DIGITALISATION IN AGRICULTURE

April 2020

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Dr. K. Smith

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DIGITALISATION IN AGRICULTURE

Capstone Report

Student Statement:
“I, Rim Boulahya, affirm that I have applied ethics to the design process and in the selection of the final proposed design. And that, I have held the safety of the public to be paramount and has addressed this in the presented design wherever may be applicable.”

Rim Boulahya

Approved by the Supervisor(s)

Dr. K. Smith

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Acknowledgments

Firstly, I would like to thank our country for keeping us safe during this global epidemic.

I would like to thank the AUI community, with special thanks to all professors that helped shape me up and provide an environment for good learning. I am deeply grateful for professors that spared me their time and knowledge. I am grateful to Dr. K. Smith for his support concerning this project.

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I would also like to thank the athletics department and the different teams I associated with for their moral support and teams’ spirit throughout my years in AUI.

I also convey my sincere gratitude to my family and their unwavering support even through my darkest times. Special thanks to my mother and I am sorry for any angst I have caused.
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Abstract

This capstone project is part of the pilot capstone between School of Business and Administration and School of Science and Engineering in hopes of proving an innovation in the agriculture sector in Morocco; in both the technical and the business aspects and take part in the international conference Salon International de l’Agriculture au Maroc (SIAM) taking place in April 2020. The main goal is to deliver an improvement to the company we are working with covering the implementation aspects of it from the technical phases to its business analysis.

The company for our project is Centrale Danone. This work aims to provide a viable innovation under Digitalization in Agriculture theme. The idea is a business model of a hub for the dairy collection and milk pasteurization using renewable energy. The sustainable source discussed in this project is solar power specifically Concentrated Solar Power Parabolic-Dish with a Stirling engine system. The project will cover the electrical need for the refrigeration system, using CSP Parabolic-Dish collectors, and Stirling engines while highlighting the main equations for thermal efficiency analysis of a parabolic dish collector.

The project was previously directed towards a feasibility analysis and modeling of an ohmic heating unit for batch pasteurization of milk in the hub, however, due to poor mechanisms away for the university’s laboratories and software, as well as lack of equipment, the topic changed towards renewable energy for refrigeration in the hub mid-semester.

The financial study of the hub is included in the overall report under capital expenses providing the whole business plan analysis.
Résumé

Ce projet de fin d'étude fait partie des projets pilotes entre SBA et SSE dans l'espoir de prouver une innovation dans le secteur agricole au Maroc; dans les aspects techniques et commerciaux et faire partie de la conférence internationale SIAM qui aurait lieu en avril 2020. Le principal objectif est de fournir un avancement ou une amélioration à l'entreprise avec laquelle nous travaillons en couvrant tous les aspects de la mise en œuvre de celui-ci à partir des phases techniques à son analyse commerciale.

La société avec qui nous nous engageons pour ce projet est Centrale Danone. L'objectif de ce travail est de fournir une innovation viable sous le thème de la digitalisation dans l'agriculture. L'idée est sous forme d’un hub pour la collecte laitière et de la pasteurisation du lait en utilisant des énergies renouvelables. La source durable discutée dans cet article est l'énergie solaire, spécifiquement énergie solaire concentrée parabolique avec un système de moteur Stirling. Le document couvrira les systèmes de réfrigération, les collecteurs paraboliques (CSP) et les moteurs Stirling, tout en soulignant les principales équations pour l'analyse de l'efficacité thermique d'un collecteur parabolique.

Le projet visait auparavant une analyse de faisabilité et une modélisation d'une unité de chauffage ohmique pour la pasteurisation par lots du lait dans le hub, cependant, en raison de mécanismes insuffisants ; les laboratoires universitaires et les logiciels, ainsi que du manque d'équipement, le sujet a changé vers énergies renouvelables pour la réfrigération mi- semestre.

L'étude financière du hub est incluse dans le rapport global sous les dépenses en capital fournissant l'analyse complète du plan d'affaires
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Chapter 1. Introduction

1.1. Introduction

In the spirit of improving the Moroccan agriculture, SIAM (Salon International de l'Agriculture au Maroc) is the place to display innovative ideas for Moroccan Agriculture. Al Akhawayne University in Ifrane is having the chance to partake in the 15th edition of this conference on April. Multiple teams from the School of Business and Administration are basing their capstone projects on different companies involved in this event. The School of Science and Engineering has been asked to contribute by providing a technological innovation in any agricultural sector for the company they are involved with. The company that we worked on was Centrale Danone. Looking through its history in Morocco for the last couple of years, the corporation has been subject to heavy boycotts, any improvement to its products or production processes or even supply chain or marketing would help lift the innovative aspect of the Moroccan agriculture as well as attract new consumers.

As a way to keep the spirit of the SIAM and work on the dairy sector, energy consumption is the target. This generated the idea of incorporating a renewable energy source in one of the most energy-consuming sections of the milk production process that can be of help not only to the company but also to the agriculturalists in general. This project will try to study the integration of a small solar power generation with a cooling system. Along with my business student colleagues, a hub model for milk collection in rural areas is established. It will incorporate the findings of this project in its cooling section as well as the possibility to rely on the energy source in other aspects.

The hub purposes to decentralize the production of pasteurized milk and make its production sustainable as well as present the hub as a distribution center of pasteurized milk to Centrale Danone’s direct business clients in the region of the hub center.

The objective is to study the feasibility of using concentrated solar power (CSP) into a refrigeration system for milk cooling in a small-scale (or medium) dairy hub. Stirling engine parabolic dish technologies can achieve the highest solar-to-electricity efficiency of all types of CSP systems; Stirling dishes do not need big freshening structures, allowing CSP to provide electricity in water-
constrained regions, they also have a small footprint and are self-contained. The capacity of the system would be used for refrigeration purposes as well as any additional electricity needs of the facility after further analysis.

The methodology of this work will start by explaining the principle behind the vapor-compression refrigeration system and identifying the milk cooling equipment selected for this project. Subsequently, presenting the different components of this technology as well as some parameters that affect their efficiency; starting with the parabolic dish than to the Stirling engine. Afterward, a section for a possible method of accommodation of the CSP dish collector-Stirling motor of 25kW capacity to the cooling tank that will need further research in future work. Then the feasibility analysis section gives the work done based on the input data for efficiency calculations of the dish collector.

With the current unfortunate events and safety measurements, the data for the simulation and testing of the envisioned system used in this paper has been grounded from different scholar reviews and research analysis, because of inadequate software for modeling the collector and performance analysis at my disposal.

The discussion section gives reasoning for the selection of this system based on different points including some financial calculations from the group report.
1.2. General Milk Production Process

In this section, a general idea of the different dairy operations in milk production and processing plants, relying on information from Bellon’s “Milk and dairy product” [1] and the material from “Market Milk” [2]. Figure 1 represents a simplified diagram for a dairy processing plant functions.

![Figure 1-1.2: Simplified flow-chart of a milk-processing unit](image)

The concern of this project; Chilling and Storage

The raw milk needs to be chilled and stored to prevent any deterioration in quality during the holding and processing period. Storage tanks store raw milk or even pasteurized milk holding it at a chilled condition of < 5°C for up to 72 hours between the reception and processing.

Cooling is also important after Heat Treatment; The common thermal process is pasteurization; the process of heating milk to at least 63°C for 30min (Low-Temperature Long-Time) or 72°C for 15s referred to as HTST (High-Temperature Short-Time) and immediately cooled to 5°C or below.

The whole plant needs to take into account the cleaning, and sanitation energy requirement.
1.3. STEEPLE Analysis

➢ Social-Cultural
The social-cultural implications of such a project go towards the developing sector of sustainable energy usage in Moroccan. This inclusion of clean energy in the production lines can bring about a new status for Centrale Danone in the Moroccan society and lessen the boycotts while also providing new business opportunities and innovative stance.

➢ Technological
This project represents a digital innovation for the Moroccan agriculture sector. It includes a design analysis for the practicality of an innovative system in Morocco. In the overall project, it provides a viable power generation system to the production process of Centrale Danone. Tools such as Matlab, MS Excel were essential in this work.

➢ Economic
Any innovation in the agriculture sector is a plus in the grand economic aspect of the company. This project is on par with the SBA part delegated to the market study and business analysis of this product. Additionally, this solution can be further analyzed to improve the Levelized energy cost and reduce the cost of electricity for different farming sides.

➢ Environmental
Although we are concerned with the dairy production company, integrating renewable resources in this industrial process would improve its energy consumption in the long-term. Moreover, since this project is under the agriculture department, any solution or innovation must be environment-friendly to help safeguard the Moroccan soil and its cattle.

➢ Political
Politically speaking, since we are looking to find innovation in the agriculture sector in Morocco, this project will not have any political implications.

➢ Legal
All the data and information used in this work is properly cited and referenced throughout. Concerning the principle of the project, it holds no legal implications.

➢ Ethical
This project does not violate any ethics.
Chapter 2. Literature Review

2.1. Energy Consumption in the Dairy Sector

Milk production and processing entail a huge amount of resources and energy. Dairy processing is placed fifth amid the most energy-intensive makings such as oil, and iron and steel manufacturing industries [9].

It is assessed that the refrigeration unit uses about 50-60% of total electricity consumption and that the processing operations account for one-third of energy expenditure in the dairy industry [8]. There are many technologies used for milk processing and product creation that determine and differentiate the energy consumption of the plants, in addition to the different annual capacity operation as well as the availability of milk depending on the processing units and seasonality [6]. From the Indian zone, the Bureau of Energy Efficiency has reported in 2016, that 250 MJ/tonne is an average thermal energy requirement for milk processing [6].

The energy in dairy plants directly points out to the service’s production and consumption in terms of steam, refrigeration, electricity, and water [10]. The heating process usually takes up a major fraction of the energy in the plant. Steam and pressurized hot water at different temperatures and pressures are commonly used as the heat transfer media for the different phases of production pasteurization, sterilization, spray drying evaporation for milk powder production, and hot water generation; Steam is produced in a captive boiler and as per the requirement of processes extracted at desired pressures [6].

The data for the production and energy consumption in the milk processing plants in Morocco is not available with adequate detail. To form a numerical idea about the energy utilization in the dairy sector, we have relied on a case study on a marketable dairy plant with a capacity of approximately 200 000 Litres/day for milk reception [8]. Tables 1, 2, and 3 put into perspective the electrical energy and the refrigeration load for such reception capacity as well as the thermal energy for the different processes.
### Table 1-2.1: Electric energy consumption in the different sections of the plant [8].

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Electrical energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product section</td>
<td>1428.00</td>
</tr>
<tr>
<td>Processing section</td>
<td>849.43</td>
</tr>
<tr>
<td>Utilities generation (Engg. Section)</td>
<td>9289.58</td>
</tr>
<tr>
<td>RMRD (Raw milk reception dock)</td>
<td>103.31</td>
</tr>
</tbody>
</table>

### Table 2-2.1: Refrigeration load of milk processing and cold storage [8].

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Refrigeration load (MJ/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milk pasteurization</td>
<td>9831.41</td>
</tr>
<tr>
<td>Cream pasteurization</td>
<td>159.091</td>
</tr>
<tr>
<td>Raw milk chilling</td>
<td>7716.48</td>
</tr>
<tr>
<td>Market milk chilling</td>
<td>1583.93</td>
</tr>
<tr>
<td>Paneer making</td>
<td>851.1183</td>
</tr>
<tr>
<td>Ice cream making</td>
<td>587.872</td>
</tr>
<tr>
<td>Cold storage</td>
<td>32990.491</td>
</tr>
</tbody>
</table>

### Table 3-2.1: Steam and thermal energy consumption in the processing section and storage tank cleaning [8]

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Milk processed (l)</th>
<th>Steam consumed (Kg/1000 l milk)</th>
<th>Thermal Energy (GJ/1000 l milk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milk pasteurization</td>
<td>121466.70</td>
<td>37.26</td>
<td>0.100</td>
</tr>
<tr>
<td>Cream pasteurization</td>
<td>2890.00</td>
<td>97.57</td>
<td>0.262</td>
</tr>
<tr>
<td>Particulars</td>
<td>Steam consumed (Kg/day)</td>
<td>Thermal energy (GJ/day)</td>
<td></td>
</tr>
<tr>
<td>Milk pasteurizer cleaning</td>
<td>802.26</td>
<td>2.156</td>
<td></td>
</tr>
<tr>
<td>Cream pasteurizer cleaning</td>
<td>584.85</td>
<td>1.571</td>
<td></td>
</tr>
<tr>
<td>Raw milk storage tank cleaning</td>
<td>251.05</td>
<td>0.675</td>
<td></td>
</tr>
<tr>
<td>Silos cleaning</td>
<td>480.38</td>
<td>1.291</td>
<td></td>
</tr>
<tr>
<td>Cream tank cleaning</td>
<td>65.00</td>
<td>0.175</td>
<td></td>
</tr>
<tr>
<td>Pre-pack cleaning</td>
<td>556.02</td>
<td>1.494</td>
<td></td>
</tr>
<tr>
<td>Lassi culturing tank cleaning</td>
<td>81.86</td>
<td>0.220</td>
<td></td>
</tr>
<tr>
<td>Flavoring tank cleaning</td>
<td>27.29</td>
<td>0.073</td>
<td></td>
</tr>
<tr>
<td>Aging tank cleaning</td>
<td>43.66</td>
<td>0.117</td>
<td></td>
</tr>
</tbody>
</table>
2.2. Innovations in agriculture

2.2.1. Advances of Group Danone

In the search of different innovations and approaches implemented in the dairy section, the international group Danone proved to be very advanced in its work regarding sustainability and inclusive innovations with a focus sustainable development. Louisa Burwood-Taylor provides a summary of the global vision Group Danone neatly in the article Danone Leads Coalition to Transition Dairy Farming to Regenerative Practices [7]. It invests in the innovations related to soil and the improvement of the overall quality of cattle as well as the raw milk it provides. The different advancements made in the dairy sector by group Danone abroad are going more and more towards the milk provided by co-operatives or dairy farms, hence the integration of renewable energies in the dairy farming of intensive milking process as well as the refrigeration and cooling systems in the area for better milk procurement. Leading researches in 25 dairy farms in the US, EU, and Russia to classify solutions for the agribusiness system; selections for breeding programs, growing animal feed, tending and nurturing animals, and producing milk. The agricultural strategy dubbed “beyond sustainable” is the regenerative agriculture that this initiative strives for. With the foresight to improve agronomic soils for the local and global ecosystem, many companies have joined including Connecterra with a startup Ida intelligence platform. This machine-learning platform represents an artificial intelligence-powered service that uses accumulated data from dairy cows and suggests recommendations and serious understanding vis-à-vis animal health and farm maneuvers.

Focusing on the Moroccan branch of the company, Centrale Danone has a vision for preserving the environment and providing a model a leading company in the Moroccan market. Several projects have been implemented in different plants concerning innovations or actions to contribute in improving the environment; one of those improvements is capable of transforming factory discharges and sewage slush from wastewater treatment process into biomass used for the making of 25% of Meknes’s plant need of steam. Also, Central Danone’s industrial platforms rely on treatment plants for wastewater which achieves an approximate performance of 97% [4].
2.2.2. **Renewable energies in the dairy sector**

Looking at renewable energies and their applications in almost all aspects of the industry, the dairy sector can greatly benefit from relying on their potential. Figure 3 presents a diagram showing how renewable energy can be integrated into agriculture.

![Diagram of energy inputs and outputs](source)


**Figure 2-2.2.2: Relationship between agriculture and energy**[5]

From the European Journal of Sustainable Development [3], different Applications of Solar energy are used in the dairy development area. It can be an electricity supply source for the different functions in the production factories, or even in the milk farming department. Another huge advantage of clean energy is the solar-based refrigeration system for milk cooling. Alternatively, solar ponds can be of considerable benefit for milk processing plants as they are a simple body of water collecting and storing solar energy. Additionally, solar water heating in rural areas for dairy farms and micro-irrigation has the potential to benefit any company or farm owners. Regarding the usual dairy operation, solar drying can be very profitable for the dairy production plants since it takes advantage of sun irradiation for the drying and dehydration processes.

The dairy sector in India provides a good example of the significant potential of solar energy usage [6]. Many projects have risen about solar energy-based process heating to meet the need for
pasteurization and other thermal treatments. Solar Industrial Process Heating (SIPH) was presented in India to promote and commercialize solar technologies in the industrial sector. The Indian advancements in this area have opened a study in a design value of direct normal irradiance on the annual performance of solar process heating systems using a model developed for hourly simulation of the performance of solar process heating systems [6]. The choice of design Direct Normal Irradiance (DNI refers to the intensity of direct (beam) component of solar radiation incident normally on the aperture of the solar collector), as well as the performance of the SIPH system, may vary at different locations [6]. The choice of design DNI for sizing a SIPH system thus affects the collector area required, useful energy delivered as well as the amount of greenhouse gas (GHG) emissions likely to be mitigated. The study concluded with the potential for a solar collector area of over 1.62 million square meters using the performance characteristics of an indigenous solar concentrator (Arun 160) being promoted in the country [6].

Solar energy practices have seen an increase in power generation plants. Three main tools are widely known for electricity generation in the 10kW to 1000+MW array; dish/engine technology for direct generation of electricity in inaccessible sites, parabolic and Fresnel trough machinery that creates high pressure superheated steam, and solar tower technology, which produces air above 1000°C or synthesis gas for gas turbine operation [12]. These represent Concentrated Solar Power (CSP) technologies. Solar energy collection especially concentrated systems use glass mirrors for high reflectivity by either point focusing or line focusing structures. Table 4 lists different CSP technologies and their characteristics and performance capacities.

<table>
<thead>
<tr>
<th>Capacity</th>
<th>Concentration</th>
<th>Peak solar efficiency</th>
<th>Annual solar efficiency</th>
<th>Thermal cycle efficiency</th>
<th>Capacity factor (solar)</th>
<th>Land use</th>
<th>1 MWh generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trough</td>
<td>10-200</td>
<td>70-80</td>
<td>21% (d)</td>
<td>10-15% (d)</td>
<td>30-40% ST</td>
<td>34% (d)</td>
<td>6-8</td>
</tr>
<tr>
<td>Fresnel</td>
<td>10-200</td>
<td>25-100</td>
<td>20% (p)</td>
<td>9-11% (p)</td>
<td>30-40% ST</td>
<td>25-70% (p)</td>
<td>4-6</td>
</tr>
<tr>
<td>Power tower</td>
<td>10-150</td>
<td>300-1000</td>
<td>20% (d)</td>
<td>8-10% (d)</td>
<td>30-40% ST</td>
<td>25-70% (p)</td>
<td>8-12</td>
</tr>
<tr>
<td>Dish-Stirling</td>
<td>0.01-0.4</td>
<td>1000-3000</td>
<td>29% (d)</td>
<td>16-18% (d)</td>
<td>30-40% Strl.</td>
<td>25% (p)</td>
<td>8-12</td>
</tr>
</tbody>
</table>

For 1MWh generation of solar electricity per year with Concentrated Solar Power (CSP), the required land area is only 4 -12 m²[12]. Figure 4 shows a EURODIH parabolic concentrator with a Stirling engine at test center Plataforma Solar de Almeria in Spain.
In the report of HITAJ and SUTTLES [5] regarding the trends of consumption and production of energy in US agriculture, energy proved to be an integral part of agriculture. Figure 5 offers expenses concerning energy sources for irrigation. Different types of irrigation systems need great amounts of energy for their power units and pumps as well as considering the surface and time of the function.

![Energy Sources and Expenses](Image)

**Figure 4-2.2.2: Energy sources and expenses for pumping irrigation water.** [5]
Chapter 3. Methodology

With the unfortunate events that have occurred this semester along with the confinement situation after our spring break, it was unmanageable to work and produce data for different modeling possibilities and testing for this project.

3.1. Refrigeration system

3.1.1. Principle

A graph of a classic vapor-compression refrigeration cycle can be imposed on a pressure-enthalpy (P-h) chart to establish the function of each component in the system [10], as in figure 6.

![Figure 5-3.1.1: refrigeration cycle in a Pressure-Enthalpy graph [10]](image)

The pressure-enthalpy chart plots the properties of a refrigerant—refrigerant pressure (vertical axis) versus enthalpy (horizontal axis) [10]. Enthalpy is a measure of the heat content, both sensible and latent, per pound [kg] of refrigerant.

The fundamental idea of the vapor-compressor refrigeration cycle is as follows, detailed in ref [10]:

**Evaporation:** Starts with a cool, low-pressure mixture of liquid and vapor refrigerant entering the evaporator (A). It absorbs heat from the relatively warm air, water, or other fluid that is being cooled. This transfer of heat evaporates the liquid refrigerant in the evaporator, and this superheated refrigerant vapor is drawn to the compressor (B) [10].

**Compression:** The compressor drags in the superheated refrigerant vapor (B) and compresses it to a pressure and temperature (C) high enough that it can castoff heat to another fluid. This hot, high-pressure refrigerant vapor then travels to the condenser [10].
**Condensation:** In the condenser, heat is transferred from the hot refrigerant vapor to relatively cool ambient air or cooling water. This decrease in the heat content of the refrigerant vapor causes it to de-superheat, condense into liquid, and then sub-cool before exiting the condenser (D) for the expansion device [10].

**Expansion:** Finally, the highly pressured liquid refrigerant (D) flows through the expansion device, causing a large pressure drop that reduces the pressure of the refrigerant to that of the evaporator. This pressure reduction causes a small portion of the liquid to boil off, or flash, cooling the remaining refrigerant to the desired evaporator temperature [10].

### 3.1.2. Refrigeration and Milk Cooling

Most refrigeration tanks used for milk cooling purposes are vapor-compressor refrigeration the reciprocating type [11]. All tanks are double- or-triple walled and well insulated with compacted polyurethane foam or expanded polystyrene to keep the milk cool for at least 12 hours with a temperature rise of no more than 1 °C at an ambient room temperature of 30 °C [11]. The proposed cooling tank for our hub model is the fully enclosed Direct Expansion (DX) milk cooling and storage tanks. Figure 7 gives a schematic idea of this system and Figure 8 provides an image for this equipment. The refrigeration evaporator pipes are particularly devised as flat pillow-shaped plates fastened to the outer side of the tank holding the milk. The DX cooling tanks require larger compressors [11]. The refrigeration compressor runs constantly during cooling operations. There is another type of cooling tank for milk refrigeration purposes; the Ice bank tank [11], and Tables 5 and 6 serve as a comparison between both tanks.

*Table 5-3.1.2: Comparison between DX and Ice banks cooling systems [11].*

<table>
<thead>
<tr>
<th>1 000-litre milk cooling tank</th>
<th>Direct expansion</th>
<th>Ice bank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment</td>
<td>100%</td>
<td>115%</td>
</tr>
<tr>
<td>Refrigeration condenser capacity</td>
<td>3.8 kW</td>
<td>2.0 kW</td>
</tr>
<tr>
<td>Average electricity consumption$^a$</td>
<td>20 Wh/litre</td>
<td>24 Wh/litre</td>
</tr>
</tbody>
</table>

$^a$ kW = kilowatt; Wh = watt hours.

Precooling of fresh warm milk at the milk collection centers can save significant energy usage. Furthermore, using mains or groundwater (temperature lower by at least 15°C than T of milk) gives way to implementing a lower capacity refrigeration unit [11].
Table 6-3.1.2: electrical power requirement with and without precooling [11].

<table>
<thead>
<tr>
<th>Equipment</th>
<th>No precooling</th>
<th>Precooling to 25 °C</th>
<th>Precooling to 20 °C</th>
<th>Precooling to 15 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>DX tank</td>
<td>20</td>
<td>13.6</td>
<td>10.4</td>
<td>7.2</td>
</tr>
<tr>
<td>Ice bank tank</td>
<td>24</td>
<td>16.32</td>
<td>12.48</td>
<td>8.58</td>
</tr>
</tbody>
</table>

Source: Frazer Moffat, 2015.

Figure 6-3.1.2 schematics of the DX cooling system with pre-cooling using mains/well water [11].

Figure 7-3.1.2: Fully Enclosed DX cooling with pre-cooling using mains/well water [11].

The selection of this type of tank was based on the publically available data regarding cooling equipment and its industrial presence in the dairy sector.
3.2. Parabolic dish collector Stirling engine

There is a high amount of energy sources to be used for refrigeration; however, this project aims to develop a renewable energy solution that can be deployed in rural areas for milk collection functions or a small-scale processing pasteurization unit. Certain regions in Morocco can have high irradiation levels, especially during the summer.

Numerous applications use solar energy for heat production as well as electricity generation. CSP technologies are based on the collection of sunrays and directing them at a small area which a focal point or focal line depending on the receiver. Line focused technologies are parabolic trough or linear Fresnel reflector; the point focus is presented in CSP power towers or parabolic dishes. Trough electric structures are the most industrialized technologies. They have a sun concentration ratio of about 75 and operate at temperatures of around 400°C at an annual efficiency of about 10% [20]. Power towers operate at a concentration ratio of around 800 and temperatures of about 560°C and have annual efficiencies of about 15% [20] Dish/engine systems are characterized by high efficiency, modularity, self-sufficient process, and an intrinsic hybrid competence (the ability to run on either solar energy and/or fossil fuel) [20]. The dish/Stirling systems are capable of becoming one of the least costly sources of renewable energy for their high solar-to-electric conversion efficiency, recorded at 31.25% in 2007 [20].

This following work will concern Solar Power, using Dish –Stirling technology.
3.2.1. Parabolic Dish collector

a. Components

The general components of a parabolic dish system consist of:
The parabolic reflector is the dish with a supporting structure; the collector, the Stirling engine positioned in the focus of the parabolic dish, a generator to generate the electrical energy [13]; the different components are shown in Figure 9. Additionally, many designs use solar tracking systems.

![Diagram of a parabolic dish collector](image)

*Figure 8- 3.2.1.: Design of the EURO DISH System. a 10-KiloWatt-electrical (kWe) solar dish Stirling [13]*

Each one of these components needs to be carefully selected. The parabolic dish collector uses an array of parabolic dish-shaped mirrors (depending on the design) to center solar power onto the receiver positioned at the focal point of the saucer reflectors. Heat transfer fluid (HTF) in the receiver gets heated up to required working temperature and pressure to produce electricity by the small engine attached to the receiver, usually Stirling engine type Alpha.

The geometry of the parabolic dish is very important to guarantee the proper functioning of the system and avoid any deviation of the solar rays at the focal point for the receiver aka the hot side of the Stirling engine.
The characteristics of appropriate solar dish reflectors depend: hardness against deflection and wind load, durability against the different weather conditions (moisture and temperature changes), and have a reasonable weight [13].

**b. Theoretical Efficiency of the Parabolic Dish**

Analyses of the thermal and optical efficiencies of the dish are also necessary to maximize the output of the system. The optical efficiency is based on the reflective material used for the collector usually fiberglass resin.

A thorough breakdown of the methodological efficiency study on the dish collector is examined in reference [17]. Additionally, it should consider the heat transfer between the absorber tube and the working fluid under different conditions [16].

Here is the general equation for parabolic dish collector thermal efficiency.

The thermal efficiency of the collector $\eta_c$ is the ratio of useful energy provided to the energy incident on the concentrator:

$$\eta_c = \frac{Q_u}{Q_s} \quad (1)$$

The useful heat is the energy absorbed by the heat transfer fluid; $Q_r$ the radiant solar energy on the receiver with $Q_l$ heat losses:

$$Q_u = Q_r - Q_l \quad (2)$$

$Q_s$ represents the net solar heat transferred or the solar energy; it is proportional to the aperture area of the collector $A_a$ and the direct normal insolation DNI per unit collector area that depends on the locations of the installation and time of day of operation as well weather conditions and dish concentrator orientation.

As the optical efficiency $\eta_o$, as well as the receiver efficiency $\eta_r$, determine the efficiency of the collector with $Q_r$ radiation on the receiver.

$$\eta_o = \frac{Q_r}{Q_s} \quad (3)$$

$$\eta_r = \frac{Q_u}{Q_r} \quad (4)$$

Figure 10 summarizes how the solar energy $Q_s$ encounters heat loss; either through radiation or the convection and conduction heat losses in the cavity of the receiver.
The efficiency of the collector is:

\[
\eta_c = \frac{Q_u}{Q_s} = \frac{Q_r}{Q_s} \cdot \frac{Q_u}{Q_r} = \eta_o \cdot \eta_r = \eta_o \cdot \frac{Q_r - Q_l}{Q_r} = \eta_o \left(1 - \frac{Q_l}{Q_r}\right)
\]

\[
= \eta_o \left(1 - \frac{Q_l}{\eta_o Q_s}\right) = \eta_o - \frac{Q_l}{Q_s}
\]

Exergy analysis can also be performed as it aims to observe and to evaluate quantitatively the effect of irreversible occurrences [17]. It is a more meaningful evaluation referring to the second thermodynamic law analysis that is grounded on the law of degradation of available energy as in the quality of energy which is the more realistic and true measure of the deviation of an actual system from the ideal system [17].

The exergy flow of the solar irradiation (Exs) is calculated using the Petela model which is a suitable model for the solar beam irradiation close to straight solar irradiation [14].

The useful exergy (equation 6), The exergy flow of solar irradiation (7)
Exergy efficiency:
\[ \eta_{ex} = \frac{Ex_u}{Ex_s} \] (8)

3.2.2. Stirling Engine

a. Principle
Stirling engines operate with a closed regenerative thermodynamic cycle that has theoretical thermal efficiency the same as the Carnot cycle [19] displayed in Figure 11. Stirling cycle engines rely on compressible working fluid such as air, nitrogen, helium and hydrogen, even water vapor, etc and experience rhythmically compression and expansion at different temperature levels converting thermal energy into mechanical work, type of Stirling engines are shown in Figure 12.

A brief notion of the diagrams; Process 1-2: Isothermal Compression Process. Process 2-3: Constant Volume Regeneration Transfer Process where no work is done with an increase in entropy and internal energy of the working fluid. Process 3-4: Isothermal expansion process where work is done by the working fluid on piston equals the heat supplied with an increase in entropy of the working fluid. Process 4-1: Constant Volume Regeneration Transfer Process. This is an ideal cycle process which is thermodynamically reversible; however, the operation of the actual engine has irreversibility to account for.
Figure 11-3.2.2: Three basic types of arrangements of pistons in Stirling engines (C: Cooler, R: Regenerator, H: Heater, DP: Displacer, PP: Power piston) [19]

The most common type of Stirling engine is the Alpha Stirling Engine displayed in the following figure 13.

Figure 12-3.2.2: schematic of an Alpha Stirling Engine in the following figure.

b. Thermodynamic equations and Effects on the engine

Equations

Regenerative effectiveness for the hot and cold sides:

\[ E_H = \frac{T_Y - T_2}{T_3 - T_2} = \frac{T_Y - T_C}{T_H - T_C}, \]

\[ E_C = \frac{T_H - T_V}{T_H - T_C}. \]  

(9)

For the ideal regenerator, the effectiveness is equal to one [18]. To consider the Stirling engines which do not use regenerator, the effectiveness should be set equal to zero [18]. The temperatures at the exit of the regenerator are defined as
\[ T_{3'} = T_C + E_h(T_H - T_C), \]
\[ T_{1'} = T_H - E_c(T_H - T_C). \]  \hspace{1cm} (10)

If we consider that \( Q_{2-3'} = Q_{4-1'} \), the regenerator should have the same effectiveness for cold and hot sides \( E_H = E_C = E \).

In the following equations for the volumes, \( \phi \) is the angle of the crankshaft, and ALPH (Phase Angle Difference) is the phase angle difference between hot and cold pistons, respectively.

\[ V_{HP} = \frac{V_{HPSV}}{2} (1 - \sin(\phi)) + V_{HPDV}, \]
\[ V_{CP} = \frac{V_{CPSV}}{2} (1 - \sin(\phi - \text{ALPH})) + V_{CPDV}, \]
\[ V_{TV} = V_{HP} + V_{RDV} + V_{CP}. \]  \hspace{1cm} (11)

The volumes are relative to the crankshaft angle.

The pressure equation assumes idea gas for the working gas with the total mass of the working fluid as a sum of hot piston dead volume, regenerator dead volume, cold piston dead volume, cold piston volume and hot piston volume

\[ m_{HP} = \frac{P_{HP} V_{HP}}{RT_{H}}, \] \hspace{1cm} (12)
\[ m_T = \frac{P}{R} \left[ \frac{V_{HP}}{T_H} + \frac{V_{RDV}}{T_{RDV}} + \frac{V_{CP}}{T_C} \right]. \] \hspace{1cm} (13)

P-V diagram presented in Figure 14 is called a work-diagram since it can integrate areas and the work can then be calculated, from expansion work, compression work, to net-work. The expansion work, which ideally ensues in process 3-4, is equal to the auxiliary heat; compression work, which theoretically occurs in process 1-2, is equal to absorbed heat during the cycle. Therefore, by having the work diagram, added heat and absorbed heat can be calculated.
The thermal efficiency considers regenerator deficiency and dead volumes.

$$\eta_{th} = \frac{W_{net}}{Q_{total \ input \ heat}}. \quad (14)$$

**Effects**

Many features affect the efficiency or the Stirling engine. The work of Asnaghi et al. in [18] provides a numerical and graphic data for different variations that affect the thermal efficiency of the SOLO 161 Solar Stirling engine; the working gas, the regenerator effectiveness, the phase angle difference…

The following (Tables 7 and 8) present a sample of parameters for the engine in the conducted analysis in [18].

**Table 7-3.2.2: Values of Basic engine parameter [18]**

| Hot piston sweep volume = 160.0 cm³ | Cold piston sweep volume = 160.0 cm³ |
| Hot piston dead volume = 40.0 cm³ | Cold piston dead volume = 30.0 cm³ |
| Regenerator dead volume = 30.0 cm³ | Total dead volume = 100.0 cm³ |
| Regenerator effectiveness = 0.85 | Phase angle difference = 90.0 degree |
| Heater temperature = 923 K | Cooler temperature = 300 K |
| Average working pressure = 10 MPa | Frequency of engine = 1800 rpm |

**Table 8-3.2.2: Performance characteristics of the basic engine [18]**

<table>
<thead>
<tr>
<th>Working fluid</th>
<th>PAVG (MPa)</th>
<th>Net work (J)</th>
<th>Thermal efficiency</th>
<th>Total input heat (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>10</td>
<td>887,993</td>
<td>26.9%</td>
<td>3300.23</td>
</tr>
</tbody>
</table>

The following graph (Figure 15) shows some of those effects concerning regenerative effectiveness.
Figure 14-3.2.2: Variations of thermal efficiency against hot temperature for different regenerator effectiveness values [18]

A gain in hot temperatures will increase total input heat and net-work. The work in [18] has provided insight on how the efficiency of a basic Stirling engine can be improved; the engine performance is directly affected by the phase angle alteration between hot and cold piston shaft. It was observed that for the basic engine to reach its maximum net-work at $\text{ALPH}=90\text{degree}$ is needed and for a maximum thermal efficiency $\text{ALPH}=110\text{degree}$ [18].

3.3. Adaptation of the CSP dish-Stirling to the refrigeration system

From the previous sections, a comprehension of the functioning of the Stirling engine and the refrigeration system was formed. Since the compressor-based refrigeration system relies on crankshaft rotation, the pistons of the compressor can have any drive for their rotation. The Stirling engine provides the rotation input needed for the piston and therefore rotating the crankshaft. This idea can be further explored in forming a suitable design and mechanism for this type of piston function.
3.4. Feasibility analysis for the design of Parabolic Dish collector

This section will cover the testing and calculations for a feasible design required for a 25kW Stirling engine. Random data for the parameter generation within the acceptable ranges deduced from previous design performance analysis will be used in an excel file to calculate the efficiency of the Parabolic Dish design that would generate 25kW with a Stirling engine.

There are many important parameters to calculate to reach the efficiency; wind velocity, ambient temperature, the thermal fluid, and its mass flow, inlet and outlet temperatures of the receiver as well as inside it, the angle of inclination of the receiver, the reflective material, and other specific properties of all the equipment. Figure 16 provides a diagram of the defining parameters needed. Besides, the different types of losses through either the transmission or just the heat losses affecting the collector’s efficiency. A thorough breakdown of the different equations and calculations of the possible heat losses for an in-depth study is provided in [15] as well as some design parameter samples for the range of those factors in references [20] and [21].

![Diagram of defining parameters needed](image)

*Figure 15-3.4: the overall parameters needed for performance analysis [21].*

The importance of the location and weather data is reflected in the maintenance costs, the durability of the materials, and the output generated concerning the meteorological conditions of the region. For example, the case study in [21] was done in Malaysia. Its tropical climate of heavy rainfall, as
well as the high value of humidity and cloud cover, provide very low solar irradiance of 223W/m² and above which affects the output power of this system and its annual energy [21]. This, in turn, can put a dent in the economic feasibility of this system even though the system is technically feasible in this region.

The excel sheet in Figure 17 gives a part of the whole table of the input parameters used in the calculations of this analysis with the output of the convective and conductive heat losses.

![Figure 16-3.4: the excel sheet with the input parameters and the output result for heat loss calculation.](image)

The original excel sheet has included multiple loss calculation factors and the results were not satisfying. Some parameters were used in calculating multiple sub equations, which would have misused the correct numbers in the correct equation. The outputs presented do not include every parameter calculated and have just stated the total heat loss based on the initial specifications. The calculations performed did not cover the possibility of coating the material of the receiver.
Chapter 4. Results and Discussion

4.1. Results
Relying on the input parameters stated previously, and following heat loss equations from the concentrator dish based on heat transfer between the glass material and the environment due to convection and radiation. Those calculations included Nusselt number and relied on wind conditions in the region.

The following Figure 18 is a graph presenting the changing thermal efficiency of the proposed parameters throughout the temperature of a random day near the Marrakech region with a minimum DNI of 950 W/m².

![Total Efficiency](image)

*Figure 17-4.1: Graph of the thermal efficiency throughout a random day*

The efficiency changes based on the time of the day and if the system is equipped with a tracking system for maximum solar collection as well as the environmental condition from wind, rain, and dust situation. Based on the parameters selected for this 25kW Parabolic Dish Collector- Stirling Engine analysis, the calculations led to the total efficiency of the receiver to $\eta_r\approx15\%$ and average thermal efficiency of the collector to $\eta_{th}\approx44.7\%$. 
4.2. Discussion

This section will provide the rationale for using this Parabolic Dish Collector-Stirling engine system and not considering other technologies.

For the hub model of this overall project, electricity power generation for heating as well as cooling systems were considered. The need for a great amount of electric power and thermal energy for a heating process of minimum 72°C for pasteurization, parabolic dish-Stirling technologies provides a viable way for power generation. Different facets were considered in the selection of this technology.

➢ **Location**

With the location and space available for the hub model, the selection of the solar system was based on a smaller area for the installation of the system. The energy used along the different sections in the hub and most importantly for the refrigeration unit would need a vast space when using the most common solar technologies (solar panels or other solar technologies) if the installation was on the ground near the facility.

Considering the area for the installation, a normal solar panel would take 1m² for an average of 1kW, which would require a 1000m² for the 10MW needed for the hub for minimum needs. It is a third of the space if the hub occupies approximately 3000m², which is not practical.

➢ **Materials and Operational Systems**

Reference [17] provides an example of different specifications concerning Dish-Stirling technologies in Table 9.
Based on the electric energy requirement for the Direct Expansion cooling tank selected for the hub model provided in section 3.1.2., a 25kW capacity would be able to operate its electrical need as well as that of the facility (excluding the heat treatment unit) which would be explained later in this section. Many studies and performance analysis simulations regarding this type of CSP have taken place over the past decade.

> **Weather Condition**

Bearing in mind the project is to be in Morocco, through the irradiation map in Figure 18 the weather data regarding the solar irradiation and environment conditions are needed to perform the calculations for the net output energy.
This irradiation map shows that the minimum DNI (900 W/m²) needed for the average performance of this system are present all over the Moroccan terrain, meaning that this technology can be used in the farming regions for its vast space and minimum shading possibilities and yield possible great results upon further improvements and material analysis.

- **Previous working prototypes**

A 25kW CSP parabolic dish Stirling Engine is technically feasible, from the analysis based on Matlab Simulation in [21]. Table 10 presents the parameters of the design for a ~82m²-concentrator aperture area in the aforementioned case study in [21].

**Table 10-4: receiver, concentrator parameters for 25kW ParabolicDish Stirling system [21].**

<table>
<thead>
<tr>
<th>No</th>
<th>Parameter</th>
<th>Parameter value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>PD concentrator diameter $D_{con}$ (m)</td>
<td>10.181</td>
</tr>
<tr>
<td>2.</td>
<td>Concentrator aperture area (m²)</td>
<td>81.4</td>
</tr>
<tr>
<td>3.</td>
<td>Reflective material (Aluminium)</td>
<td>0.92%</td>
</tr>
<tr>
<td>4.</td>
<td>Rim angle $\phi_{rim}$ (degree)</td>
<td>45</td>
</tr>
<tr>
<td>5.</td>
<td>Focal length (m)</td>
<td>6.15</td>
</tr>
<tr>
<td>6.</td>
<td>Focal Point Diameter (m)</td>
<td>0.05</td>
</tr>
<tr>
<td>7.</td>
<td>Receiver aperture area (m²)</td>
<td>0.184</td>
</tr>
<tr>
<td>8.</td>
<td>Intercept factor</td>
<td>0.1</td>
</tr>
<tr>
<td>9.</td>
<td>Stirling engine type</td>
<td>SES</td>
</tr>
</tbody>
</table>

In the article [20], a very similar configuration set to the one in the Feasibility section was used for modeling of PD Stirling system. The efficiency of the receiver for that model was = 19.8%. and the average actual efficiency of the collector was ~51%. This shows that the calculations done in this work could be more developed for better results. In other words, a Dish-Stirling system 25kW
capacity is attainable for a space of 100 m². This CSP technology can yield even greater results upon further testing and simulation of various materials.

➢ Energy consumption

Concerning energy consumption and after consulting different machinery needed for small-scale milk collection centers as well as different small-scale milk processing plant, a round number of 180 MJ of thermal energy requirement and a 90MJ of electric energy. If we consider simplified plants that contain milk cooling equipment and container washing additionally to pasteurization machines, some equations have been developed in chapter 3 of G. Riva’s book *Utilization of renewable energy sources and energy-saving technologies by small-scale milk plants and collection centers* [23].

The values for the $m$ terms are quantities in tonne/day and the energy values in MJ/tonne of processed milk:

$m_p$: milk pasteurized and packed into a small container  
$m_c$: chilled milk  
$m_t$: milk processed into yogurt and cheese

Thermal energy requirement  
$$E_t = 25m_c + 180(m_p + m_t) \quad (14)$$

Electric energy requirement  
$$E_e = 145m_c + 90(m_p + m_t) \quad (15)$$

For the hub, expectations for preliminary calculations, reception, and cooling tank capacity have an average of 5000Litres/ day (5 tonnes/day) from which at least 2.5 tonnes of milk pasteurized and the other quantity sent for other product processing such as yogurt or cheese. Since the center works 7 to 8 hours a day for the processing and needs 24hours for refrigeration, the electric energy based on equation (15) is around 995MJ per tonne that is around 276kWh. The refrigeration requirement takes up to 50%, which makes it 138 kWh for the electrical need for refrigeration purposes.

If we take the 25kW Parabolic Dish Collector-Stirling system proposed in this project, with an average of 6 hours for peak sun-hours, we get 150kWh, and for a remote location with minimum shading as well as high insolation, it can be up to 8hours that gives 200kWh. We can also take into consideration the variation of the power over time to determine the amount of electric energy generated after careful analysis in the said location of the system. Overall, this system can provide sufficient energy for refrigeration purposes during the day. During the breaks from the processing in
the hub, the generated electricity can be sold to the government. The produced electricity can be integrated into the grid, traded for electricity for the refrigeration during nighttime if there is no storage station for the energy generated from this system.

This type of technology can have annual solar-to-electricity efficiency of up to 25% under ideal conditions, and annual capacity factor between 20-25 % [24].

➢ Financials

Concerning the financial and investment analysis, the complete breakdown of investment opportunities is done in the group report. The proposed system needs to reduce the average cost of energy supplied over its lifetime. The Levelized Cost of Energy (LCOE) or Levelized Energy Cost (LEC) can define the economics of any energy production system. This fundamental factor provides the cost of production over the amount produced about energy. The following is the equation for LEC with $i$ the interest rate on capital and $n$ the life of the system:

$$\text{LEC} = \frac{\text{OMC} + \text{CC}}{E} \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right]$$  \hspace{1cm} (16)

Taking into consideration that the Moroccan environment, especially in the rural areas, provides great conditions for DNI collection, the output energy of the system can be good if not high enough depending on the efficiency of the system. Vis-à-vis the cost of this system for the hub, it will depend on either the possibility to obtain an already functioning system from a manufacturer or the opportunity to design one with adequate material purchase which would need further analysis.

Regarding the existing functioning systems, the EURODISH Stirling engine shown previously in Figure 4-2.3.2 provides a good example of power with high solar-to-electric efficiency; it has an average of 5500 euro/kWe. From the economic feasibility of the case study in [21], the LEC of CSP Parabolic Dish (PD) plants ranges in the USD 0.19 -0.43/ kWh. Taking into consideration that the solar irradiance in the US is approximately similar to that of Morocco, the output energy will only depend on the capacity of the system. With low-cost high-quality material and suitable modeling of this system, the LEC would be reasonable and the system economically feasible. From
the International Renewable Energy Agency references [24], the global weighted average LEC using CSP is USD 0.185 /kWh.

The different costs are detailed in the group report including the different financial supports available regarding this technology for the hub model, which will not be including a thermal energy storage unit that composes a great part of the cost of the system.

This hub is going to be under the name of Centrale Danone, and it factors in decentralizing its supply chain regarding milk collection, distribution for pasteurized milk. Additionally, it represents a project for social development and improvement for the dairy sector and as renewable energy is a current trend it benefits from the high number of investors.

In the financial section of the group report, the return on investment estimated for this whole hub based on the equipment and machinery, the different capital expenses as well as the operating expenses with the addition of supply cost. It is inclusive of the PD collector Stirling engine minimum cost after providing the business students with different possible suppliers of this system’s components as well as estimations of the materials that would build the system in case we decide on making a prototype. Some estimation was included to generate reasonable scenarios for the production quantities and the revenues ranging from pessimistic to realistic to optimistic. Table 11 summarizes the most important findings of 3 years of the hub project, based on a realistic scenario.

Table 11-4.2: ROI summary for the Hub over 3years based on Realistic scenario

<table>
<thead>
<tr>
<th></th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>1,898,818,800.00</td>
<td>1,940,601,540.00</td>
<td>1,940,594,540.00</td>
</tr>
<tr>
<td>Value of Project</td>
<td>1,789,967,772.99</td>
<td>1,953,392,919.20</td>
<td>2,175,744,815.14</td>
</tr>
<tr>
<td>ROI</td>
<td>-5.73%</td>
<td>0.66%</td>
<td>12.12%</td>
</tr>
</tbody>
</table>

From the table above, the hub project will face a negative ROI in the first year of operation, however, it would benefit from a high positive ROI in the 3rd year.
Conclusion

Alterations in international Renewable Energy markets, industries, and policies have been so quick in recent years. The investments in this industry have changed. In the path toward sustainable development and clean energy sources, renewable technologies have witnessed a soaring expansion and detailed analyses in terms of the technical part as well as the financials. Following the trend of wind and PV technologies already as a growing industry, CSP and specifically Parabolic Dish Collector systems have high initial costs. However, as the skills and expertise along with available machinery mature, the installed capacity of the systems increases along with the Cumulative Capacity (MW).

Nevertheless, the lack of data and production companies of the necessary equipment for this technology causes the high costs for initial investments, which lowers the drive to rely on them and further analyze improvement strategies for different applications. In the CSP world, there is a lack of proper actual small-scale installations for this technology.

Concerning the applications of the parabolic dish Stirling system, the possibility to have different units of higher capacity would provide a sustainable solution of the hub proposed in the overall project. However, the costs would outweigh the benefits even with the different financing options provided by companies interested either in the technology or by selling the power to the government.

The selection of the different equipment and material for this system would be based on the parameter specifications shown throughout this work; to attain the 25kW capacity of the system and supply the hub with the needed energy. The complete financial analysis would be in the overall group report of the team.
References


