030, 2019). These elements will make PV systems more cost-effective in the near future. The current payback period of installing photovoltaics for the specific case is around 10 years. However, this would only improve with the raising fossil fuel prices and the reducing cost of solar technologies. Integrating PV panels saved energy equivalent to 31% of the current consumption which equalled to 65 tons of CO_2 emissions per year. The study was expected to encourage public authorities and private businesses to convert mid-size buildings into more sustainable using PV panels (A. Alajmi, 2020).

Another study conducted in Tsukuba, Japan attracts important points of attention. The examined building is the research building of the National Institute for Materials Science (NIMS). In this study many parameters and variables are taken into consideration such as exact location of solar panels, number, shape, hourly solar irradiation data, hourly electricity prices and national holidays. The National Institute for Materials Science building is the first commercial building in Japan to be equipped with a "Micro-Grid System." This is a renewable energy system (RES) that consists of four solar panel arrays (photovoltaic (PV) electricity generation) and a lead-acid battery, allowing for energy savings during peak hours of electricity consumption and costs, as well as a backup energy supply during emergencies. As a result, it could be concluded that the solar panels could suffer from shade due to design problems. Some cells were overheating, while others got shadows by the structure or tightly spaced antennae. Other problems were related to maintenance, dirt accumulation, overgrown plants and shade from other buildings. The charging of the battery has always been higher than the discharging. Therefore, the cost was outweighing the benefits. Also, the solar panel efficiency has been decreasing on average to 2,02% annually which is larger than the expected ≤1% (Vink, 2019). The study shows us that the installation of solar panels is not always as efficient and worth as expected. The design plays vital role, the maintenance and the purpose of usage of the building.

K2 Storage Solutions is a company located in Burnley, United Kingdom which also decides to jump on board and switch to generating electricity using solar panels in 2016. The warehouse is around $9500\ m^2$ in size and includes a 250 kW solar panel system comprised of 1000 solar panels. The new system produces 200 000 kWh per year and saves approximately 104 tonnes of CO_2 per year. In financial terms it saves 40 000 £ per year. Another similar example is the company Pendle Frozen Foods, United Kingdom, which has a cold-storage warehouse with an area of $1500\ m^2$. They installed a solar panel system which generates 111 kW with an annual output of 88 800 kWh and 24 000 £ in terms of saved money. Unfortunately, it is still unknown the exact amount of saved CO_2 per year (Low Carbon Energy, 2022).

3. Problem Statement and Research Objective

This section of the report covers the problem statement and the research objective.

3.1. Problem Statement

The need to shift from traditional to renewable energy sources is rapidly increasing with the higher costs of conventional electricity due to the pricy fossil fuels as well as the emergent need to reduce the negative impact people have on the environment. In addition, geopolitical crises and supply chain interruptions are becoming more and more common. Therefore, analyzing the current situation, shifting towards renewable energy, finding cost-effective alternatives, reducing the carbon footprint, and becoming more independent would improve the human wellbeing and the prosperity of businesses. Taking into account everything above mentioned and the lack of similar studies performed the analysis of transition towards Photovoltaics installed on a cold-storage building would give an idea whether the shift towards renewable energy covers the energy needs of the warehouse, is economically worthwhile and essential for the improvement of the environment.

3.2. Research Objective

The objective of this thesis is to determine the amount of energy that can be produced by the photovoltaics and the amount of lost electricity along the power grid for the end user. Furthermore, to give a solution for storing the produced energy and finally, give recommendations based on the results.

4. Research Questions

In this chapter, a main research question is given which needs to be answered at the end of the project and sub-questions are created which support and guide the process towards the end product.

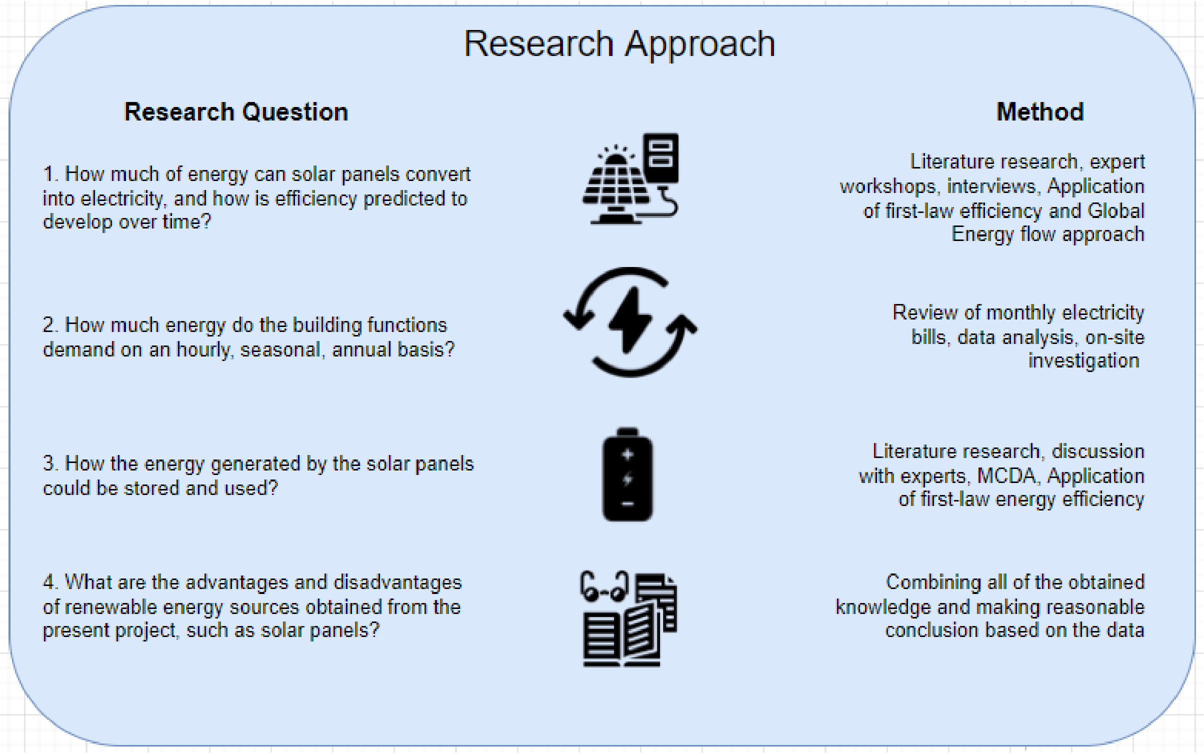
- To what extent do PVs (photovoltaics) promote human well-being and the environment, improve the financial elements of a building related to energy expenditure, and assure independence from geopolitical crises and supply chain disruptions related to a cold storage warehouse? The building itself is located in Sofia, Bulgaria.
    - How much energy do the building functions demand on an hourly, seasonal, and annual basis?
    - How much solar energy can solar panels convert into electricity, and how is their efficiency predicted to develop over time (degradation percentage)?
    - How could the energy generated by the solar panels be stored and used?
    - What are the advantages and disadvantages of renewable energy sources obtained from the present project, such as solar panels?

5. Methodology

This chapter discusses the methods that were utilized during the project's execution. A summary of most of the approaches is shown below followed by a more detailed explanation of the application of these methods for different purposes.

- On-site investigation and experiments
- Literature review, expert workshops, discussion with stakeholders, data collection and analysis
- Multi Criteria Decision Analysis (MCDA)
- Application of the First-law energy efficiency
- Global Energy Flow approach

It is important to formulate a methodology that can be applied to answer the research questions. For better understanding a graph is developed showing the connections between the research questions and the methods. The visualisation is shown in Figure 3. The overall goal is to gather answers to each of the research questions and provide relevant results at the conclusion of the project.



Research Approach

Research Question	Method
1. How much of energy can solar panels convert into electricity, and how is efficiency predicted to develop over time?	Literature research, expert workshops, interviews, Application of first-law efficiency and Global Energy flow approach
2. How much energy do the building functions demand on an hourly, seasonal, annual basis?	Review of monthly electricity bills, data analysis, on-site investigation
3. How the energy generated by the solar panels could be stored and used?	Literature research, discussion with experts, MCDA, Application of first-law energy efficiency
4. What are the advantages and disadvantages of renewable energy sources obtained from the present project, such as solar panels?	Combining all of the obtained knowledge and making reasonable conclusion based on the data

Figure 3. Research questions and methods

5.1. Discussion with stakeholders (General for the whole project)

This method was not specifically assigned to a particular research question. However, to achieve complete understanding of the overall situation, a discussion with the stakeholders was carried out at the beginning of the project execution. First of all, the input data regarding the building characteristics was determined with the external supervisor. The main possible solutions and concepts were discussed, and direction of the project was given. After that, exchange of views with different experts, two electrical and one structural from the company were made. To prevent biases, extra literature was used and the opinion of a neutral electrical engineer who is not directly engaged in the project's implementation was taken into account. There was no clear method for determining if an expert's advice is beneficial or not, if it was biased or insufficiently qualified for the specific topic. Also, the resources that we had are limited, therefore we could not ask infinite number of experts. However, what could be done, was to identify the "good" experts based on their working experience (for example, what kind of projects they participated in), to be technically prepared, ask very specific questions which require mostly expert knowledge and not just an opinion, make it clear and simple and avoid subjective questions. Furthermore, a consultation with the current clients (BILLA, METRO, LIDL) about the new changes, the perspectives and benefits for the business were made. In Appendix B most of the questions that were asked to the company and clients are shown.

5.2. Methodology related to Research Question 1 - How much energy do the building functions demand on an hourly, seasonal, annual basis?

In order to understand how to optimize and improve the current power grid and energy efficiency of the cold-storage warehouse, most importantly, it is required to collect data about the exact energy consumption during the whole year. It was expected that in the summer, when the temperatures are higher and the sun is shining over the building, making the surface warmer, the energy consumption will be the highest because the most energy would be needed for the cooling compressors to cool down the warehouse. In the same way, during the winter, the consumption of energy would be lower. However, for precise results, the exact amount of energy is needed which is why the best method is to get the monthly electricity bills which show the exact amount of energy.

An official statement towards the company-executor of the project has been sent to get the monthly payments for electricity. The received file consists of an excel table which shows power supply consumption of 2020 year per 15 minutes, per day and per month. From there, the average hour, day and month consumption were determined, as well as the total annual consumption of the building (data analysis).

After that a graph depicting the building's energy usage over a 24-hour period was constructed, in order to better comprehend the building's electric consumption. For each season of the year, one representative month was chosen. In this way, January represented winter, April – spring, July – summer and October – autumn. For each of the chosen months, an excel table was created consisting of the 15 minutes consumption over the day. For most accurate results, an average was created over all days in the month per 15 minutes interval. As a result, a graph for each season was created showing the consumption of the cold-storage warehouse for 24-hour period. To compare the values and the pattern between the different seasons, a final graph was created consisting with the data of all 4 seasons.

5.3. Choice of solar panel model

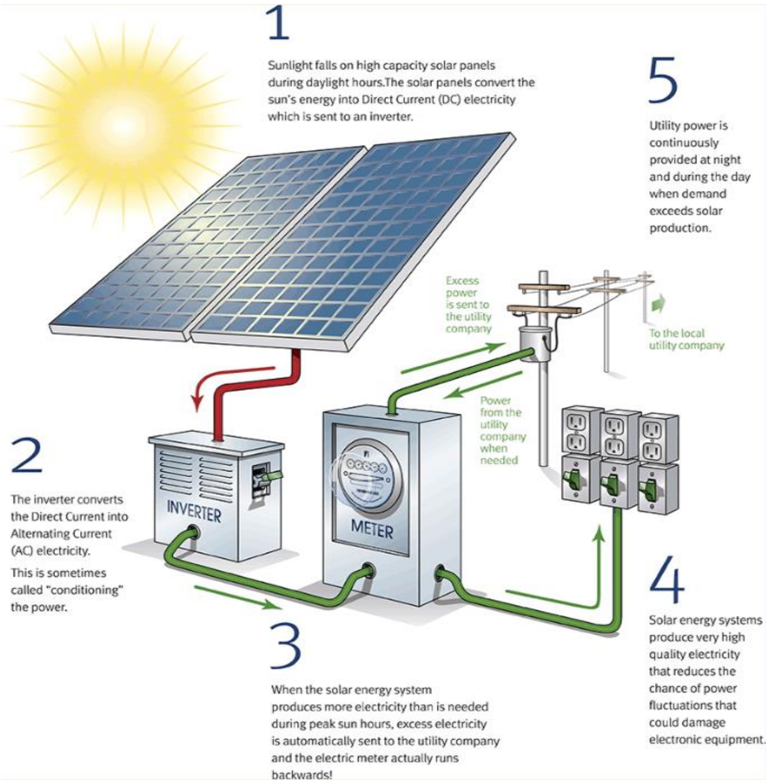
To choose a specific model of solar panels, a criterion with the company was determined. As a result, from one of the interviews with the company ("What criterion do you have for the choice of solar panels?"), the requirements were set to be: cost, efficiency, power output, degradation over the years and warranty. Many panels were found in the web, and they were compared based on the above-mentioned criteria. The final decision was mostly dependent on the company (the client in this case).

5.4. Methodology related to Research Question 2 - How much solar energy can solar panels convert into electricity, and how is their efficiency predicted to develop over time (degradation percentage)?

Literature research is vital element of resolving any question. It provides the reader with different points of view and alternatives, which is why this method was used. This was done by reading and comparing different publications and sorting the relevant information. In this situation, many scientific search engines such as Google Scholar, Web of Science, Scopus, and others were employed. Various keywords, such as renewable energy, solar panels, efficiency, degradation, and so on, were utilized to synthesize the information.

Expert workshops consist of meetings with stakeholders and experts to discuss the potential decisions and the outcome. For example, after good amount of research was done, it was presented and consulted with experts and other interested parties to exchange views and eventually deliver the best possible solution. The case with the interviews was the same, where the opinion of external parties was taken into consideration. Both methods were employed since they took into account as many perspectives as feasible and benefit the project's final conclusion.

According to the University of Minnesota Duluth, a solar panel generates energy by enabling photons, or light particles, to knock electrons loose from atoms. Solar panels are made up of numerous smaller components called photovoltaic cells, which convert sunlight into energy. A solar panel is made up of several cells that are joined together (A. Harvey, 2022). To understand better the process of producing electricity, an image showing the general steps is shown in Figure 4. The most significant benefit of PV technology is that the sun provides an endless supply of electricity. The panels' efficiency, on the other hand, is rather low, 15-18 percent. The most obvious concern is that solar energy is unevenly distributed and intermittently generated. Despite these constraints, it is conceivable to power the entire planet and make a change for good (Bielinskas, 2012).



1

Sunlight falls on high capacity solar panels during daylight hours.The solar panels convert the sun's energy into Direct Current (DC) electricity which is sent to an inverter.

2

The inverter converts the Direct Current into Alternating Current (AC) electricity.

This is sometimes called "conditioning" the power.

3

When the solar energy system produces more electricity than is needed during peak sun hours, excess electricity is automatically sent to the utility company and the electric meter actually runs backwards!

4

Solar energy systems produce very high quality electricity that reduces the chance of power fluctuations that could damage electronic equipment.

5

Utility power is continuously provided at night and during the day when demand exceeds solar production.

Figure 4. How solar energy is produced (Caminiti, 2021)

The first law of energy was unavoidably used to determine the efficiency of solar panels. This method was in the core of energy calculation. It states that energy cannot be created or destroyed but can be converted from one form of energy to another. Solar Energy System was developed and shown in Figure 5 to illustrate the transition from sun to electricity. We were interested in the Primary Energy, Secondary Energy and Final Energy.

Primary Energy is the energy sources, which are provided by nature in direct form, such as natural gas, oil, uranium, firewood and so on. For this technology the solar radiation will be primary energy. According to UTIA, University of Tennessee, the energy from sun is $1000W/m2$ on a clear day.

The secondary energy would be electricity, which means that the primary energy is converted into electricity. It equals the amount of energy the solar panel could generate.

The final energy in our case would also be electricity. However, due to losses caused by the distribution in the power line, wiring etc., the losses from secondary to final energy are estimated to be roughly about 10%. This number is used widely by experts in this field; therefore, it was used in this study as well.

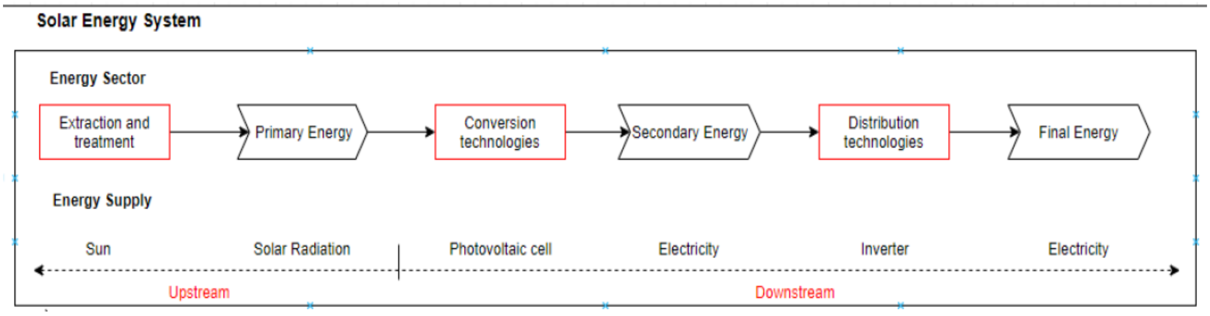


Figure 5. Solar Energy System

The efficiency is determined by numerous of parameters, including the amount of sunlight received by the panel, its direction relative to the sun, temperature, and a range of other variables. The simplest approach to determine the efficiency of a solar panel was to look at the product specifications provided by the developer. However, we wanted to check this by ourselves and make a comparison. The most straightforward method used for efficiency of solar panels was to multiply the amount of sunlight that hits the earth's surface in our area (known as the "incident radiation flux") by the area of our panel (measured in square meters) and divide the maximum wattage on the panel by this number (Human, 2021). This is shown in the formula below:

$$Efficiency\ (\%) = \frac{\frac{Pmax}{Area}}{1000} * 100\%$$

Where:

- $Pmax - solar\ panel\ peak\ power\ (Watts)$
- $Area - the\ area\ of\ the\ solar\ panel\ (m^2)$
- $1000 - STC\ (Standars\ Test\ Condition)\ irradiance\ (\frac{Watts}{m2})$

This was the best theoretical method to apply in our study due to the lack of complexity and the reduced amount of required parameters. Also, the results were expected to be reliable and creditable enough.

The next step was to estimate the number of solar panels that could be installed on the roof of the building. For this purpose, the technical drawings of the warehouse made in AutoCAD were used. The scheme can be seen in Appendix C. The total area of the roof was measured. After that, the useful area of the roof was defined because the solar panels could not be installed everywhere. After consultation with a construction expert from the company, the result was about 80% of the total roof area could be used for solar panels. The potential number of installed solar panels would be:

$$Number\ of\ solar\ panels = \frac{Useful\ area\ of\ the\ roof}{Area\ of\ the\ solar\ panel}$$

From here, the potential electricity produced by the solar system per hour could be defined in the following way:

$$System\ Energy\ Output = Number\ of\ solar\ panels * Pmax\ of\ the\ solar\ panels$$

To calculate the total potentially produced sun energy per year, a specific software was used provided by Apex Solar OOD. The program uses the percentage of loss in the system, the total number of sunshine hours and the solar system power output. The detailed information about calculating sun hours can be found in Appendix D.1.

However, it was unknown whether the software considers the different irradiance values because depending on the month and the period of the day, this value differs. In perfect conditions, the irradiance value is $1000W/m^2$, but this is not realistic. For example, the irradiance in July at 9 o'clock is lower than the irradiance at 13:00 o'clock. Therefore, it was decided to calculate manually the total energy production and compare it to the previously gained results and see how reliable the program is.

To do so, it was used PVGIS Photovoltaic Geographical Information System provided by the European Commission (PVGIS Photovoltaic Geographical Information System, 2022). By giving coordinates of the specific location, this tool gave information about the average irradiance for the selected month on hourly bases. An excel table was created with all 12 months of the year for the hours starting at 4:00 o'clock and ending at 20:00 o'clock. An average value of the irradiance was created for each month. By having this value and counting the number of sun hours for each of the months on average, the potentially produced energy per day was determined. From there, the produced energy was multiplied by the number of days in the month and the total energy per month was defined. Finally, the total annual energy was calculated.

The next step was to show on a graph and compare the values between potentially produced energy by the solar panels and the actual consumption of the cold storage warehouse each month. The electricity from the solar panels is produced only during the day, but the building uses electricity 24-hours. This implies that even if we do not create more energy than the building consumes overall, there would be times when there is a surplus of electricity while the solar panels are operational. The aim was to reproduce a graph which simulates the real consumption of the building and the production of electricity. In this way it could be seen whether there was a surplus of energy and how much it was. To do so, consultation with an expert in the field has been carried. A real project example of the production of energy in ideal conditions (mostly sunny during the whole day) is given in Appendix D.2.

Finally, the degradation percentage was examined. According to NREL (national laboratory of the U.S. Department of Energy) study, solar panels degrade at a rate of roughly 0.5 percent every year. A 0.5 percent degradation rate means that the output of a solar panel will drop by 0.5 percent every year.

This indicates that the module is producing almost 90% of the power it produced in year one in year 20 (D. Jordan, 2015). Furthermore, the provided data for the chosen solar panel was used.

5.5. Methodology related to Research Question 3 - How could the energy generated by the solar panels be stored and used?

The principle for the following methods: literature research, discussion with experts and the application of first-law energy efficiency was explained in the methodology part of Research Question 2, therefore, no repetition is needed. The differences are related to the keywords, which in this case were "energy generation, energy storage, solar panels, efficiency, batteries, hydrogen, etc.". The reasons for the use of these methods overlap with the previous explanation.

For this project, different energy storage alternatives were proposed such as Hydrogen, Solar Batteries, Sale of Electricity, Hybrid (solar batteries + sale). To justify the final choice, Multi Criteria Decision Analysis (MCDA) was created. This is the best method to be applied in the current situation because MCDA is both a method and a collection of procedures aimed at producing an overall ranking of possibilities, from the most favoured to the least liked. It is a process of looking at complex problems with a mix of monetary and non-monetary objectives, breaking the problem down into more manageable pieces to allow data and judgments to be applied to the pieces, and then putting the pieces back together to present a coherent overall picture to decision makers (E. House, January 2009). Furthermore, the approach is simple to implement and does not require the use of additional resources, which can make the analysis unfeasible.

Multi Criteria Analysis may be performed in a variety of ways. As a result, in the following paragraph, several of them were compared and the best-fitting one based on our needs was selected.

The first approach to be investigated was the Weighted sum model (WSM), also known as simple additive weighting (SAW). This is the most well-known and simplest multi-criteria decision analysis approach for weighing a variety of alternatives against a set of decision criteria. The principle of work is given in Appendix E.1.

Another approach was the so-called Analytical Hierarchy Process (AHP) which is more complex than the Weighted sum model. A pairwise comparison of the criteria is done to find the weight of each criterion. Finally, the alternatives are ranked and, in this way, the best one is chosen. Users generally find the pairwise comparison form of data input straightforward and convenient. Because the pairwise comparison matrix contains some redundant information regarding relative values, some cross-checking is possible. The resulting weights or scores may be more stable and consistent than if they were based on a restricted range of judgments, according to some. AHP also works well in situations where judgments, rather than, example, performance metrics, are the primary kind of input information. However, as with all methods, there are weaknesses and limitations as well. The rank reversal phenomena, in particular, has raised concerns. This is the potential that by just adding another choice to the list of alternatives being considered, the ranking of two other options that are unrelated to the new one can be reversed. Another possible problem could be the use of the 1-10 scale which has the potential to be inconsistent (E. House, January 2009). To avoid some of the concerns, the scale and the criteria needs to be explained and well-grounded by literature. For example, why option A scores 5, whereas option B scores 7.

There were other methods, such as ELECTRE, PROMETHEE, TOPSIS which are more complicated to work with, need additional parameters and most of the times require specific software to work with. Therefore, due to the complexity and time-consuming nature, these methods were not to be selected to work with. In research for hydropower plants in the Alpine area, seven different MCDA methods were applied (SHARE MCA, SAW, WPM, AHP, TOPSIS, VIKOR, ELECTRE III) and the obtained results were compared to each other. The outcome from VIKOR and ELECTRE could not be directly compared to the others because the results were of different format. However, the rest scored quite the same (Basso, 2021). This indicates that the complexity of a method does not define it as more accurate. The full table with the final rankings from each method could be seen in Appendix A, Table 12.

For the current project, it seemed appropriate to make a combination between Weighted sum model and Analytical Hierarchy Process. Simply put, the pairwise comparison which is part of the AHP is sued within the Weighted sum. Both methods separately are straightforward and relatively easy to explain to a non-technical user. In addition, they do not require too much time to be set and special software. It was expected that by combining both methods, some of the weaknesses would be eliminated or lowered to certain extend. The scale had to be set carefully, all criteria and alternatives needed to be defined from the beginning, to limit the chance of reversing options or manipulating the results.

Before explaining in details, the steps of conducting an MCDA, a literature review was done separately for each energy storage alternative and the information is presented in the form of bullet points in Appendix E.2. This would help the reader to understand the reasoning behind some of the scores given later in the MCDA.

5.5.1. MCDA

Out of the wide range of MCDAs, combination between Weighted sum model and Analytical Hierarchy Process was chosen for this project. It consists of a specific algorithm which is listed below.

1. Definition of alternatives and criteria
2. Determination of the weights
3. Consistency check
4. Relative Ranking

5.5.1.1. Definition of alternatives and criteria

- Alternatives

The alternatives explained above will be used for the analysis: Alternative 1 – Hydrogen, Alternative 2 – Solar Batteries, Alternative 3 – Sale of Electricity, Alternative 4 – Hybrid (sale + solar batteries storage).

- Criteria

Six major criteria were chosen for the following analysis: Cost, Environmental Impact, Maintenance, Independence, Storage ability, Complexity. Each one of them is explained below to help the reader.

By Cost it is meant the installation costs, the cost of the equipment and the additional technologies needed. For example, the equipment required for the make of hydrogen or the installation of the batteries itself.

Environmental Impact represents a positive quality. It means how much the specific alternative contributes to the environmental wellbeing. For example, how much it reduces the CO_2 emissions.

By Maintenance is meant the after installation required maintenance during the years. For example, the correct exploitation of the batteries, the change of parts, consummative and etc.

Independence is the ability to continue the work of the cold-storage warehouse in case of power outage or some extreme conditions which are unfavourable for the company.

By Storage ability is meant the amount of time that the energy could be stored without discharging and losing power and the degradation of the storage capacity over time.

By Complexity is meant how complex the process of storing energy is, how much time, equipment and specialised working force requires.

5.5.1.2. Determination of matrix weights

The weights were adjusted in this section of the study based on pairwise comparisons between each of the criteria, using Saaty's comparison scale, which can be seen in Appendix F.1, Figure 21.

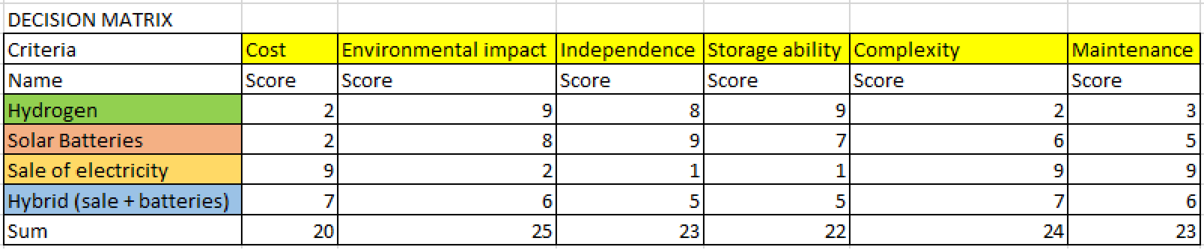
5.5.1.3. Consistency check

To verify if the subjective decisions done previously were consistent, the consistency ratio was calculated. The ratio could be maximum 10%, if higher the subjective judgement was inconsistent and needs to be repeated. All steps of checking the ratio could be seen in Appendix F.2.

5.5.1.4. Relative Ranking

Decision Matrix scores are explained here. The score is from 1 – 10 (1 is the worst, 10 is the best).

Table 1. Decision Matrix



DECISION MATRIX						
Criteria	Cost	Environmental impact	Independence	Storage ability	Complexity	Maintenance
Name	Score	Score	Score	Score	Score	Score
Hydrogen	2	9	8	9	2	3
Solar Batteries	2	8	9	7	6	5
Sale of electricity	9	2	1	1	9	9
Hybrid (sale + batteries)	7	6	5	5	7	6
Sum	20	25	23	22	24	23

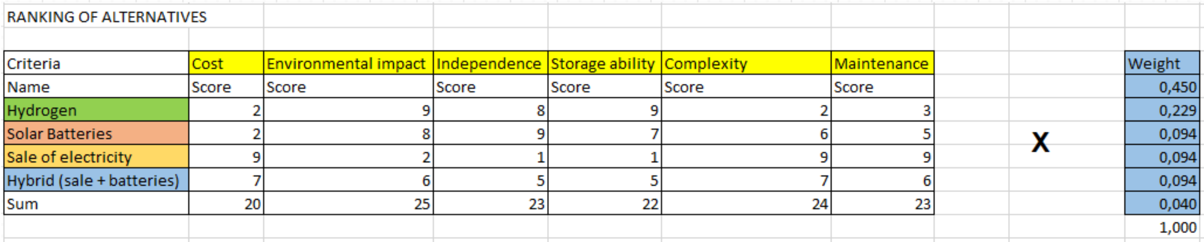
- Cost: Hydrogen and solar batteries received the lowest grade of 2 because they demand a significant financial investment in technology and extra equipment. The needed batteries would cost roughly $2 million (Solar Choice Staff, 2022), and the process of producing hydrogen, as explained above, demands a significant amount of resources and time. The cheapest option is to sell directly to the main power grid, as there are essentially no fees with this option. The final option, the hybrid, was ranked in the middle because the battery investment is substantially lower.
- Environmental impact: Because the produced energy comes from a renewable source, hydrogen and solar batteries rank the highest in this category. Hydrogen has a modest advantage over solar batteries since the only end result of its utilization is water, whereas solar batteries release heat. The sale of energy has the lowest score of all since, by selling to the main power grid, it does not contribute and promote environmental well-being as much as the others. The hybrid solution looks to be locked in the centre once more, which is why it received a score of 6.
- Independence: Hydrogen received the highest score because, as previously stated, it can store an indefinite quantity of energy, allowing the cold-storage warehouse to operate for a longer period of time than the others in the event of a power loss. Due to the limited amount of stored energy that solar batteries indicate, they receive a lower grade. To store a large amount of energy, a much larger battery and storage area is required. The worst alternative is to sell power, which does not provide any independence because it does not allow for the storage of electricity. The hybrid option scores somewhere between solar batteries and sale of electricity since it does not allow you to store big amount of energy, but still gives certain level of independence.

- Storage ability: Hydrogen scored the best, because as explained before, the energy could be stored for independent amount of time without any losses. This implies that you are free to utilize as much as you are capable of producing. Furthermore, it does not deteriorate with time. Solar batteries got a lower score since the storage capacity of the batteries degrades over time owing to deterioration. The hybrid was the next option, which is similar to solar batteries but has a lower storage capacity due to the smaller number of batteries. The ultimate and worst alternative was to sell power, which has no storage capacity.
- Complexity: The least complicated option is the selling of power, which does not need the installation of specific equipment and so received a 9. The hybrid option, which consists of the sale of energy and a small battery pack and does not require as much free space, battery cooling, and so on, was the second-best option with a score of 7. The solar batteries came next, with a somewhat lower score due to the fact that there are more components in the system. The worst of all was hydrogen, which needs reservoir tank, specialized equipment, and highly trained personnel. In addition, in order to use the produced hydrogen, there must be a machine which can work with the hydrogen and generate energy.
- Maintenance: The highest-scoring alternative was the selling of energy, which does not need any special or frequent maintenance aside from the use of appropriate cables for power delivery. Solar batteries received a 5 because they must be put in a suitable location and the exploitation must occasionally be checked to ensure that it is as indicated in the product specifications. Only because the hybrid option has less batteries, which means less maintenance, it scored slightly higher than solar batteries. Finally, with a score of 3, hydrogen was the poorest. It necessitates routine maintenance of the hydrogen-producing equipment. Furthermore, competent professionals who know how to operate with hydrogen systems are difficult to come by in Bulgaria.

5.5.1.5. Final Score

To compute the final score, matrix multiplication on the decision matrix and eigenvector needs to be applied. The higher the score, means the higher ranking. In Table 2 the process is illustrated. Each value of each row needs to be multiplied with the corresponding row value of the weight (eigenvector).

Table 2. Final Score Calculation and Ranking



RANKING OF ALTERNATIVES

Criteria	Cost	Environmental impact	Independence	Storage ability	Complexity	Maintenance		Weight
Name	Score	Score	Score	Score	Score	Score		0,450
Hydrogen	2	9	8	9	2	3		0,229
Solar Batteries	2	8	9	7	6	5	X	0,094
Sale of electricity	9	2	1	1	9	9		0,094
Hybrid (sale + batteries)	7	6	5	5	7	6		0,094
Sum	20	25	23	22	24	23		0,040
								1,000

5.6. Methodology related to Research Question 4 – What are the advantages and disadvantages of renewable energy sources obtained from the present project?

Finally, after addressing the first three Research Questions, the data may be thoroughly reviewed, and the benefits and drawbacks stated. This was accomplished by synthesizing all of the acquired knowledge and drawing appropriate conclusions based on the facts before making suggestions.

6. Results

6.1. Energy consumption of the building functions – Research Question 1

This chapter shows the results related to Research Question 1 – "How much energy do the building functions demand on a hourly, seasonal, and annual basis?" in accordance to methodology, section 2. The consumption of the cold-storage warehouse is depicted in Table 3. It shows the average consumption per hour, per day, per month and annually. The total consumption of the building is 3090.246 MW. The results were successfully derived with the help of the interviews with the company.

Table 3. Average energy consumption per hour, day, month and year

Month (2020)	Energy Consumption (MW)
January	201,7255
February	202,5805
March	220,2705
April	208,7155
May	290,61375
June	294,4035
July	332,86925
August	332,5355
September	296,557
October	272,4155
November	222,418
December	215,1415
On average per hour	0,3527
On average per day	8,4664
On average per month	257,5205
Total (Annual)	3090,246

The graphs showing the 24-hour average consumption in January – winter, April – spring, July – summer and October – autumn are shown below. The peak consumption of January is recorded to be 79.63 kWh and the peak in July is 135.83 kWh. The large discrepancy is due to the ambient temps. The outside temperatures are substantially lower in the winter, which aids in the cooling of the cold-storage warehouse and reduces the amount of energy required to maintain negative temperatures inside. However, the patterns of energy usage in both graphs are remarkably similar in relation to the hour of the day. It can be observed that the building consumes roughly the same amount of power throughout the day. This indicates that the solar panels could not meet the energy needs of the building, because during the night, the warehouse is functional, whereas the photovoltaics are not.

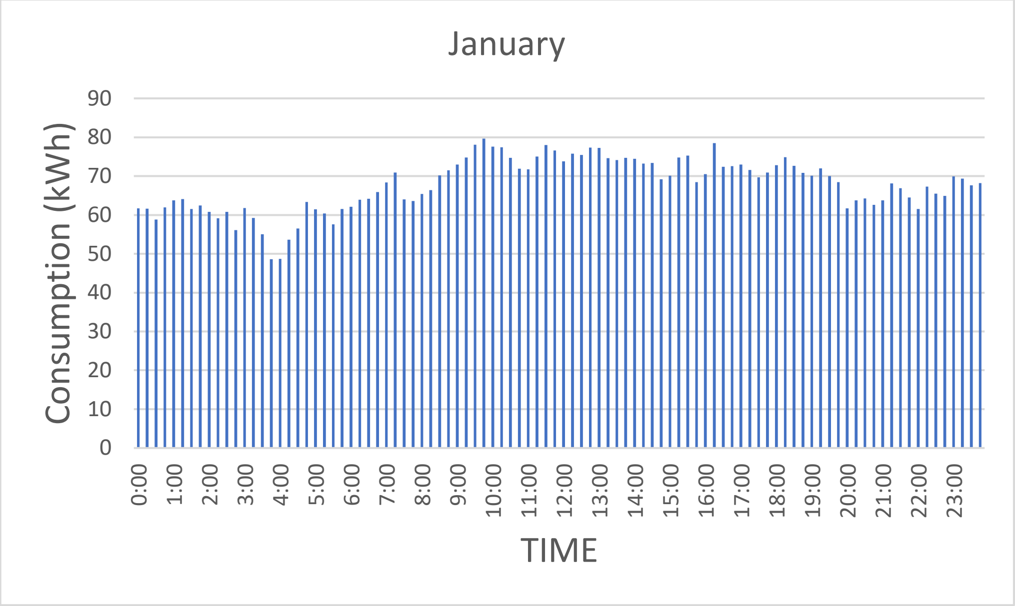


Figure 6. Average energy consumption in January

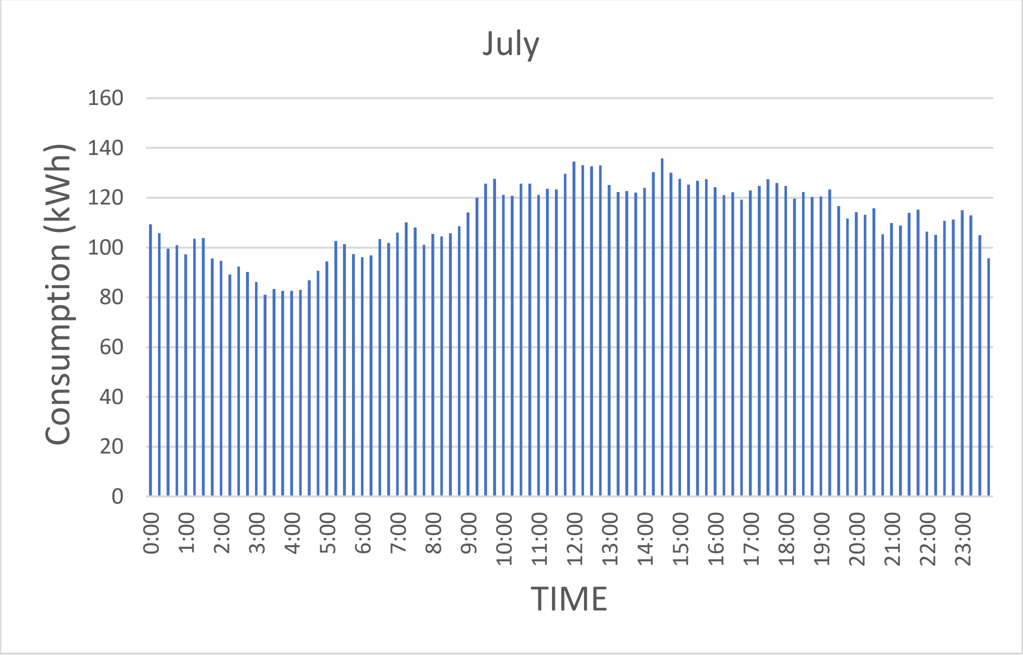


Figure 7. Average energy consumption in July

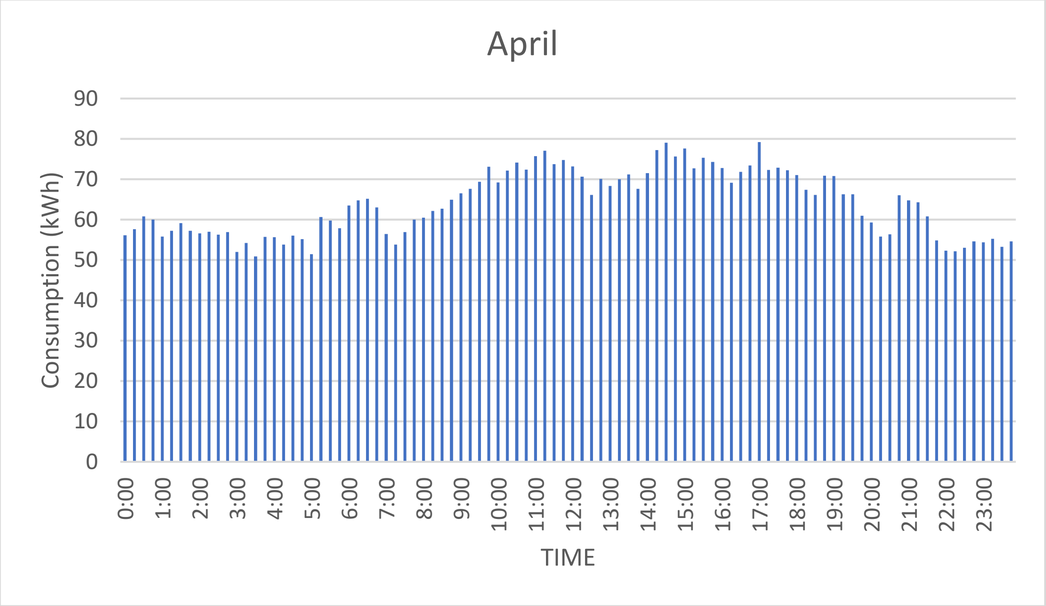


Figure 8. Average energy consumption in April

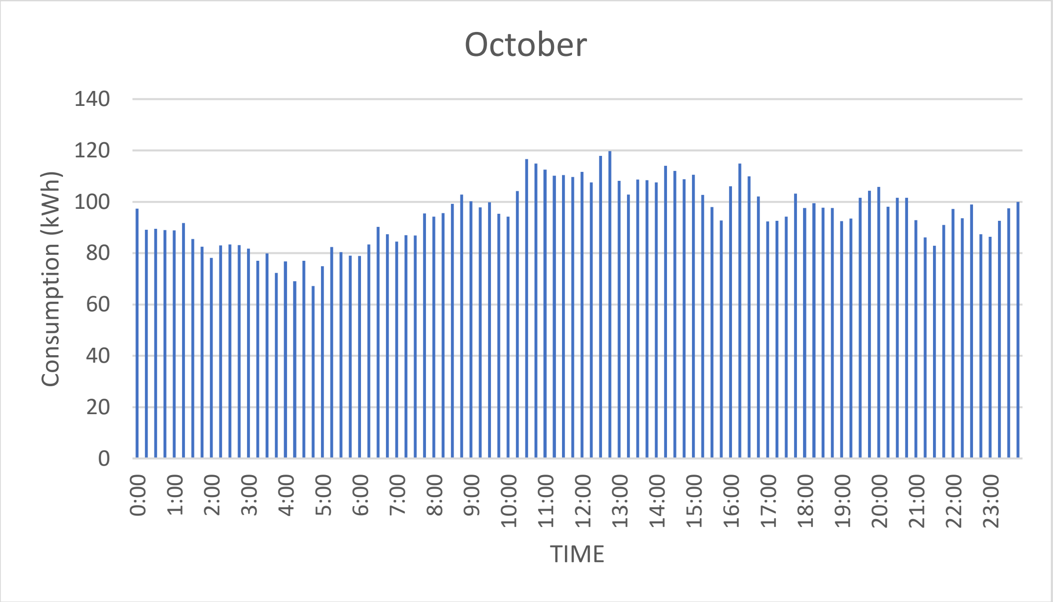


Figure 9. Average energy consumption in October

Finally, to compare the results, all months are plotted on the same graph in Figure 10. It can be seen that the patterns are very similar to each other.

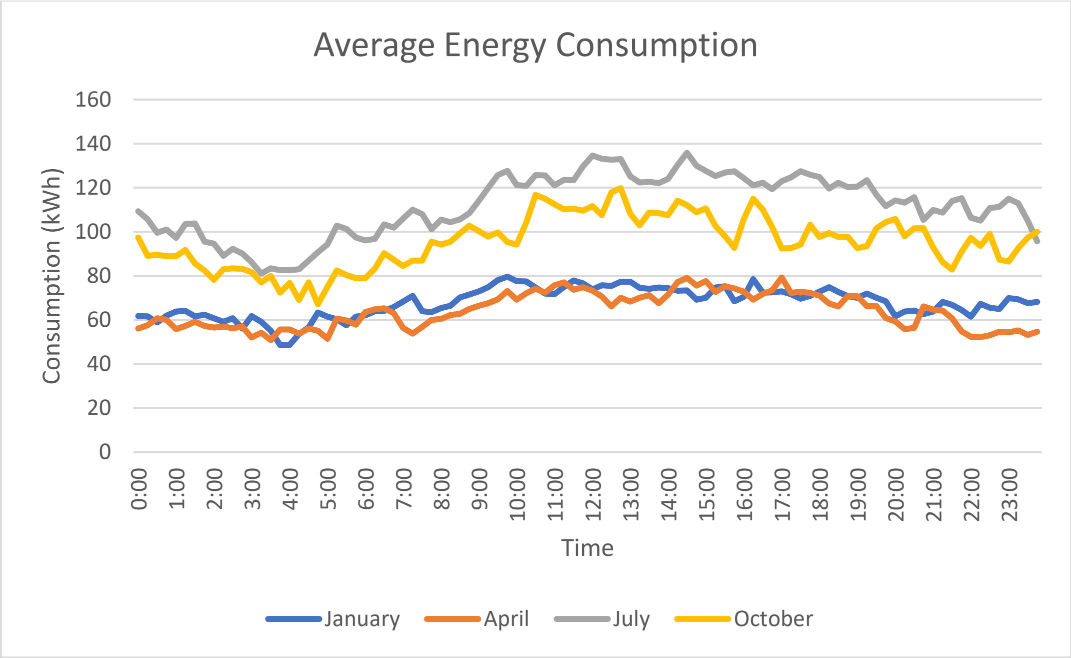
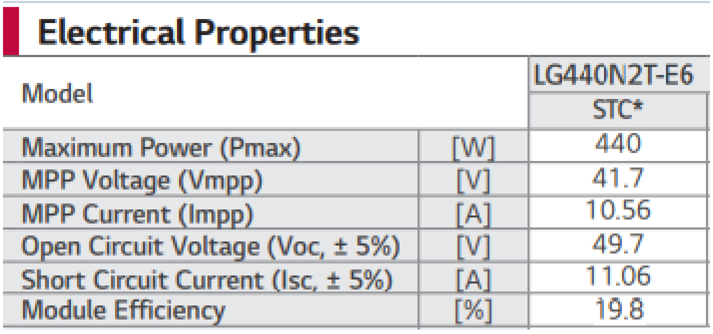


Figure 10. Average energy consumption for January, April, July and October

6.2. Choice of solar panel – preparation for Research Question 2

Before determining the efficiency of the solar panels and the amount of energy that can be produced, the exact solar panel type needs to be defined, which is why this chapter was linked to Research Question 2. This is done according to the explanation in methodology, section 3. The model of the solar panel that has been chosen to be used is LG Neon H Bifacial (LG440N2T-E6) with module dimensions (L x W x H) = 2,130 x 1,042 x 40 mm. This is claimed to be one of the most powerful and versatile modules on the market today with warranty of 25 years. The specific model has characteristics as follows:



Electrical Properties

Model		LG440N2T-E6 STC*
Maximum Power (Pmax)	[W]	440
MPP Voltage (Vmpp)	[V]	41.7
MPP Current (Impp)	[A]	10.56
Open Circuit Voltage (Voc, ± 5%)	[V]	49.7
Short Circuit Current (Isc, ± 5%)	[A]	11.06
Module Efficiency	[%]	19.8

Figure 11. Electrical properties of the solar panel

6.3. Efficiency of the solar panels and total PV system energy production – Research Question 2

This chapter answers Research Question 2 – "How much solar energy can solar panels convert into electricity, and how is their efficiency predicted to develop over time (degradation percentage)?" in accordance with methodology, section 4.

The claimed efficiency of the solar panel is 19.8%. However, this was checked manually as well, as shown below.

$$Efficiency\ (\%) = \frac{\frac{440\ W}{1.04m * 2.13m}}{1000} * 100\% = 19.86\%$$

It appeared that the claimed efficiency by the developer and the calculations coincide. So, the efficiency of transforming the Primary energy into Secondary is 19.9 %, which equals to 199W.

The final energy in our case would also be electricity. However, due to losses caused by the distribution in the power line, wiring etc., the efficiency is estimated to be roughly about 90%. Therefore, the final energy was calculated to be $0{,}9 \times 199 = 179.1 W/m^2$.

The electricity demand of the cold-storage warehouse on average is 257,5 MW/per month. The area of the roof of the building is $8000\ m^2$. The useful area for installing solar panels would be $6400\ m^2$. Potentially the number of solar panels that could be installed is:

$$Number\ of\ solar\ panels = \frac{6400}{2.21} = 2895\ panels$$

The potential electricity produced by the solar system per hour is:

$$2895 * 179.1 \frac{W}{m^2} * 2.21\ m^2 = 1\ 145\ 872\ W = 1145.872\ kW$$

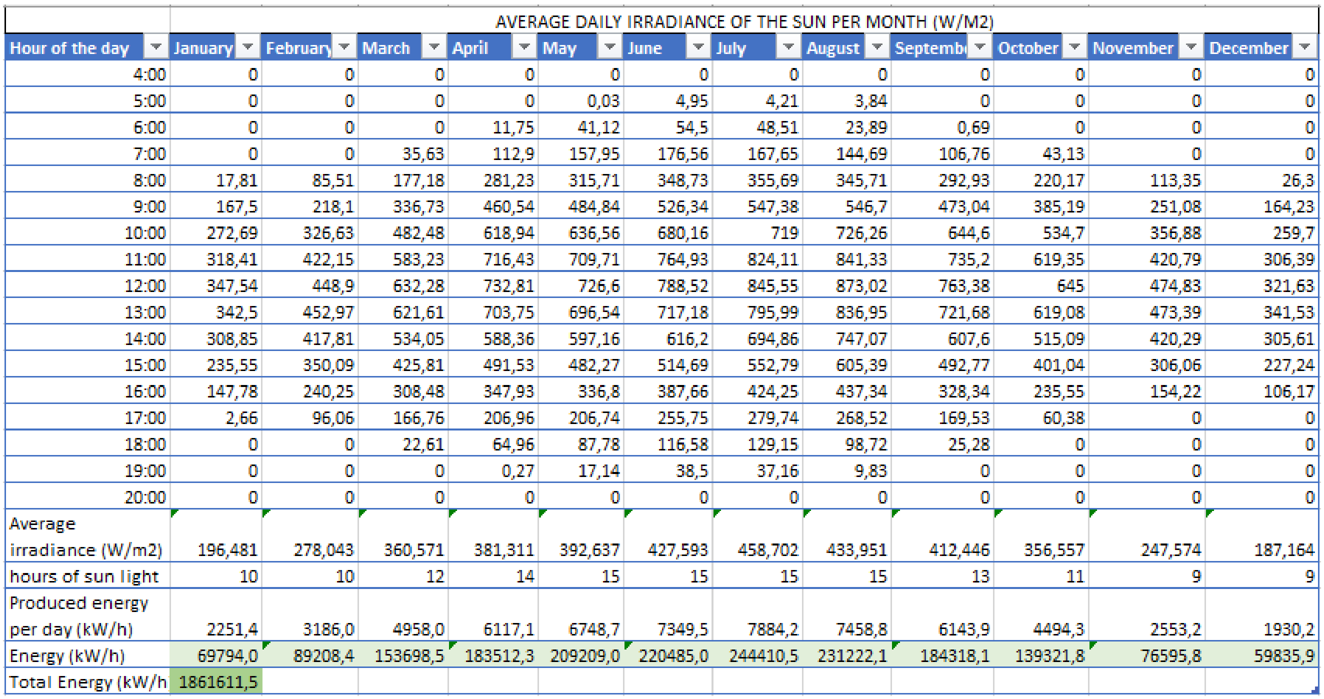
This led us to the number of $1\ 838\ 195\ kW = 1838.195\ MW/year$. Table 4 shows the distribution of sun hours and produced energy for each month.

Table 4. Details related to produced energy based on the month

Month	Sun hours	Production in %	kWh	MWh
January	57,28	3,58%	65807,38	65,80738
February	82,88	5,18%	95218,5	95,2185
March	133,28	8,33%	153121,6	153,1216
April	165,92	10,37%	190620,8	190,6208
May	201,12	12,57%	231061,1	231,0611
June	187,52	11,72%	215436,5	215,4365
July	213,44	13,34%	245215,2	245,2152
August	195,68	12,23%	224811,2	224,8112
September	146,88	9,18%	168746,3	168,7463
October	120,96	7,56%	138967,5	138,9675
November	52,96	3,31%	60844,25	60,84425
December	42,08	2,63%	48344,53	48,34453
Total	1600	100,00%	1838195	1838,195

As explained in the methodology chapter, one more method was used to check the truthfulness of the final result. Table 5 shows the irradiance of the sun per different hour and month. It represents the average irradiance for each month, the sun hours, the produced energy per day and per month. In the end, the total amount of produced energy was calculated which equalled to $1861{,}6115\ MW/year$. This represents a difference of less than 2%. Therefore, it could be said that the software gave reliable information. For future interventions, the manually calculated number of $1861{,}612\ MWh$ was used because it was more precisely calculated. With the help of a special calculator, it was determined a reduction of CO_2 emissions of roughly 433 tons annually (KWH-to- CO2, 2022).

Table 5. Average daily irradiance of the sun per month (W/m2)



	AVERAGE DAILY IRRADIANCE OF THE SUN PER MONTH (W/M2)											
Hour of the day	January	February	March	April	May	June	July	August	Septemb	October	November	December
4:00	0	0	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0,03	4,95	4,21	3,84	0	0	0	0
6:00	0	0	0	11,75	41,12	54,5	48,51	23,89	0,69	0	0	0
7:00	0	0	35,63	112,9	157,95	176,56	167,65	144,69	106,76	43,13	0	0
8:00	17,81	85,51	177,18	281,23	315,71	348,73	355,69	345,71	292,93	220,17	113,35	26,3
9:00	167,5	218,1	336,73	460,54	484,84	526,34	547,38	546,7	473,04	385,19	251,08	164,23
10:00	272,69	326,63	482,48	618,94	636,56	680,16	719	726,26	644,6	534,7	356,88	259,7
11:00	318,41	422,15	583,23	716,43	709,71	764,93	824,11	841,33	735,2	619,35	420,79	306,39
12:00	347,54	448,9	632,28	732,81	726,6	788,52	845,55	873,02	763,38	645	474,83	321,63
13:00	342,5	452,97	621,61	703,75	696,54	717,18	795,99	836,95	721,68	619,08	473,39	341,53
14:00	308,85	417,81	534,05	588,36	597,16	616,2	694,86	747,07	607,6	515,09	420,29	305,61
15:00	235,55	350,09	425,81	491,53	482,27	514,69	552,79	605,39	492,77	401,04	306,06	227,24
16:00	147,78	240,25	308,48	347,93	336,8	387,66	424,25	437,34	328,34	235,55	154,22	106,17
17:00	2,66	96,06	166,76	206,96	206,74	255,75	279,74	268,52	169,53	60,38	0	0
18:00	0	0	22,61	64,96	87,78	116,58	129,15	98,72	25,28	0	0	0
19:00	0	0	0	0,27	17,14	38,5	37,16	9,83	0	0	0	0
20:00	0	0	0	0	0	0	0	0	0	0	0	0
Average irradiance (W/m2)	196,481	278,043	360,571	381,311	392,637	427,593	458,702	433,951	412,446	356,557	247,574	187,164
hours of sun light	10	10	12	14	15	15	15	15	13	11	9	9
Produced energy per day (kW/h)	2251,4	3186,0	4958,0	6117,1	6748,7	7349,5	7884,2	7458,8	6143,9	4494,3	2553,2	1930,2
Energy (kW/h)	69794,0	89208,4	153698,5	183512,3	209209,0	220485,0	244410,5	231222,1	184318,1	139321,8	76595,8	59835,9
Total Energy (kW/h	1861611,5											

After that, the produced energy for each month is compared to the consumed energy per month. The result is presented below in Table 6.

Table 6. Monthly produced and used energy

Month	Produced energy MW/month	Used energy MW/month
January	69,794011	201,7255
February	89,208385	202,5805
March	153,6985	220,2705
April	183,51232	208,7155
May	209,20904	290,61375
June	220,48501	294,4035
July	244,41048	332,86925
August	231,22214	332,5355
September	184,31809	296,557
October	139,32179	272,4155
November	76,595842	222,418
December	59,835894	215,14
Total (year)	1861,6115	3090,2445

Using the above presented information, a graph was created showing visually the amount of produced energy against the used energy per month. The visualisation is shown in Figure 12. It can be observed that the energy provided by the solar panels never completely meets the building's needs. However, for a few months, it is coming extremely close. The total produced energy equals to $\frac{1861.612}{3090.245} = 60.24\ \%$ of the required energy per year.

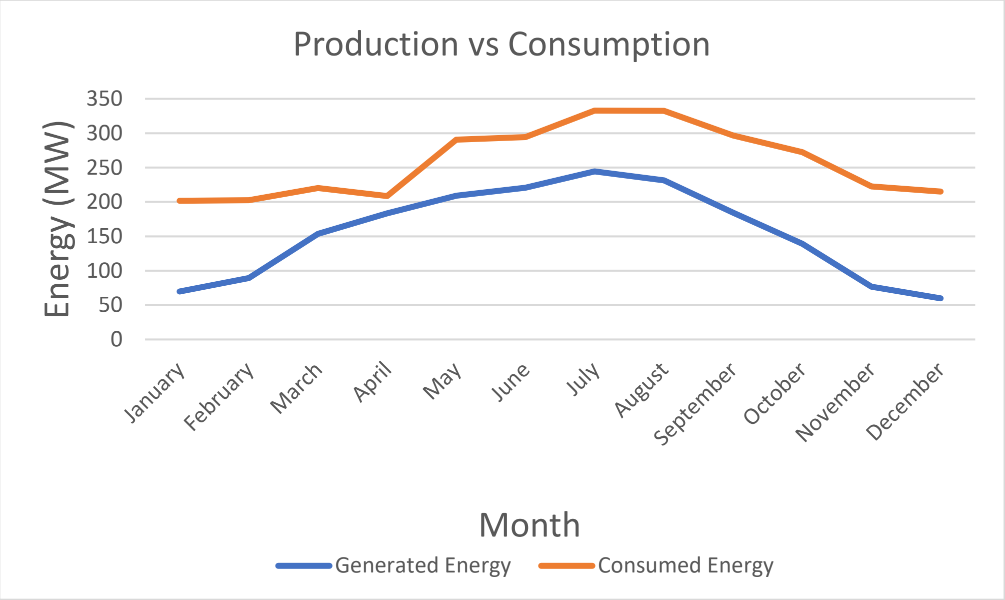


Figure 12. Generated Energy against Consumed Energy

Using the information from Table 5, it became possible to create graphs and tables for each season which represent the actual production against the actual consumption during the hours at which the solar panels are active. It can be seen from the tables and the graphs that there is a surplus of energy which equals the most of 5601 kWh per day in July. However, in the rest of the months there is a surplus as well. It needs to be noted that there was surplus only during the working hours of the photovoltaics and not for the whole day, because the building consumes energy in the night as well when the solar system in inactive.

Table 7. Production vs Consumption of energy in January during the photovoltaics' working hours

January			
Time	Production (kWh)	Consumption (kWh)	Surplus (kWh)
5:00	0,00	61,47	-61,47
6:00	0,00	62,09	-62,09
7:00	0,00	68,33	-68,33
8:00	20,41	65,43	-45,02
9:00	191,93	73,00	118,93
10:00	312,47	77,58	234,89
11:00	364,86	71,71	293,15
12:00	398,24	73,82	324,41
13:00	392,46	77,27	315,19
14:00	353,90	74,42	279,48
15:00	269,91	70,06	199,85
16:00	169,34	70,51	98,83
17:00	3,05	72,94	-69,89
18:00	0,00	72,80	-72,80
19:00	0,00	70,12	-70,12
Total energy (kWh)	2476,56	1061,55	1415,01

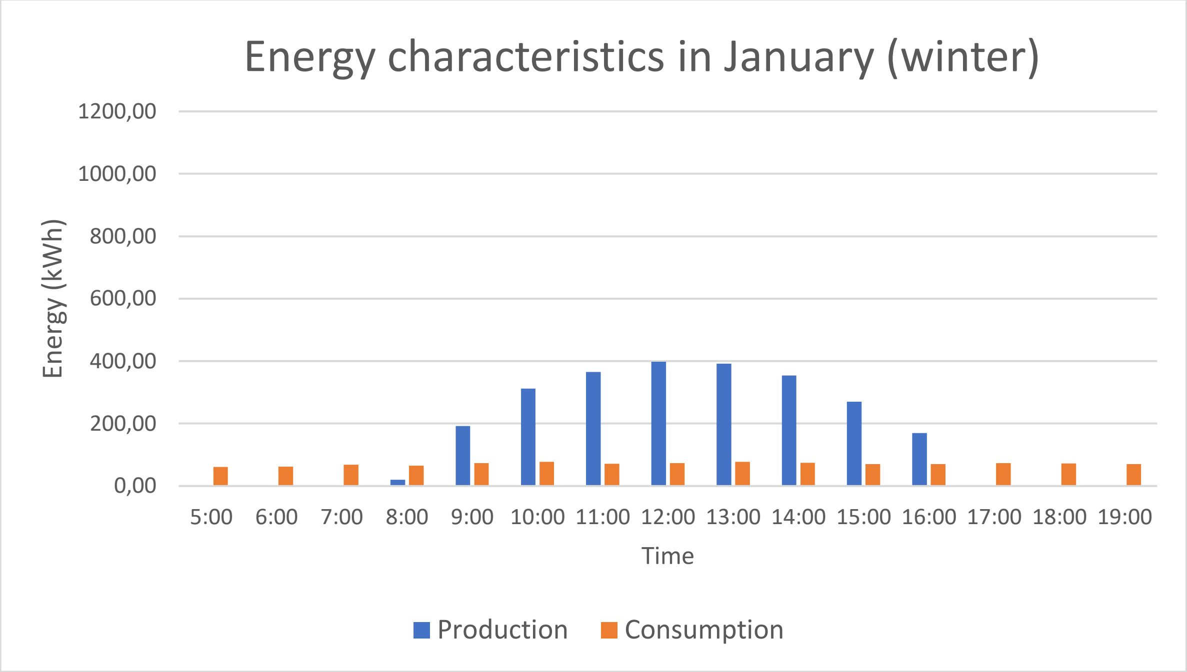


Figure 13. Visual representation of the production against consumption of January in the working hours of the solar panel

Table 8. Production vs Consumption of energy in April during the photovoltaics' working hours

April			
Time	Production (kWh)	Consumption (kWh)	Surplus (kWh)
5:00	0,00	51,45	-51,45
6:00	13,46	63,53	-50,07
7:00	129,37	56,42	72,95
8:00	322,25	60,48	261,77
9:00	527,72	66,48	461,24
10:00	709,23	69,25	639,98
11:00	820,94	75,69	745,25
12:00	839,71	73,22	766,49
13:00	806,41	68,33	738,08
14:00	674,19	71,53	602,65
15:00	563,23	77,64	485,59
16:00	398,68	72,78	325,90
17:00	237,15	79,23	157,92
18:00	74,44	71,02	3,42
19:00	0,31	70,83	-70,52
Total energy (kWh)	6117,08	1027,89	5089,19

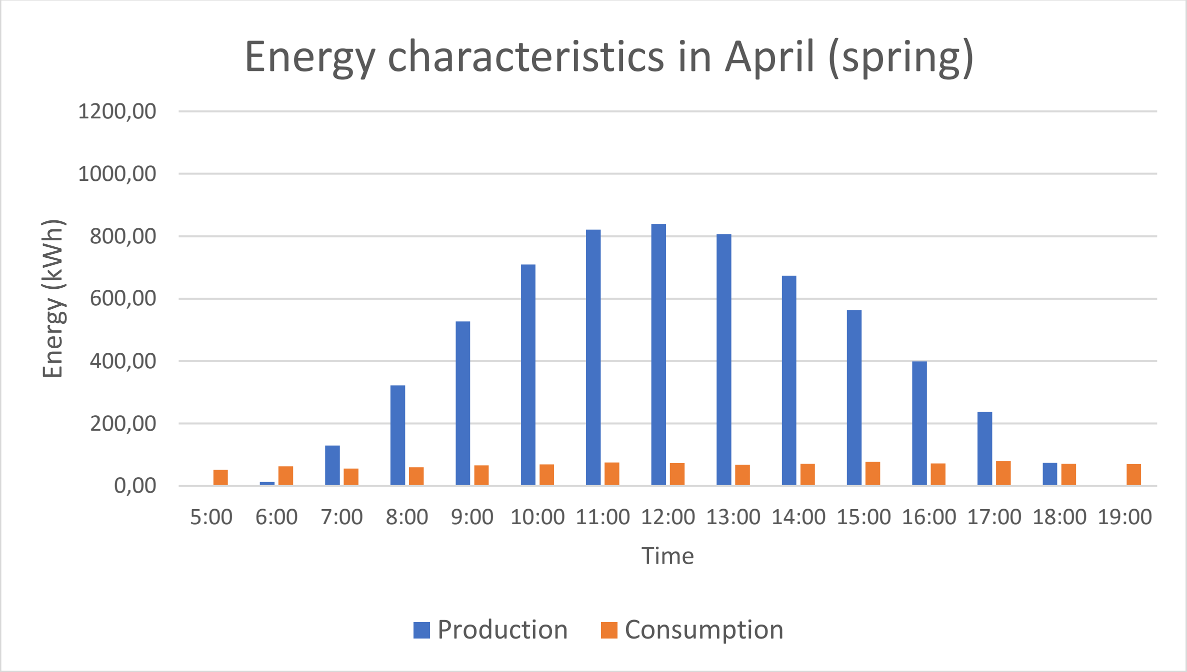


Figure 14. Visual representation of the production against consumption of April in the working hours of the solar panel

Table 9. Production vs Consumption of energy in July during the photovoltaics' working hours

July			
Time	Production (kWh)	Consumption (kWh)	Surplus (kWh)
5:00	4,82	94,35	-89,53
6:00	55,59	96,05	-40,46
7:00	192,11	106,01	86,10
8:00	407,58	105,50	302,08
9:00	627,23	114,13	513,10
10:00	823,88	121,21	702,67
11:00	944,32	121,14	823,19
12:00	968,89	134,55	834,34
13:00	912,10	125,17	786,93
14:00	796,22	123,95	672,27
15:00	633,43	127,54	505,89
16:00	486,14	124,27	361,87
17:00	320,55	122,96	197,59
18:00	147,99	124,79	23,20
19:00	42,58	120,54	-77,96
Total energy (kWh)	7363,42	1762,15	5601,27

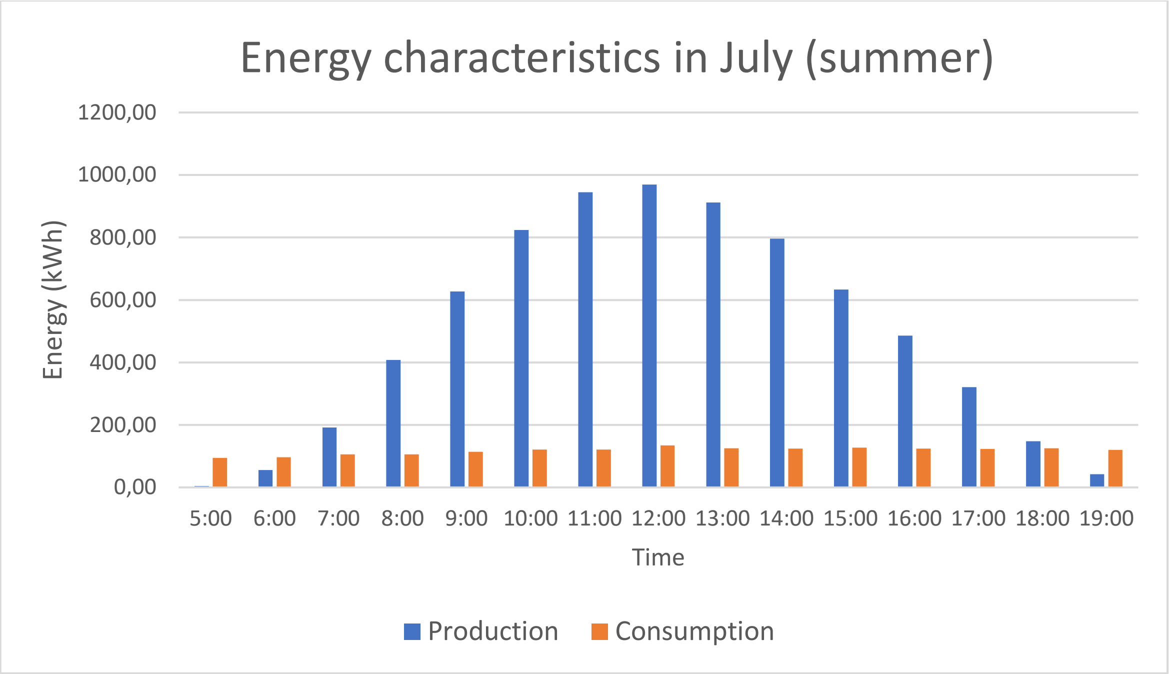


Figure 15. Visual representation of the production against consumption of July in the working hours of the solar panel

Table 10. Production vs Consumption of energy in October during the photovoltaics' working hours

October			
Time	Production (kWh)	Consumption (kWh)	Surplus (kWh)
5:00	0,00	74,93	-74,93
6:00	0,00	78,90	-78,90
7:00	49,42	84,50	-35,08
8:00	252,29	94,17	158,12
9:00	441,38	100,22	341,16
10:00	612,70	94,25	518,45
11:00	709,70	112,47	597,23
12:00	739,09	111,62	627,47
13:00	709,39	108,17	601,22
14:00	590,23	107,55	482,68
15:00	459,54	110,55	348,99
16:00	269,91	106,02	163,89
17:00	69,19	92,40	-23,21
18:00	0,00	97,60	-97,60
19:00	0,00	92,52	-92,52
Total energy (kWh)	4902,82	1465,85	3436,97

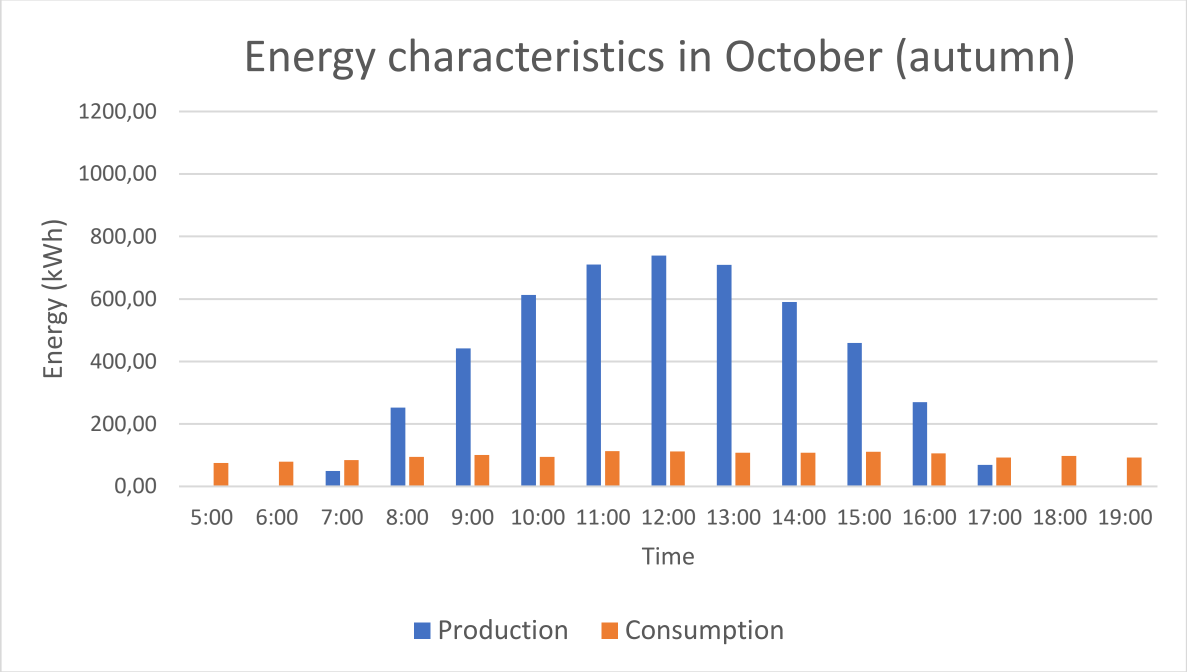


Figure 16. Visual representation of the production against consumption of October in the working hours of the solar panel

Finally, the degradation of the solar panels was analysed. According to NREL (national laboratory of the U.S. Department of Energy) study, monocrystalline solar panels degrade at a rate of roughly 0.5 percent every year. A 0.5 percent degradation rate means that the output of a solar panel will drop by 0.5 percent every year. This indicates that the module is producing almost 90% of the power it produced in year one in year 20 (D. Jordan, 2015). Figure 17 shows the results over 2128 cases.

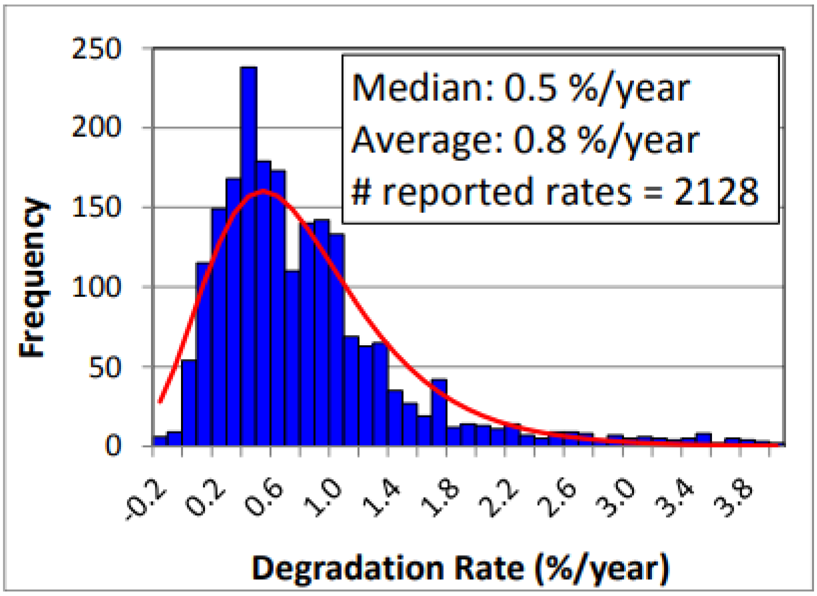


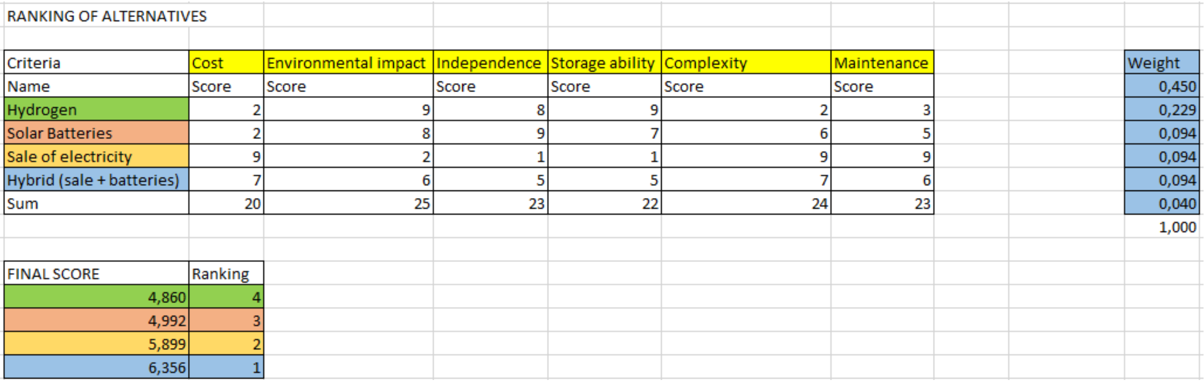
Figure 17. Degradation rate of monocrystalline solar panels (D. Jordan, 2015)

The initially chosen monocrystalline solar panel LG NeON BiFacial provides with 25 years Performance Warranty and guarantees after 25 years of use at least 96.4% of initial performance (LG Global, 2021) This results in an average year degradation of only 0.144%, which was one of the reasons to choose this panel. After 25 years, the solar system would be able to produce at least 1794.6 $MW/year$.

6.4. MCDA – Research Question 3

Finally, the results of the MCDA are discussed. It gives an answer to Research Question 3 – “How could the energy generated by the solar panels be stored and used?”, in accordance with methodology, section 5. Table 11 below shows the final scores and the ranking of the alternatives. As a results, it appears that the best option is the Hybrid one, followed by Sale of electricity, Solar batteries and Hydrogen. The hybrid and sale of electricity are very close to each other, because they both score high on the most influential factor (Cost). In this case, the final choice goes to the Hybrid one, however, the result could be easily flipped by slightly changing the scores and removing or adding a certain criterion which favours only one of the alternatives. This decision could be subject to a discussion, but the final say falls onto the client.

Table 11. Final score and ranking



RANKING OF ALTERNATIVES

Criteria	Cost	Environmental impact	Independence	Storage ability	Complexity	Maintenance	Weight
Name	Score	Score	Score	Score	Score	Score	0,450
Hydrogen	2	9	8	9	2	3	0,229
Solar Batteries	2	8	9	7	6	5	0,094
Sale of electricity	9	2	1	1	9	9	0,094
Hybrid (sale + batteries)	7	6	5	5	7	6	0,094
Sum	20	25	23	22	24	23	0,040
							1,000

FINAL SCORE	Ranking
4,860	4
4,992	3
5,899	2
6,356	1

Lastly, Research Question 4 states “What are the advantages and disadvantages of renewable energy sources obtained from the present project, such as solar panels?” The answer to this question is provided in the “Discussion” chapter, where the interpretation of the above shown results is given.

7. Discussion

The current thesis had as an aim to contribute to the understanding of the installation of solar panels on a cold-storage warehouse. In this chapter, the results and challenges are discussed followed by a discussion whether the proposed design reach the initially set goals (consuming less energy, generating renewable energy, being more independent in energy supply, paying less for energy and having smaller footprint).

First off, Figure 10 demonstrates that the pattern of energy use is mostly constant throughout the year. The cold-storage warehouse consumes electricity continuously, making it impossible for the solar panels to completely meet the building's energy needs because they only produce energy during the day. This means that installing solar panels would be most effective if the building's primary energy use occurred daytime when the solar panels could be used to their maximum potential.

The second finding was that there is still an excess of energy during the day which implies the need of analysing energy storage alternatives The hybrid (solar battery + sale of electricity) was determined to be the optimum choice based on the MCDA analysis. On the one hand, this option results in a reduction of CO_2 emissions of roughly 433 tons annually (KWH-to- CO2, 2022) that, in turn, helps to achieve the ultimate goal of a greater degree of environmental welfare. On the other hand, the smaller battery pack does not provide the client with high margin of energy independence due to the fact that it offers energy for about 2-3 hours.

Next, the financial aspects of installing solar panels will be discussed. The cost of the solar panels is roughly estimated to be between 1.1 and 1.2 million euros, which includes 750 000 euros for the solar panels (LG Neon H Bifacial , 2022), 200 000 euros for the solar battery (Solar Choice Staff, 2022), and 200 000 euros for the labour. These numbers, however, are influenced by a variety of factors, including supply chain interruptions, the availability of skilled labour, the nation of origin of the goods, etc. Additionally, it is difficult to estimate when an investment in PVs would pay for itself due to the volatile electricity prices. It is expected that the initial investment would be recovered in 5-7 years by utilizing and selling partly the energy. This time frame might change at any time.

From exploitation point of view, the manufacturer promises a deterioration coefficient of 0.144 percent and a 25-year guarantee. However, if the necessary maintenance of the solar panels is not performed in accordance with the product's instructions, this number may vary.

The current thesis has several limitations that need to be considered. To begin with, literature research was the first place to face some obstacles, because of the significant gaps in writings related to the topic. In addition to the aforementioned deficiencies in the literature, the academic information on solar panels and energy storage measures is quite developed and instructive in itself but does not differentiate between the solar system measures for various building types.

The complexity of the project and the involvement of several parties made coordination difficult, which ultimately led to a constraint. For instance, it was challenging to schedule stakeholder consultations since they required a lot of time, and some people found it challenging to find the time. Moreover, the expert opinion was subjective at some moments which made it harder for evaluation. The criteria for choosing the solar panel model were set by the author and the company. Some of the data, however, could not be thoroughly validated, implying the inability for making general conclusions. For instance, depending on how many items we want to purchase, we may negotiate the cost of the solar panels. Consequently, this means that the price may be altered. In addition, one of the most influential factors was the MCDA, which indicates the best alternative. However, the final decision could differ by slightly changing some of the scores, as they could not be fully validated.

Next, Table 4 shows the sun hours and the production of renewable energy for each month. The calculations of the total produced energy consider the number of sun hours, the exact location, the number of panels and the hourly solar irradiance for each month. However, the installation angle for the solar panels was not chosen manually. The PVGIS software's recommended setting of 35 degrees was utilized. The findings varied by up to 3 percent after manually altering the slope value, which on its side contributed to some uncertainty. Yet, it was deemed to be insignificant.

The criteria of the MCDA analysis were also consulted with the client. However, as with most of the MCDAs, the scores could be manipulated. The best possible explanation was given to each number but as a result, two of the alternatives were very close to each other (sale of electricity and hybrid). This makes it easy to control the result by slightly changing some of the numbers.

Another limitation is related to the study design which collects data only at one point in time. This indicates that different results may be provided if questionnaires are given in another timeframe. For instance, the current price of electricity is unstable and high, and the relationship between the EU and Russia is unpredictable, both of which suggest the need for change. However, if the situation changes in future the analysis's conclusion could be different. In addition, the number of previous studies conducted in the past which are related to cold-storage warehouse is very limited. This indicates the necessity of similar studies and possibility of being useful for more research in the future.

Currently, there is no other evidence of similar analyses of the implementation of solar panels on a cold-storage warehouse. All required methods are thoroughly discussed in the present thesis, which will assist other businesses that use the majority of their energy during the day and considerably less at night in installing solar panels to increase their energy independence and environmental friendliness.

There are many studies analysing the shift towards renewable energy in buildings, but this study is set to be one of the first academic writings related to the installation of solar panels on such a specific building as cold-storage warehouses, making this research a foundation for further development in this particular field.

8. Conclusion

Despite above stated limitations and challenges, the present study provides crucial knowledge and insights for future companies, which intend to install solar panels. The main research question with the sub-questions were answered by offering methodology which could be applied not only for cold-storage warehouses, but other industrial buildings as well.

The energy needs of the cold-storage warehouse were shown to be constant throughout the twenty-four hours which gave an answer to the first Research Question. This demonstrated the inability of the solar panels which are functional only during the bright part of the day, to fully meet the electricity demands. Yet, by covering 80% of the roof area with panels having 19.9% efficiency, it becomes possible to produce around 60% of the total energy needs of the building. Moreover, in the current case it would save around 433 tons of CO_2 emissions. The degradation is estimated to be 0.144% per year, or 96.4% predicted efficiency in 25 years of time, which gave an answer also to the second Research Question.

According to the MCDA study, the hybrid option, which combines solar batteries with power sales, was the best option for storing energy which gives solution to the third Research Question. However, the scores could be slightly altered, and a criterion that favors only one of the choices might be removed or added, which would easily reverse some of the findings. From financial point of view, due to the fluctuating price of power and the constantly shifting political atmosphere, it was impossible to calculate the exact return on investment, nevertheless, it was anticipated that the funds would be recovered in about 5-7 years.

The thesis demonstrated that the building would use less electricity from the main power system, benefiting the environment and lowering the energy expenses. However, this comes with a certain price tag. Future studies on other energy storage options, including hydrogen, might be conducted. The MCDA's final scores would be more appropriate in this manner. Additionally, by examining the technology of the solar system in greater detail, more effective solar panels may be found. With this, the last Research Question was addressed. Finally, more research employing various renewable energy sources in a cold-storage facility might be carried out in order to compare the findings and select the best alternative.

References

A. Alajmi, A. S. (2020). Detailed energy efficiency strategies for converting an existing office building to NZEB. *Energy Efficiency*, 1089-1104.

Basso, S. (2021). Comparing Multi-Criteria Decision-Making Methods for the Assessment of Flow Release Scenarios From Small Hydropower Plants in the Alpine Area. *Frontiers in Environmental Science*, Volume 9.

Baxter, T. (2020, November 15). *Which sectors need Hydrogen, which don't: Transport, Heating, Electricity, Storage, Industry?* Retrieved from Energy Post: https://energypost.eu/which-sectors-need-hydrogen-which-dont-transport-heating-electricity-storage-industry/

Cambridge, T. (2019). *What is Green Energy? (Definition, Types and Examples)*. Retrieved from TWI: https://www.twi-global.com/technical-knowledge/faqs/what-is-green-energy

Caminiti, G. P. (2021, April 24). *Implementation of Solar Energy*. Retrieved from ArcGIS StoryMaps: https://storymaps.arcgis.com/stories/70d4da4a613a4829b4f258ad3e724923

Clover, I. (2016, June 15). *IRENA Forecasts 59% Solar PV Price Reduction By 2025*. Retrieved from PV-magazine: https://www.pv-magazine.com/2016/06/15/irena-forecasts-59-solar-pv-price-reduction-by-2025_100024986/#ixzz4CJTSTOnm

Contributors, W. (2021, July 14). *Weighted sum model*. Retrieved from Wikipedia: https://en.wikipedia.org/wiki/Weighted_sum_model

D. Jordan, S. K. (2015, September 14). *STAT FAQs Part 2: Lifetime of PV Panels*. Retrieved from State, Local, and Tribal Governments | NREL: https://www.nrel.gov/state-local-tribal/blog/posts/stat-faqs-part2-lifetime-of-pv-panels.html#:~:text=NREL%20research%20has%20shown%20that,rate%20of%200.5%25%20per%20year.

Dolan, C. (2019, July 22). *Unlocking the Potential of Hydrogen Energy Storage*. Retrieved from Fuel Cell & Hydrogen Energy Association: https://www.fchea.org/in-transition/2019/7/22/unlocking-the-potential-of-hydrogen-energy-storage#:~:text=Hydrogen%20energy%20storage%20is%20a,in%20order%20to%20separate%20hydrogen.

E. House. (January 2009). Multi-criteria analysis: a manual. *Department for Communities and Local Government: London*, 46-71.

Human, S. (2021, December 18). *Post author: Super Human*. Retrieved from Solar Powered Blog: https://solarpoweredblog.com/calculate-solar-panel-efficiency/

Hydrogen Basics - Solar Production. (n.d.). Retrieved from Florida Solar Energy Center: http://www.fsec.ucf.edu/en/consumer/hydrogen/basics/production-solar.htm#:~:text=The%20use%20of%20solar%20energy,The%20process%20works

Hydrogen Production: Electrolysis. (2021). Retrieved from Energy.gov: https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis#:~:text=Electrolysis%20is%20a%20promising%20option,a%20unit%20called%20an%20electrolyzer.

JAES. (n.d.). *How to produce hydrogen?* JAES Company.

KWH-to- CO2. (2022). Retrieved from RenSmart: https://www.rensmart.com/Calculators/KWH-to-CO2

LG Global. (2021). *LG NeON H BiFacial*. Retrieved from LG Global: https://www.lg.com/global/business/neon-h-series/lg-lg440n2t-e6

LG Neon H Bifacial . (2022). Retrieved from Europe Solar Store: https://www.europe-solarstore.com/lg-neon-h-bifacial-lg435n2t-e6.html

Low Carbon Energy. (2022, April 22). *Coach House*. Retrieved from Low Carbon Energy Company: https://www.lowcarbonenergy.co/case-studies/

Matters, E. (2021, November 1). *How Long Do Solar Storage Batteries Last in 2021?* Retrieved from Energy Matters: https://www.energymatters.com.au/renewable-news/how-long-do-solar-storage-batteries-last-in-2021/#:~:text=As%20with%20any%20product%2C%20batteries,'%20and%20'warrantied%20life'.

Nova, T. (2022, May 23). *Pros and Cons of Solar Battery Storage - Is It Worth It?* Retrieved from Instyle Solar: https://instylesolar.com/blog/pros-and-cons-of-installing-a-solar-battery/

Palmetto. (2021, August 12). *How Does A Solar Battery Work? | Energy Storage Explained*. Retrieved from Palmetto: https://palmetto.com/learning-center/blog/how-does-a-solar-battery-work

Production of hydrogen - U.S. Energy Information Administration (EIA). (2022, January 21). Retrieved from U.S. Energy Information Administration (EIA): https://www.eia.gov/energyexplained/hydrogen/production-of-hydrogen.php#:~:text=To%20produce%20hydrogen%2C%20it%20must,electrolysis%20(splitting%20water%20with%20electricity.

PVGIS Photovoltaic Geographical Information System. (2022, March 1). Retrieved from European Commission: https://re-jrc-ec-europa-eu.ezproxy2.utwente.nl/pvg_tools/en/

Ritchie, H., & Roser, M. (2020). Energy. *Our World in Data*.

Smoot, G. (2021). *Green Energy vs Renewable Energy: What's the Difference?* Retrieved from Impactful Ninja: https://impactful.ninja/green-vs-renewable-energy-differences/#:~:text=Green%20energy%20is%20the%20generation,fight%20against%20global%20climate%20change.

Solar Cell Efficiency. (2021). Retrieved from Infinity PV: https://infinitypv.com/learn/teacher-guides/solar-cell-efficiency?tmpl=print&learn-lan=

Solar Choice Staff. (2022, May 5). *Solar Battery Price Index – May 2022*. Retrieved from Solar Choice: https://www.solarchoice.net.au/blog/battery-storage-price/

Solar PV powering through to 2030. (2019). Retrieved from TECHNOLOGY OUTLOOK 2030: https://www.dnv.com/to2030/technology/solar-pv-powering-through-to-2030.html#:~:text=Silicon%20module%20efficiency%20will%20begin,structure%20or%20CAPEX%20for%20manufacturing.

Team, S. E. (2021, July 22). *What Is Environmental Sustainability?* Retrieved from Sphera: https://sphera.com/glossary/what-is-environmental-sustainability/

Teneva, M. (2021). *Photovoltaics in Bulgaria - Legal Advice*. Retrieved from Danailova, Todorov and Partners: https://lawfirm.bg/en/publications/photovoltaics-in-bulgaria

Vink, K. (2019). Performance and cost analysis of building scale micro-grid. *ScienceDirect*.

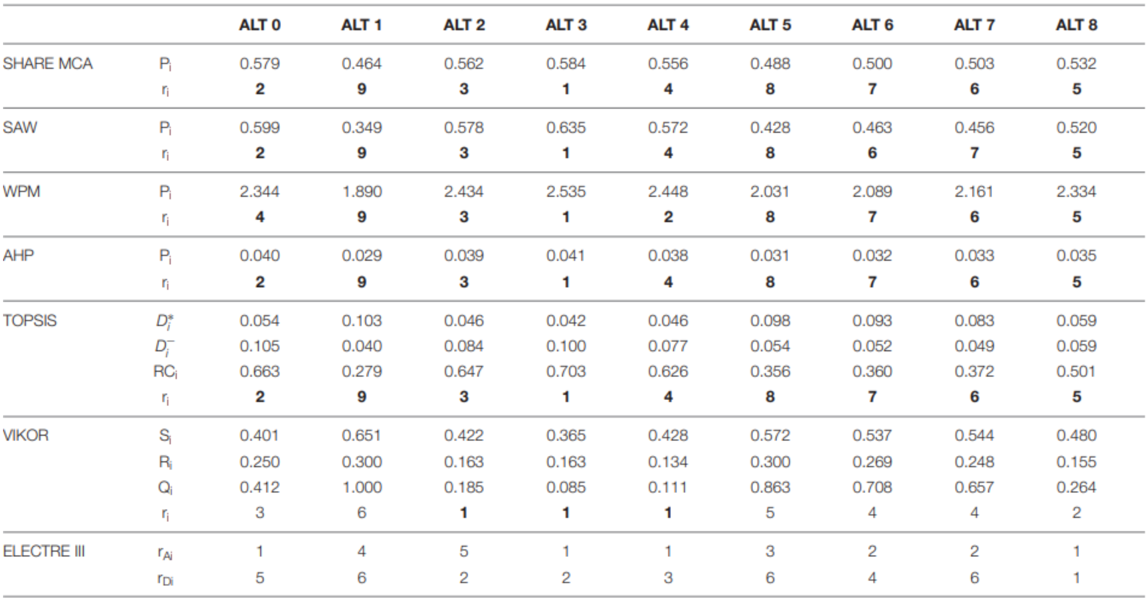
Y. Abdelilah, H. B. (2021). Renewables 2021. *Analysis and forecast to 2026*, 21-34.

Appendix

Appendix A – results according to the different MCDA methods

The table below shows the final scores of the different MCDA methods and make it possible to directly compare them.

Table 12. Results according to the different MCDM methods, using the first scheme of weights (Pi = final performance value of alternative i; ri = position in the ranking; D ∗ i = distance from the ideal solution, D − i = distance from the negative-ideal solution, RCi = relative closeness, calculated in TOPSIS; Si , Ri , Qi = values calculated in VIKOR; rAi = position in the ascending ranking, rDi = position in the descending ranking, for ELECTRE III).



		ALT 0	**ALT 1**	**ALT 2**	**ALT 3**	**ALT 4**	**ALT 5**	**ALT 6**	**ALT 7**	**ALT 8**
SHARE MCA	P_i	0.579	0.464	0.562	0.584	0.556	0.488	0.500	0.503	0.532
	r_i	**2**	**9**	**3**	**1**	**4**	**8**	**7**	**6**	**5**
SAW	P_i	0.599	0.349	0.578	0.635	0.572	0.428	0.463	0.456	0.520
	r_i	**2**	**9**	**3**	**1**	**4**	**8**	**6**	**7**	**5**
WPM	P_i	2.344	1.890	2.434	2.535	2.448	2.031	2.089	2.161	2.334
	r_i	**4**	**9**	**3**	**1**	**2**	**8**	**7**	**6**	**5**
AHP	P_i	0.040	0.029	0.039	0.041	0.038	0.031	0.032	0.033	0.035
	r_i	**2**	**9**	**3**	**1**	**4**	**8**	**7**	**6**	**5**
TOPSIS	D_i^*	0.054	0.103	0.046	0.042	0.046	0.098	0.093	0.083	0.059
	D_i^-	0.105	0.040	0.084	0.100	0.077	0.054	0.052	0.049	0.059
	RC_i	0.663	0.279	0.647	0.703	0.626	0.356	0.360	0.372	0.501
	r_i	**2**	**9**	**3**	**1**	**4**	**8**	**7**	**6**	**5**
VIKOR	S_i	0.401	0.651	0.422	0.365	0.428	0.572	0.537	0.544	0.480
	R_i	0.250	0.300	0.163	0.163	0.134	0.300	0.269	0.248	0.155
	Q_i	0.412	1.000	0.185	0.085	0.111	0.863	0.708	0.657	0.264
	r_i	3	6	**1**	**1**	**1**	5	4	4	2
ELECTRE III	r_{Ai}	1	4	5	1	1	3	2	2	1
	r_{Di}	5	6	2	2	3	6	4	6	1

Appendix B – Questions to the stakeholders

Although questions were prepared in advance for the interviews, the direction of the interview was followed instead of rigidly adhering to it to provide the interviewees more time to speak. Depending on what the interviewee would say, the sequence of the questions would alter, new questions may be added, or old ones might be dropped entirely. The interview's questions are included here for your convenience. It should be mentioned that the interviewees provided information about several topics on their own initiative even when not specifically questioned about them, which is why further in-depth inquiries were not made. The main questions asked to the company were as follows:

1. What is the amount of energy that the cold-storage warehouse is currently using?
2. How much useful area is available for the installation of the solar panels?
3. Are there any limitations in terms of investment?
4. Who were the actors involved?

5. How familiar were the other people from the company with the transition towards renewable energy?
6. What criterion do you have for the choice of solar panels?
7. How many cold cells there are and what is the temperature they want to achieve?
8. How much is the loss of electricity in the power grid?
9. How much weight can the structure withstand?

The main questions that were asked to the current clients (BILLA, METRO, LIDL) which rent the warehouse for food service were as follows:

1. What do you think about the implementation of solar panels and the start of the production of renewable energy?
2. Would you agree to pay higher rent, but reduce the energy costs?
3. Would it be beneficial for your business to promote renewable energy resources?

Appendix C – technical drawings of the roof of the structure

Below is shown the drawings of the roof made in AutoCAD.

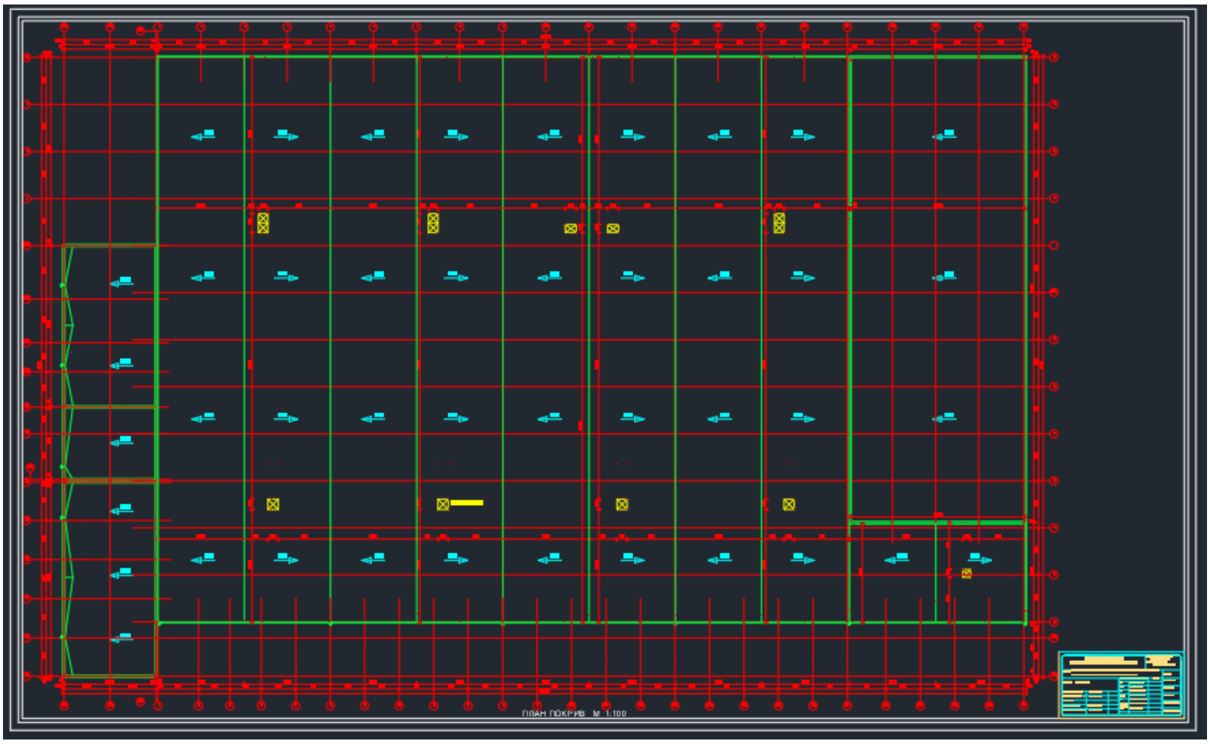


Figure 18. Technical drawings of the roof made in AutoCAD

Appendix D

Appendix D.1 – number of sun hours during the year

The climate of Sofia, the capital of Bulgaria, is continental, with cold winters and warm summers. The amount of sunshine in Sofia is good from May to September, when the sun often shines, while it is quite low from November to February, when the weather is often dull and sometimes foggy. In total there are around 1600 hours of sunshine per year (Sofia climate: Average weather, temperature, rainfall, sunshine hours, 2020).

Appendix D.2 – real project example

A real project example of the production of energy in ideal conditions (mostly sunny during the whole day) is given in Figure 19 during the month May (21st of May). The panels start generating power at 06:00 o'clock and stop at 19:00 o'clock. To reproduce a similar graph, the production of energy was determined for each hour for each season (January – winter, April – spring, July – summer, October – autumn) and it was plotted against the consumption of the building for the same period of time.

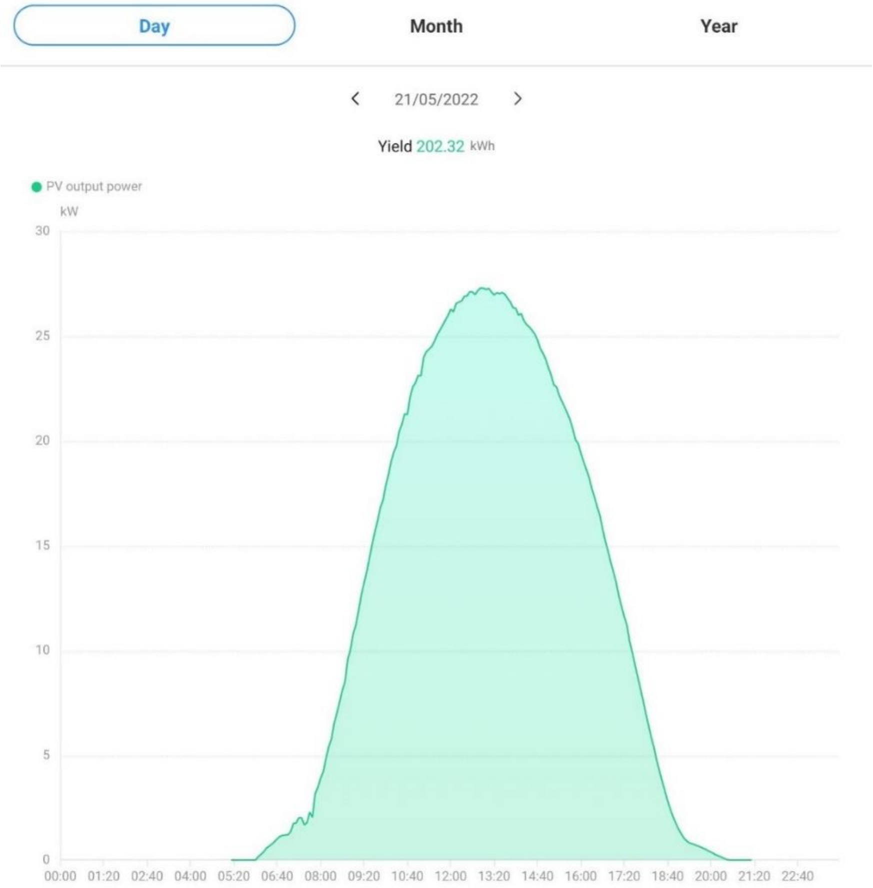


Figure 19. Real project case of producing electricity using solar panels

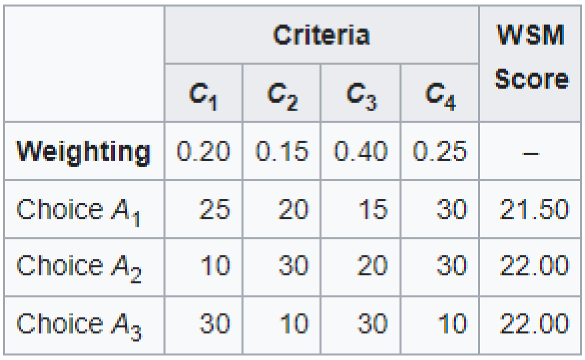
As a result, from the visual representations of each season of the year, it was expected to see when and how much the surplus of energy was, if there was any, because this was vital for the answer of the next research question of the report – "How could the energy generated by the solar panels be stored and used?".

Appendix E

Appendix E.1 – explanation of the work of Weighted sum model (WSM)

The working steps are to give weights to different criteria, calculate the result and compare the scores. The higher the score, the better the alternative. An example is shown in Table 13 (Contributors, 2021). This technique has a simple intuitive appeal and transparency that guarantees it plays a major position in every MCA debate. It may, however, be misused, as with many instruments. If the steps of applying MCDA are not followed carefully, it could be critical for the final outcome. It could result in an MCDA that seems straightforward and well-founded but is really deceptive and does not accurately reflect the decision-making group's grasp of the situation (E. House, January 2009).

Table 13. Application of Weighted sum model (WSM) (Contributors, 2021)



	Criteria				WSM Score
	C_1	C_2	C_3	C_4	
Weighting	0.20	0.15	0.40	0.25	–
Choice A_1	25	20	15	30	21.50
Choice A_2	10	30	20	30	22.00
Choice A_3	30	10	30	10	22.00

Appendix E.2 – Energy storage alternatives

Before explaining in detail, the steps of conducting an MCDA, a literature review was done separately for each energy storage alternative and the information is presented below in the form of bullet points. This would help the reader to understand the reasoning behind some of the scores given later in the MCDA.

- Hydrogen as energy storage alternative

In the fight against climate change, hydrogen produced from renewable energy (referred as green hydrogen) is increasingly considered as a solution for industries with particularly persistent emissions, such as heavy industry. Hydrogen energy storage is a procedure in which renewable energy surpluses are utilized to power electrolysis, a process in which an electrical current is carried through a chemical solution to separate hydrogen, during periods of low energy demand. After electrolysis, hydrogen can be utilized in stationary fuel cells for power production, as fuel for fuel cell automobiles, injected into natural gas pipelines to reduce carbon intensity, or even stored as compressed gas, cryogenic liquid, or a variety of loosely-bonded hydride compounds for later use (Dolan, 2019).

While batteries and other kinds of energy storage can meet the same dispatchable energy demands, they have constraints that hydrogen energy storage can solve. Batteries degrade over time and can only store a certain quantity of energy, but hydrogen fuel may be stored indefinitely and in amounts limited only by the size of storage facilities. "Batteries are most suited to discharge periods of 4 hours or fewer," says Steve Szymanski, Director of Business Development at FCHEA member Nel Hydrogen, whereas hydrogen energy storage can help with longer-term demands (say days or even weeks).

Hydrogen energy storage has begun to show potential in the United States, thanks to continuous studies and promising initiatives. SoCalGas, a Southern California-based natural gas supplier, has engaged in hydrogen energy storage projects, for example. SoCalGas developed an electrolyser driven by the on-campus solar electric system, which creates renewable hydrogen to be fed into the campus power plant, in collaboration with the National Fuel Cell Research Center at the University of California, Irvine. SoCalGas collaborated with the National Renewable Energy Laboratory to build a bio methanation reactor system that employs a water electrolyser to manufacture hydrogen from renewable energy via a bioreactor that transforms hydrogen and carbon dioxide into methane and water (Dolan, 2019).

Electrolysis is one of the most popular techniques of creating hydrogen. Electrolysis is a method that uses an electric current to separate hydrogen from water. In high school science classrooms, electrolysis is frequently used to show chemical processes and hydrogen generation. On a big scale, the process is known as power-to-gas, where power is electricity and hydrogen is gas. Other than hydrogen and oxygen, electrolysis produces no wastes or emissions. The power used for electrolysis can come from renewable sources, such as our PV system. (Production of hydrogen - U.S. Energy Information Administration (EIA), 2022). Simply put, the water reacts at the anode to form oxygen and positively charged hydrogen ions (protons). The electrons flow through an external circuit and the hydrogen ions selectively move to the cathode. At the cathode, hydrogen ions combine with electrons from the external circuit to form hydrogen gas (Hydrogen Production: Electrolysis, 2021). This is illustrated in Figure 20.

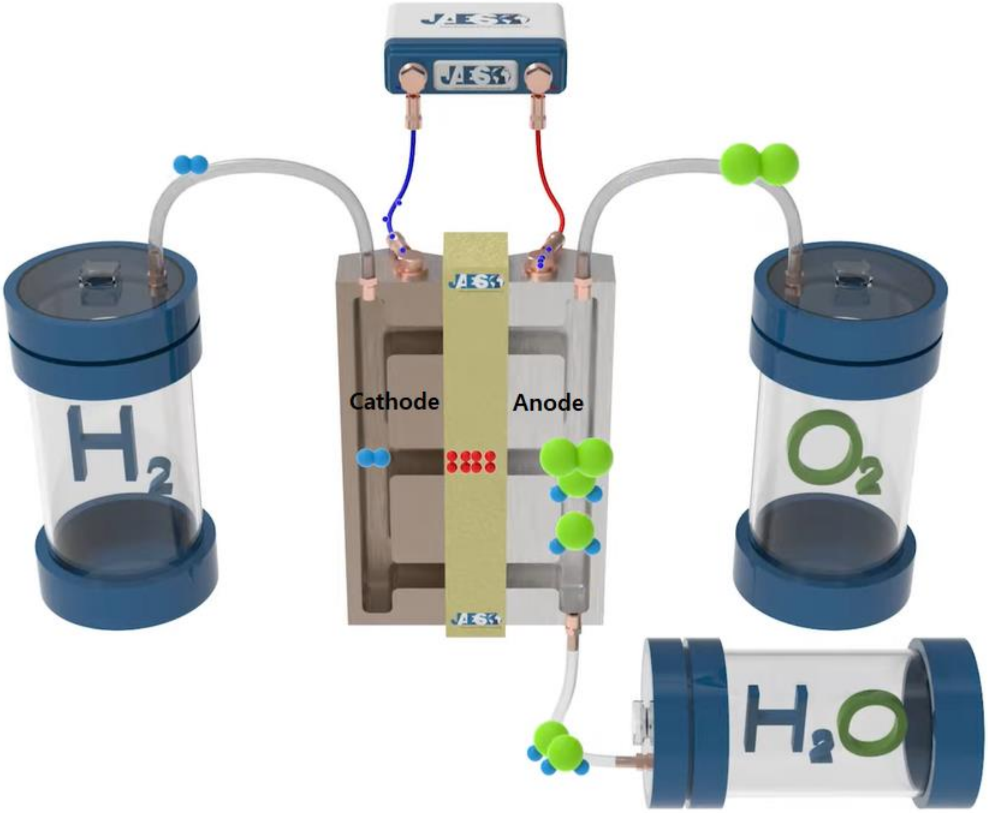


Figure 20. Principle of work of electrolyse (JAES)

We have mentioned earlier in this bullet point most of the advantages of the hydrogen. However, there are many limitations as well. When hydrogen is produced by electrolysis, 30-40% of the initial electric energy is wasted. You'll also need a water tank to conduct the electrolysis and bottles to store the hydrogen. Unfortunately, because hydrogen is the lightest gas, it is difficult to store and transport. It may be liquefied or kept at extreme pressures. However, green hydrogen is still two to three times more expensive than natural gas-produced hydrogen, and the expenses are much greater if an electrolyser is only used occasionally. This complicates and increases the cost of the process. (Baxter, 2020).

According to six academics from the United Kingdom and the Netherlands - Tom Baxter, Ernst Worrell, Hu Li, Petra de Jongh, Stephen Carr, and Valeska Ting - hydrogen is still very expensive, so it should be used primarily when there are no other low-emission alternatives and other benefits outweigh higher costs. The extremely high energy density of liquid hydrogen can aid both freight (trucks to trains) and aircraft. Heavy manufacturing requires high temperatures, which hydrogen can provide better than electricity. However, cheaper green options exist for automobiles, heating, energy, and storage, implying that hydrogen will simply serve as a diversion (Baxter, 2020).

So, when will it make sense to manufacture hydrogen from solar energy? The response is that we will want to produce hydrogen whenever power cannot be utilized, such as during off-peak hours in distant places and during seasonal changes. When the resource does not meet the electrical system load profile, hydrogen from wind, hydro, geothermal, or any other kind of solar-generated power is beneficial (Hydrogen Basics - Solar Production, n.d.).

Green hydrogen will be further compared to the other storage alternatives using MCDA analysis and the results will be discussed.

- Lithium batteries as storage alternative (solar batteries)

A solar battery is a device that may be added to your solar power system to store surplus energy generated by your solar panels. You may then utilize the stored energy to power your home when your solar panels aren't producing enough electricity, such as at night, on cloudy days, or during power outages.

A solar battery's purpose is to let you use more of the solar energy you generate. If you don't have battery storage, any surplus solar power goes to the grid, which means you're creating power and distributing it to others without fully utilizing the electricity your panels generate.

Lithium-ion batteries are the most common type of solar battery on the market today. This technique is also employed in cell phones and other high-tech batteries. Lithium-ion batteries function by storing chemical energy before converting it to electrical energy via a chemical process. The process takes place when lithium ions emit free electrons, which flow from the negatively charged anode to the positively charged cathode.

The lithium-salt electrolyte, a liquid inside the battery that balances the reaction by delivering the required positive ions, encourages and enhances this movement. This flow of free electrons generates the current required for people to utilize electricity (Palmetto, 2021).

When power is taken from the battery, lithium ions travel through the electrolyte to the positive electrode. Simultaneously, electrons go from the negative electrode to the positive electrode via the outside circuit, powering the plugged-in device.

There are two types of solar batteries available: lithium-ion and lead-acid. Lithium-ion batteries are preferred by solar panel manufacturers because they can store more energy, keep that energy longer than conventional batteries, and have a higher Depth of Discharge which is why only lithium batteries will be examined (Palmetto, 2021).

Overall, the main benefits of adding solar batteries are: energy independence - you may have greater control over where your energy originates from, how it is utilized, and what you can do with it thanks to solar energy storage technology; increase savings - you may use the cheaper electricity produced by your solar panels even at night or during a storm by pulling power from your solar battery; it is better for the environment - by boosting the energy-producing capacity of the solar PV system, it can be reduced the reliance on fossil fuels even more, lowering the environmental carbon footprint and supporting innovations that will aid in the international push for a better climate future.

However, it is not only advantages that the solar batteries have. There are some drawbacks which could be vital in the decision making. The cost of energy storage is relatively expensive and can easily raise the cost of a solar PV system significantly. So, installing an energy storage system may not always make financial sense—it all depends on the consumption tariff rate. As a result, it is worthwhile to calculate the return on investment in a solar battery system. The design and installation of an energy storage system adds to the complexity of the solar PV system. This also implies that more things may go wrong in the battery system's design, installation, and operation. During the design process, it is critical that the battery system is properly scaled for the needs and that the appropriate connections and switches are placed. Finally, the lifespan of the batteries is limited. Solar batteries degrade far more, and faster, than solar panels do. It can be expected that the battery system needs to be replaced at least once during the lifespan of the PV system (Nova, 2022). The batteries degrade over time Approximately in a 10-year period the battery will be 60% as efficient as it was in year one. This is a normal and unavoidable phenomenon. A solar battery can last anywhere from 5 to 20 years, depending on a variety of factors such as how often the battery is cycled, what is the temperature where the batteries are stored and how they are maintained (Matters, 2021).

- Connection to the main power grid and sale of produced electricity

Another alternative would be to sell all the excess electricity and with the money buy back when it is needed. As it is shown previously, the surplus of energy is generated during the day (between 7:00 o'clock and 18:00 o'clock). This energy could be sold out to the main power grid and in the periods when the solar panels do not fulfil the needs of the building to buy back from the main power grid. In this way, there are no additional costs and investments for special equipment such as solar batteries. In addition, this process does not require maintenance.

Currently, the company has the same tariff for the daily and the night electricity. In case they deliver energy to the main grid, the price of selling would be a bit smaller than the price of buying it. However, this cannot be defined precisely due to the fact that the prices change frequently. Another possibility would be to sell the electricity on the stock energy market. The prices differ for each hour. It could be a decent strategy to sell electricity at higher prices and buy at lower point. In general, during the peak hours (09:00 – 20:00) the prices are higher compared to off-peak hours (01:00 – 08:00 & 21:00 – 00:00). The surplus of energy is generated during peak hours which could result in sale at higher prices and then buying back in the night at lower prices. However, this cannot be guaranteed for everyday because it happens that the off-peak prices are the higher ones.

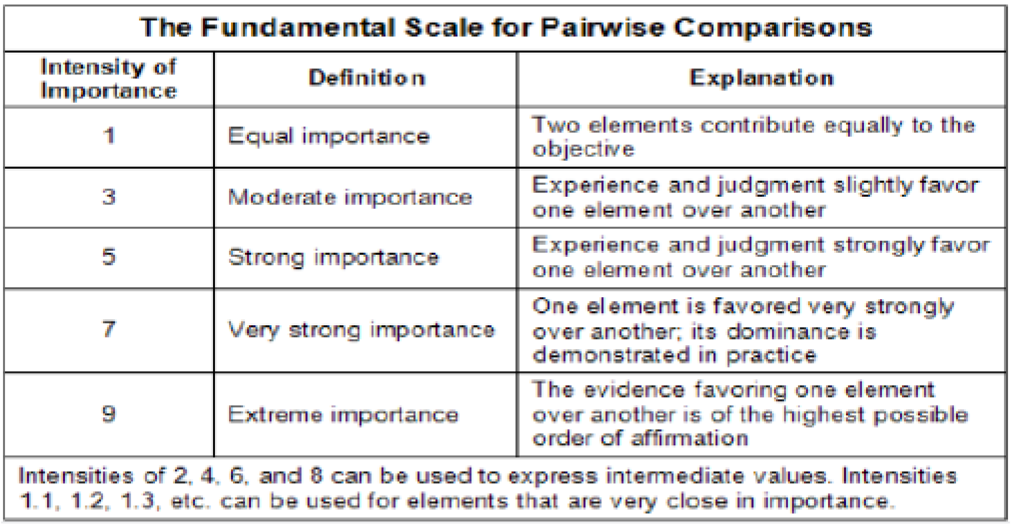
- Hybrid (sale of electricity + solar battery)

The final alternative would be to store some energy and the rest to be sold. In this way, the owner of the cold-storage warehouse would be saving money from the sale of energy and at the same time be able to store electric power which gives him independence and security in case of power outage. In addition, by storing energy and being able to use it whenever is needed, the company could choose a better time and prices for buying back electricity. However, due to the high cost of the batteries and the mounting space they require, after consultation with a financial and construction expert, it was decided to use no more than 200 kWh battery pack. This means that the cold-storage building could use the power from the battery for about 2 hours in July and 3 hours in January. This time would be enough for picking better prices of electricity or fixing problem with power outage.

Appendix F

Appendix F.1 – pairwise comparison

The fundamental scale for pairwise comparisons is explained below.

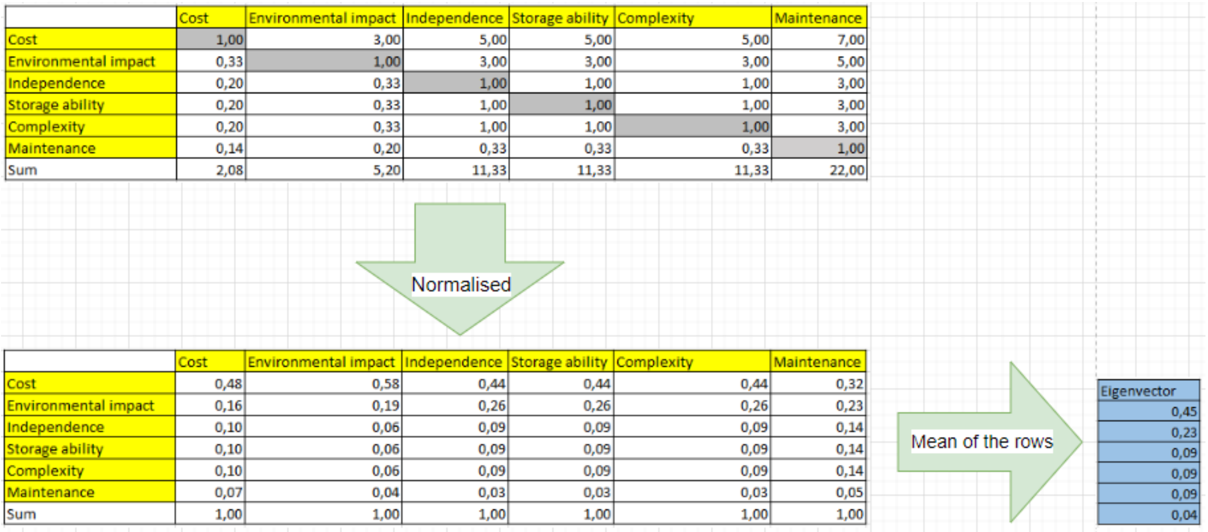


The Fundamental Scale for Pairwise Comparisons		
Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
Intensities of 2, 4, 6, and 8 can be used to express intermediate values. Intensities 1.1, 1.2, 1.3, etc. can be used for elements that are very close in importance.		

Figure 21. Scale for Weights

The comparison matrix, as well as the normalised priority matrix, were created using the Saaty Scale for Pairwise Comparisons as shown in Table 14. The Eigenvector was then determined by taking the mean of the rows in the normalised version. Cost and environmental impact have been deemed the most essential criteria, while maintenance has been considered the least important of the six. This may be observed in the Eigenvector results as well.

Table 14. Pairwise Comparison, Normalisation and Eigenvector



	Cost	Environmental impact	Independence	Storage ability	Complexity	Maintenance
Cost	1,00	3,00	5,00	5,00	5,00	7,00
Environmental impact	0,33	1,00	3,00	3,00	3,00	5,00
Independence	0,20	0,33	1,00	1,00	1,00	3,00
Storage ability	0,20	0,33	1,00	1,00	1,00	3,00
Complexity	0,20	0,33	1,00	1,00	1,00	3,00
Maintenance	0,14	0,20	0,33	0,33	0,33	1,00
Sum	2,08	5,20	11,33	11,33	11,33	22,00

	Cost	Environmental impact	Independence	Storage ability	Complexity	Maintenance
Cost	0,48	0,58	0,44	0,44	0,44	0,32
Environmental impact	0,16	0,19	0,26	0,26	0,26	0,23
Independence	0,10	0,06	0,09	0,09	0,09	0,14
Storage ability	0,10	0,06	0,09	0,09	0,09	0,14
Complexity	0,10	0,06	0,09	0,09	0,09	0,14
Maintenance	0,07	0,04	0,03	0,03	0,03	0,05
Sum	1,00	1,00	1,00	1,00	1,00	1,00

Eigenvector
0,45
0,23
0,09
0,09
0,09
0,04

Appendix F.2 - steps of the consistency ratio check

In this part, all steps of checking the consistency ratio are explained.

- Step 1: First, each priority vector needs to be multiplied by its corresponding column from the pairwise comparison matrix and then the sum of each row needs to be calculated to find the weighted sum.

Equation 1. Weighted Sum

$$0.45 \times \overset{\text{Cost}}{\begin{Bmatrix}1\\0.33\\0.20\\0.20\\0.20\\0.14\end{Bmatrix}} + 0.23 \times \overset{\text{Env. Impact}}{\begin{Bmatrix}\cdots\\\cdots\\\cdots\\\cdots\\\cdots\\\cdots\end{Bmatrix}} + \ldots \overset{\text{Independ.}}{\begin{Bmatrix}\cdots\\\cdots\\\cdots\\\cdots\\\cdots\\\cdots\end{Bmatrix}} + \ldots \overset{\text{Storage ability}}{\begin{Bmatrix}\cdots\\\cdots\\\cdots\\\cdots\\\cdots\\\cdots\end{Bmatrix}} + \ldots \overset{\text{Complexity}}{\begin{Bmatrix}\cdots\\\cdots\\\cdots\\\cdots\\\cdots\\\cdots\end{Bmatrix}} + \ldots \overset{\text{Maintenance}}{\begin{Bmatrix}\cdots\\\cdots\\\cdots\\\cdots\\\cdots\\\cdots\end{Bmatrix}} = \overset{\text{Weighted sum}}{\begin{Bmatrix}\cdots\\\cdots\\\cdots\\\cdots\\\cdots\\\cdots\end{Bmatrix}}$$

- Step 2: After that, the elements of the weighted sum need to be divided by the corresponding vectors from the eigenvector.
- Step 3: The average of the values from Step 2 is computed.
- Step 4: The Consistency index is calculated.

$$CI = \frac{\lambda \max - n}{n-1}; \text{ } n - \text{number of criteria (6)}$$

- Step 5: The Consistency ratio is being calculated.

$$CR = \frac{CI}{RI}$$

*RI represents the consistency index of a randomly generated pairwise comparison matrix and is provided from the table below.

Table 15. RI table based on number of criteria.

The matrix order	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.89	1.12	1.26	1.36	1.41

If $CR < 0.1$, then the judgment matrix is considered to meet the consistency test requirements; if $CR \geq 0.1$, then