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Project Report

Design Considerations for Reducing Battery Storage in Off-Grid, Stand-Alone, Photovoltaic-Powered Cold Storage in Rural Applications

Johan Meyer * and Sune von Solms

Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg 2006, South Africa; svonsolms@uj.ac.za

* Correspondence: johanm@uj.ac.za

Abstract: This paper presents design considerations for the design and implementation of stand-alone photovoltaic-powered containerized cold storage solutions for rural off-grid applications. The work presented is based on a case study of an off-grid photovoltaic-powered cold storage unit located in rural South Africa. Although solar-powered solutions for off-grid rural applications are very attractive and offer many benefits, including increased food security, skills development, income generation, and productivity due to the presence of solar power, the application of cold storage requires careful consideration of the design aspects to ensure that the solution is feasible and sustainable. The challenge of maintaining low temperatures inside a cold storage system in an excessively warm environment, such as that frequently encountered in most African rural settings, has stimulated discussions of design considerations for optimal efficiency. Not only are the design aspects of the PV panel mounting and tilt associated with the geographic location of the application, but the heating implications are also derived from the physical orientation of the storage unit. Results from mathematical models are substantiated with field data collected from a case deployment. The design considerations for the sizing of the electrical components in the system are presented. The paper concludes by answering the research question as to what design aspects should be considered for an off-grid, PV-powered containerized cold storage system to reduce the size of the battery storage unit.

Keywords: cold storage; off grid; photovoltaic design; rural development

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1. Introduction

The availability and accessibility of electricity have always been important factors when it comes to the improvement of societal sectors and wellbeing. Be that as it may, about 1.3 billion people still do not have adequate access [1]. Despite the growth of urbanization in Africa over the last 20 years, a lot of places are still yet to be developed. Most of the affected individuals are the inhabitants of scattered and isolated rural areas mostly in developing nations [1]. These places are usually associated with poor infrastructure. Sub-Saharan Africa ranks last in the world when it comes to electrification levels [2], with several of the regions therein undeveloped and with electrification levels not exceeding the 5% average [2]. Research has estimated that 68% of people in Sub-Saharan Africa reside in rural areas [3]. The emphasis on rural electrification has been growing, with off-grid generation gaining momentum. With most of the people in rural settlements, the conventional ways of grid electrification are found to be very costly economically and, therefore, are less likely to be implemented. Some of the factors adding to the high costs of electrification are the long distances from the existing electricity grid and the poor topographies as, in most cases, nothing has been developed. The costs involved in grid extensions, transmission, and distribution to scattered homesteads are high, which drives the focus on decentralized energy generation technologies that best fit the nature of the scattered rural regions [2].

1.1. Background and Purpose

One cannot talk about increasing the standards of living for people without talking about food security, especially in rural areas where subsistence farming is the main source of food supply. Failure to store the food until the next season equates to starving for most people or loss when it comes to commercial farmers and businesses [4]. Research conducted by Kantide et al. shows that, at present, about 40% of the food produced globally must be kept under some form of refrigeration [5]; therefore, there is a need for cold food storage facilities in rural settlements. The shortage of cold storages has posed a problem for the market price of food. This increase in the price is caused by the loss of food due to the lack of cold storage [5]. The increase in demand for fresh food has risen proportionally to the food intake globally. The quality of food decreases immensely with time owing to its perishable nature. It has been shown that, if fresh food is exposed to a temperature of 35 °C for an hour, then the quality will deteriorate the same as if it were to spend 20 h in a cold storage in ideal conditions [4]. The cooling inside a room can be improved immensely using cold storages [1]. The advantages of cooling include removing field heat, which decreases the growth of micro-organisms and ethylene. It also buys farmers time to bring food to market or transport it for further storage [4].

In some developing countries that are heavily dependent on agriculture, e.g., India, there is a significant number of food storage systems in operation, ranging around six thousand in number [5]. The cold storages run on high power and are, therefore, powered by renewable sources. Statistics suggest that about 30 to 50 kWh/m^3 of energy is consumed annually by conventional cold storage. Hence, a considerable amount of the annual energy budget is directed towards this sector. A literature study conducted by Kantide et al. indicates that about 11% of the global energy goes to cold storage [6]. In Africa, particularly rural South Africa, which has poor infrastructure, solar power is now the principal substitute source [4], resulting in cold storages in these areas being operated using solar power and, sometimes, backup battery systems for night and cloudy days [4].

The purpose of this paper is to report on design considerations that can be utilized to reduce the size of battery energy storage for an off-grid, PV-powered rural cold storage system. An off-grid, PV-powered cold storage solution can be realized through the design and implementation of a PV micro-grid capable of supplying the electrical demand of the cold storage unit. However, the implementation of developmental rural PV cold storage systems presents several challenges.

1.1.1. Security of PV panels

PV panels are considered to be a high-value commodity, especially in rural areas with little to no grid connectivity. In the provision of PV solutions for rural areas, sufficient care must be taken in the design of the security around the PV panel installation. It is desirable to place the panels on top of the cold storage, which will increase the security compared to an open terrestrial mounting; however, the number of panels that can be installed on top of the cold storage facility is limited by the size the container. Elaborate PV mounting construction systems will inevitably increase the cost and deployment complexity of these solutions.

1.1.2. High Ambient Temperatures

In many cases, rural areas are characterized by high ambient temperatures. In the case of the Gwakwani village, the case study used in this paper, the ambient temperature can reach above 45 °C in summer. It was found that the high ambient temperature resulted in a battery bay temperature in the range of 40–60 °C. The high temperature in the battery bay had a detrimental effect on the lifetime of the lead acid batteries utilized in the application. It is accepted that the life of a lead–acid battery subjected to an average temperature of 40 °C with a maximum of 50 °C can be reduced by as much as 66%. Since lead–acid batteries are significantly less expensive and more available than lithium derivatives, it is a preferred technology in low-technology, less expensive rural applications.

1.1.3. Limited Maintenance Competence

In rural development applications, there are a limited number of people with the skills necessary to maintain the technology. Lead–acid batteries require regular maintenance in terms of electrolyte levels, which are often neglected in rural environments. Hence, there is a need to limit the battery energy storage size, which may then make alternative more expensive, low-maintenance battery technologies more viable.

1.1.4. Limited Complexity

It is beneficial to limit the technological complexity of rural development solutions, as maintenance and repair in these often remote areas are costly. Several alternative cold storage solutions are presented in the literature section, varying from solar thermal solutions to hybrid solar PV systems. Many of these solutions require the modification of existing equipment or complex installations. It is the aim of this paper to report on design considerations that do not require the extensive modification of existing refrigeration equipment or complex hybrid technology installations.

1.1.5. Limited Capital Investment

It is often the case that rural development is sponsored by donor funders with limited budgets. The design considerations presented here are focused on the use of existing and available technologies and methods to limit the cost and maintenance of rural developmental applications.

1.2. Litterature Overview

The main technologies used for the powering of cold storage facilities from solar energy include solar thermal-driven applications and solar PV applications [6]. A comparison of solar absorption system configurations is reported on by Molero-Villar et al. [7]. Syed et al. confirmed that, in the Kingdom of Saudi Arabia, more than 60% of electrical energy consumption is spent on air conditioning and refrigeration. They then proceeded to provide in-depth reviews of alternative designs for a 24 h operating solar-powered absorption refrigeration systems [8].

The concept of combined solar thermal–PV systems was investigated by Basu and Ganguly [9]. In the work of Luerssen et al., comparisons between combinations of PV, battery, and thermal energy storage and diesel energy generation in terms of life cycle cost analysis were performed and presented They found that the battery properties, reliability, and price are important factors to consider in the design of cold storage systems, which supports the rationale in this study for minimizing the size of the battery used for energy storage [10]. Rech et al. used a multicriteria approach that included energetic, exergetic, and economic factors to assess the best integrated solution for compressor and absorption refrigeration solutions. They found that due to its high efficiency, compressor-based technologies out performed abortion-based technologies [11].

Energy storage is essential in PV cooling systems to maintain service when solar outage is encountered during nighttime operations. Energy storage may be obtained using battery storage to conserve the surplus electricity produced by solar panels, or cold thermal storage to store the excess cooling capacity generated. Cold thermal storage can be obtained using phase change materials [12] in the design of the cold storage unit. Wang and Dennis reported on the influencing factors for the energy savings of combined battery and phase change cold storage devices [13]. The design of a solar-powered domestic refrigerator using a solar-powered variable speed drive and phase change materials to support the cooling during low irradiance levels was reported on by Radhi [14]. A techno-economic evaluation of a PV integrated refrigeration system was performed by Ikram et al., which showed, with mathematical modelling, how the condenser, evaporator, and compressor motor could be optimized in the design of a conventional banana cold storage facility [15]. The design steps for a solar PV-powered cold storage system are presented by Mouloud et al., taking into account the geographic location of the cold storage facility for the purpose of calculating the heat load and available PV energy and then sizing the electrical energy requirement and the PV array [16]. Iqbal et al. suggested means for the performance optimization of the compressor in an off-grid PV-powered cold storage application by swapping the alternating current motor-driven compressor with a brushless direct current motor-driven compressor to reduce the cost of the inverter system [17]. Gupta et al. reported on the sizing of the PV panel, battery capacity, and insulation thickness of a small, PV-powered domestic refrigerator. They demonstrate the importance of the insulation material thickness and the choice of lead–acid battery technology for energy storage [18].

1.3. Contribution

One of the high-cost items in a PV-powered cold storage system is the energy storage battery, and this accounts for not only the initial procurement cost, but also the maintenance, especially in the harsh climate of rural areas. The contribution of this paper is the presentation of different design concepts focused on reducing the size of the battery storage unit, resulting in an overall cost reduction for these applications. Although more sophisticated battery technologies are available, the cost of these units is significantly more than the traditionally used lead–acid batteries. By reducing the battery size, the use of more expensive battery technologies could be considered. In addition, we present design concepts that do not require significant additional cost in a cold storage solution, as they deal with the physical orientation and placement of the solar panels and geographical orientation of the cold storage container. We have demonstrated that by considering a container's geographic orientation, solar panel orientation, and the choice of insulation material thickness, the battery energy storage capacity for nighttime operation can be reduced to approximately 7.5 kWh at a 50% depth of discharge for a typical cold storage application, as shown in the Gwakwani case. The reduction in the capacity of the battery's energy storage makes it possible to consider the use of more expensive lithium technologies for the benefit of better lifetime and less maintenance.

2. Methods

Rural environments present challenges to the design of cold storage as, in these areas, little grid electricity is available and extremely high ambient temperatures occur. This paper reports on design concepts that can be considered in the design of the PV-powered cold storage systems applied to rural installations, as demonstrated in the Gwakwani village case in the northern Limpopo province of South Africa. These design concepts significantly enhance the chances of success for this type of project. The methodology followed in this paper involved deriving a mathematical model for the simulation of a cold storage facility employed in a harsh ambient temperature environment to investigate the different design concepts. The cold storage unit consisted of a standard 6 m steel shipping container converted for use as a cold storage unit by applying insulation material to the inside of the container's steel walls.

2.1. Gwakwani Case

The village of Gwakwani is situated in the Limpopo province in South Africa. The village is deeply rural, with approximate 100 people making a living from subsistence farming and government grants. The village is approximately 17 km from the nearest town and only accessible by a dirt road, which floods in the rainy season, isolating the village from the high school and closest medical facility. Gwakwani lacks direct mobile cellular connection and municipal water or sanitation services provided by utility suppliers. The village was recently connected to the electricity grid in 2018, but this is not used by the residents due to the high cost of grid electricity.

In this rural community, where villagers largely depend on the produce from their small-scale farms and gardens, they lack the appropriate preservation and storage mechanisms to support the food production. When fruit and vegetables are ready for harvest, they must be used, as there is little means of preservation. Additional food harvested in season cannot be preserved for out-of-season use, as the storage of produce on a long-term basis does not exist. The same applies for when an animal is slaughtered for meat, whereby the complete animal must be used at once to prevent spoiling or food wastage. The community actively engage in community food swapping, where excess garden produce is shared to spare it from becoming spoilt or composted.

Through a range of community engagement projects in the village, various solar solutions were developed to address the needs of the village and its residents. These solutions included the installation of solar borehole pumps, the development of drip irrigation systems, the installation of solar geysers, as well as the design and commissioning of a solar bakery. A shipping container was converted and equipped as a commercial bakery, powered by a solar PV system, which supported economic development within the community. Eight community members were trained in baking and operating and managing the bakery, which produces approximately 120–160 loaves of bread, depending on the season. With the success of the containerized bakery, the need of the community for a cold storage facility was highlighted. Not only did the bakery require a cold storage facility for the surplus of baking supplies, but the residents also voiced their need for a facility in which to store their excess produce. The cold storage facility was commissioned in 2019, and it consisted of a repurposed shipping container and a compressor refrigeration unit, which is PV-powered, as shown in Figure 1.

Figure 1. Gwakwani village PV-powered cold storage.

The initial design considered the use of solar panels to run the air-conditioning unit throughout the day. The insulation of the container was designed to keep the temperature of the cold storage unit below 5 °C, which is the proposed temperature for the safe preservation of produce. The parameters of the Gwakwani cold storage unit are presented in Table 1.

The solution was able to consistently cool down the cold storage container during the day when the air conditioner was running. However, on cloudy or rainy days or at night, when the air-conditioning unit was not running, the insulation was unable to keep the unit cooled down sufficiently to retain the required low temperatures. Figure 2 shows the temperature recorded inside the cold storage compared with the ambient outside temperature, alongside the power consumed by the refrigeration compressor as measured on 4 December 2018, which is nearly mid-summer in the southern hemisphere. The inability of the refrigeration compressor to maintain the inside temperature of the cold storage below 5 °C can be seen especially during the afternoon, when the available solar power decreased while the ambient temperature was still close to 40 °C.

Table 1. Gwakwani cold storage parameters.

Parameter	Value
Shipping container	Standard 6 m steel shipping container
Cold storage volume	26 m^3
Equipment bay volume	6 m^3
Refrigeration compressor power rating	2.2 kW, 380 VAC
Refrigerant	R-22
Solar panels	14 × 325 W
Solar panel V_{mppt}	37.2 V
Nominal solar energy yield per day	27 300 Wh
Solar panel tilt	Flat 0°
Insulation material	Extruded polystyrene R = 0.024 W/m^2 °C
Insulation material thickness	50 mm
Geographic location	22°34′19.3″ S 30°48′16.0″ E
Solar variable speed drive	Schneider Electric Altivar 312 Solar ATV312HU55N4412

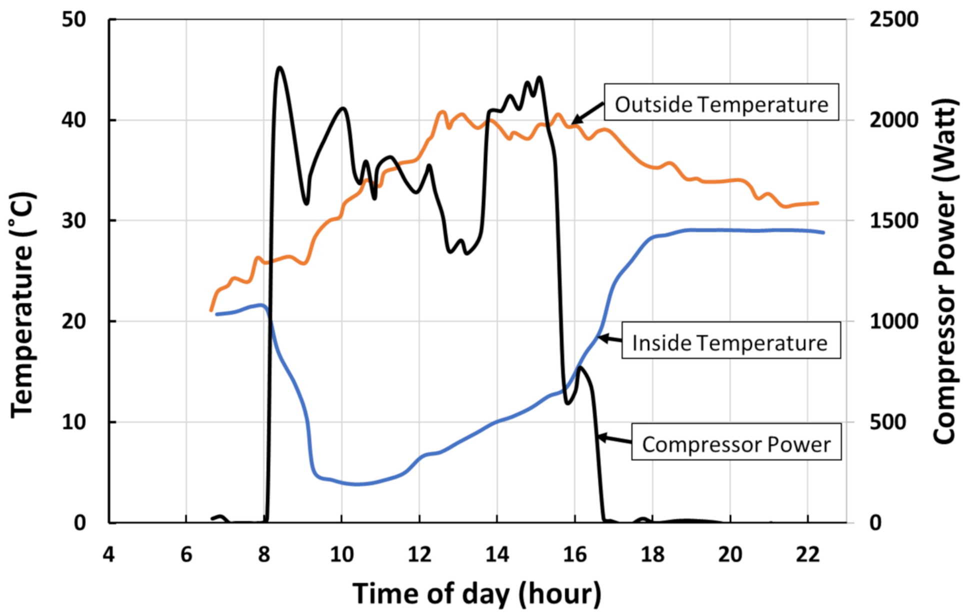

Figure 2. Gwakwani cold storage. Inside temperature, outside temperature, and compressor power consumption as measured on 4 December 2018.

From Figure 2, it can be seen that the implemented cold storage solution was not able to maintain an inside temperature of less than 10 °C, especially during solar outage at night. When the outside temperature increased to above 35 °C, the insufficient insulation resistance coupled with the reduction of compressor performance resulted in unacceptably high cold storage temperatures. With the discovery of this issue, the design considerations of the cold storage unit were reconsidered to determine what can be implemented for this solution to work. The design considerations are discussed in the next section.

2.2. Mathematical Modelling

Using mathematical modelling, the following design aspects were investigated for their ability to reduce the battery storage size and maintain the cold storage temperature below 10 °C:

1. Electrical system architecture;
2. Cold storage geographical orientation;
3. PV array mounting and tilt;
4. Insolation material thickness;
5. PV array sizing;
6. Cold storage temperature dynamic behavior.

The next steps were implemented in the modelling to obtain the required thermal power and, subsequently, the electrical power for the refrigeration compressor. The final design should allow us to obtain the required electrical power from the PV installation.

Step1: Compute the sun vector. The first step in the simulation was to use a standard sun position model to compute the sun position vector as a function of the day of the year and time of day at the geographical position of the cold storage unit (23.5° S, 30° E).

Step 2: Compute the solar insolation. The solar insolation on the Earth's surface is computed considering the solar insolation on the surface of the atmosphere (1316.2 W/m^2) and corrected for the air mass to obtain the insolation on the Earth's surface for the sun position vector.

Step 3: Compute the normal unit vectors for the sides of the container. Compute the normal unit vector for all the sides of the container as positioned in the local reference frame.

Step 4: Compute the incident solar power. Compute the incident solar power on each side of the container by taking the vector dot product between the side normal vector and the solar radiation vector.

Step 5: Compute the total incident solar power. The incident solar power on all the container sides is summed together.

Step 6: Compute the temperature of the container steel. A heat balance equation is derived, taking into account the heat absorbed by the steel walls of the container, the heat radiated by the steel walls of the container, and the heat transferred to the inside of the cold storage through the insulating material. The temperature of the steel walls of the container is obtained from the following differential equation, which is numerically solved, giving the temperature of the container steel walls:

$$mC_P T'(t) - C\left(T_{Sky}^4 - T(t)^4\right) - K(T_I - T(t)) = P_s(t) \quad (1)$$

where $T(t)$ is the temperature of the container steel wall as a function of time t, T_{Sky} is the sky temperature, C_P is the specific heat capacity of steel, m is the steel mass of the container, and $P_S(t)$ is the incident solar radiation power. The constant C is

$$C = A_S \epsilon \sigma \quad (2)$$

where A_S is the total steel surface area, ε is the emissivity of steel, and σ is the radiation constant. The constant K is given by

$$K = \frac{kA_I}{dx} \quad (3)$$

with k being the thermal conductivity of the insulation material, A_I being the surface area of the insulating material, and dx being the thickness of the insulating material.

Step 7: Compute the heat transfer to the inside of the cold storage. The heat transfer to the inside of the container Q_I is computed from the following equation:

$$Q_I(t) = K(T_I - T_S(t)) \quad (4)$$

where $Q_I(t)$ is the heat transferred to the inside of the cold storage as a function of time, K is the constant defined in Equation (3), T_I is the constant internal temperature of the cold storage, and $T_S(t)$ is the temperature of the steel container as a function of time.

Step 8: Compute the thermal power required. The thermal power required to maintain the inside of the cold storage at the preset constant temperature is then given by $Q_I(t)$. The electrical power required to maintain the cold storage temperature is obtained by scaling the thermal power $Q_I(t)$ with the Coefficient of Performance (COP) of the refrigeration system.

Step 9: Scenario testing. With the simulation model, different scenarios of container orientations and insulation thicknesses could be evaluated to obtain the required solar power for the refrigeration system.

Step 10: Develop an electrical analogous circuit. An electrical circuit simulation was developed that is analogous to the thermal characteristics of the cold storage to enable easier dynamic simulation of the cold storage system. The parameters used in the electrical simulation were validated against the observed behavior from the cold storage implemented at the Gwakwani village. From the simulation results, the electrical and refrigeration equipment can be sized, and the physical installation can be planned. The parameter values used in the mathematical modelling of the cold storage are given in Table 2.

Table 2. Model parameter values.

Simulation Parameter	Value
Maximum solar radiation on atmosphere surface	1361 W/m^2
Solar radiation computations	PV education [19]
Geographical location	23.5° S, 30° E
Time zone	GMT + 2 h
Container outside height	2.6 m
Container outside length	6.06 m
Container outside width	2.44 m
Container steel wall surface solar heat absorption factor	0.2
Container steel mass	2230 kg
Specific heat capacity of steel	500 J/kg°K
Thermal conductivity of insulation material	0.033 W/m°K
Nominal thickness of insulation material	50 mm
Stefan's constant, σ	5.667×10^{-8} $W/m^2/K^4$
Emissivity of container steel wall, ε	0.5
Ambient sky temperature T_{Sky}	297° K (20 °C)
Electrical Circuit Model Parameters	
R1, R2, R3	0.1 Ohm
R4, R5, R8	2 Ohm
R6	4.5 Ohm
R7	15 Ohm
C1	10 F
C2	1 F
C3	0.1 F
C4	0.5 F

3. Design Considerations

The technical design of the cold storage must be able to accommodate the use, capacity, and geographical location of the application. Critical focus was paid to the design aspects, such as the thermodynamics of the container, the positioning of the solar panels, the size of the compressor, the battery storage system, the container orientation and, most importantly, the overall cost. Taking into consideration the issue of changes in season and the variability of weather conditions, different aspects are taken into consideration to accommodate the difference, such as the battery banks and the solar tracking technologies.

3.1. Electrical System Architecture

The most basic electrical architecture for the solar-powered cold storage solution is shown in Figure 3. The PV array is connected to a variable speed drive (VSD), which is capable of direct solar electricity input. The VSD must be capable of maximum power point tracking to best utilize the available solar power from the PV array. The variable speed drive is sometimes also called a variable frequency drive (VFD). The VSD converts the direct current from the PV array into a variable frequency three-phase power supply. The frequency of the supply determines the load output and is varied according to the maximum power point allowed by the PV array. The VSD is connected to the three-phase input supply driving the refrigeration compressor. The VSD is sized to the maximum load of the refrigeration compressor to allow acceptable temperature levels inside the cold storage unit.

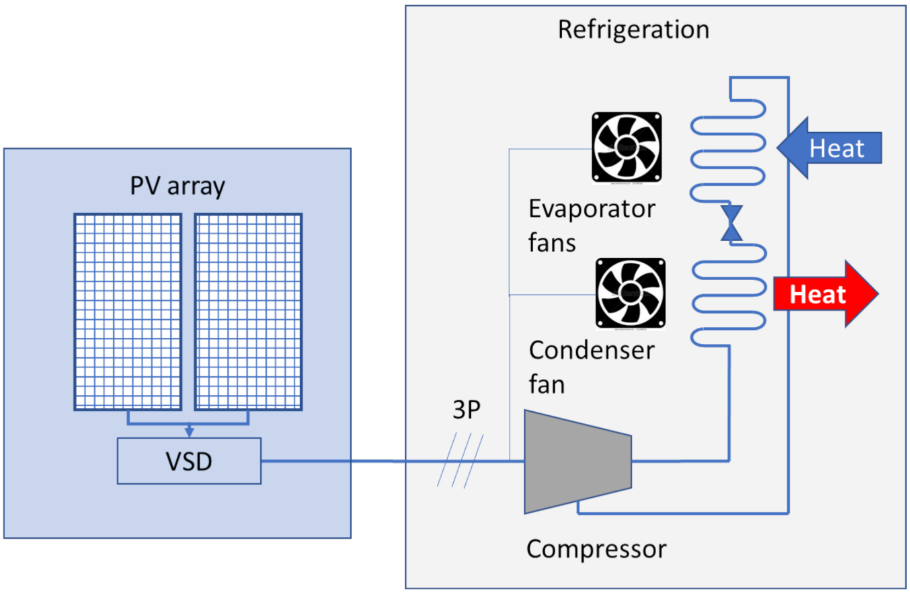

Figure 3. Basic electrical architecture for a solar-powered cold storage unit.

3.1.1. Advantages

These type of VSDs are often used for solar-powered water pumping applications and are reasonably inexpensive and readily available. The electrical connections are simple, with minimal additional equipment required besides the surge arrestors and DC input isolation switches and circuit protection switches, making for an elegant, simplistic solution. The solution works well in daytime when the refrigeration compressor speed is ramped up by the VSD, matching the compressor load to the available power yield from the solar array. The compressor is run at maximum speed or full load during the peak hours of the day when refrigerated cooling is required most.

3.1.2. Disadvantages

The biggest disadvantage of this configuration is the inability to operate the refrigeration compressor during the night when no solar power is available, since the solution is not equipped with an energy storage ability. Active temperature regulation during nighttime is impossible and temperature levels inside the cold storage unit are highly dependent on the heat capacity of the contents of the cold storage unit. Secondly, the three-phase power output from the VSD does not provide the neutral connection, but only the L1, L2, and L3 phase outputs. In many refrigeration units, the fans used to extract the heat from the condenser and the evaporator require single-phase supply, which necessitates the wiring of the fans in such a way that a star connection is established, creating a virtual neutral point. This is easy to achieve when the fans are of a similar rating and there are two fans in the evaporator unit and one fan in the condenser, resulting in a circuit with one fan supplied from each of the three-phase supplies, respectively. Care must be taken to select similar fans in the refrigeration unit so as to prevent a large phase imbalance that would prevent the VSD from operating. To overcome the disadvantage of not being able to run the cold storage refrigeration at night, the electrical architecture presented in Figure 4 is proposed.

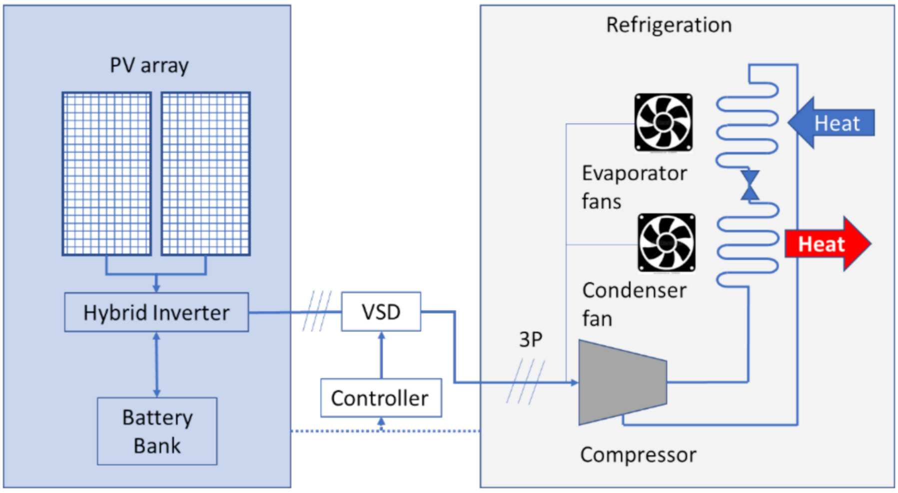

Figure 4. Advanced electrical architecture for a solar-powered cold storage unit.

A more advanced electrical architecture capable of running the cold storage refrigeration during the night is shown in Figure 4. The PV array feeds solar power into a hybrid inverter. The hybrid inverter can provide 3-phase electrical power to the VSD, and any excess available solar power can be stored in a battery bank. At nighttime, the hybrid inverter can use the stored electrical energy from the battery bank to power the refrigeration compressor through the VSD.

3.1.3. Advantages

The advantage of having an energy store in the form of a battery bank is that the excess available solar energy produced by the solar PV array after the maximum load of the refrigeration compressor has been reached can be stored. At nighttime, the stored electrical energy can be fed to the hybrid inverter driving the refrigeration compressor through the VSD. The main purpose of the controller is to reduce the operating conditions of the compressor for nighttime operation. The benefit of having a controller is that the temperature control inside the cold storage unit can be optimized on the basis of the available stored energy in the battery bank and the available solar energy yield. Having the option (although for a limited period) to supplement the solar power provided to the hybrid inverter gives additional robustness to the solution in case of cloudy conditions.

3.1.4. Disadvantages

The disadvantage of the advanced electrical energy architecture is the additional cost of the hybrid inverter, as well as that of the battery bank. The addition of the battery bank would necessitate the regular maintenance of the batteries and their replacement on a regular long-term interval. At an increased cost, the standard lead–acid batteries used in the battery bank can be replaced with more advanced lithium-based battery technologies or hybrid battery–supercapacitor combinations. This would increase the initial cost; however, the long-term gain would be a drastically reduced maintenance cost, especially in the long term.

3.2. Cold Storage Container Placement Orientation

An important design consideration is the placement orientation of the cold storage container. For this case study, a standard 6 m steel shipping container is positioned and orientated in the southern hemisphere, as shown in Figure 5.

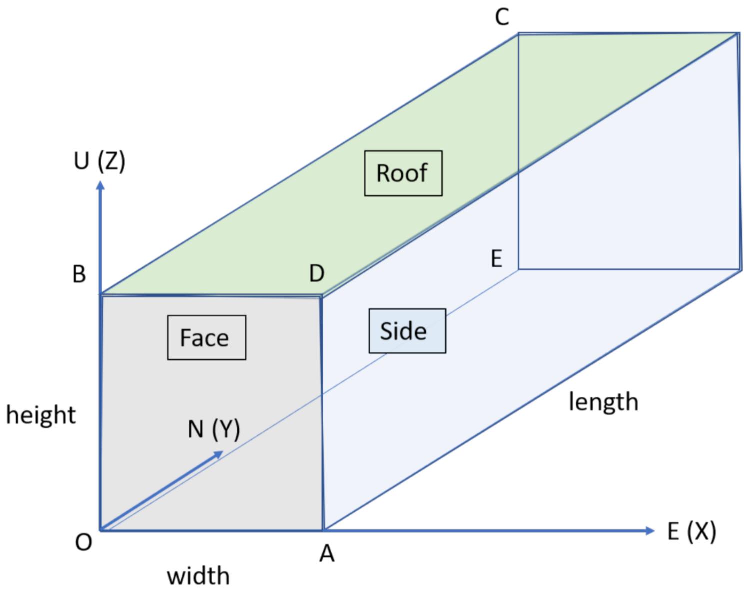

Figure 5. Cold storage container orientation definitions.

Consider a container positioned with its long side facing east and the container face pointing north. The solar radiation the sides of the container are exposed to over the period of a day in summer is shown in Figure 6.

From Figure 6, it can be seen how, at sunrise, the eastern-facing side is exposed to the incident solar radiation, which increases at first and then decreases to a value of 0 W when the Sun is directly overhead at midday. This process inverts for the western-facing side towards sunset. The incident solar radiation on the north-pointing face initially increases and then decreases towards 0 W at midday. After midday, the north-pointing face increases initially then decreases to 0 W at sunset. Due to the latitude orientation of the container, the south-pointing face does not receive any incident solar radiation. The incident solar radiation on the roof increases from sunrise, reaching a maximum at midday, and then decreases to 0 W at sunset.

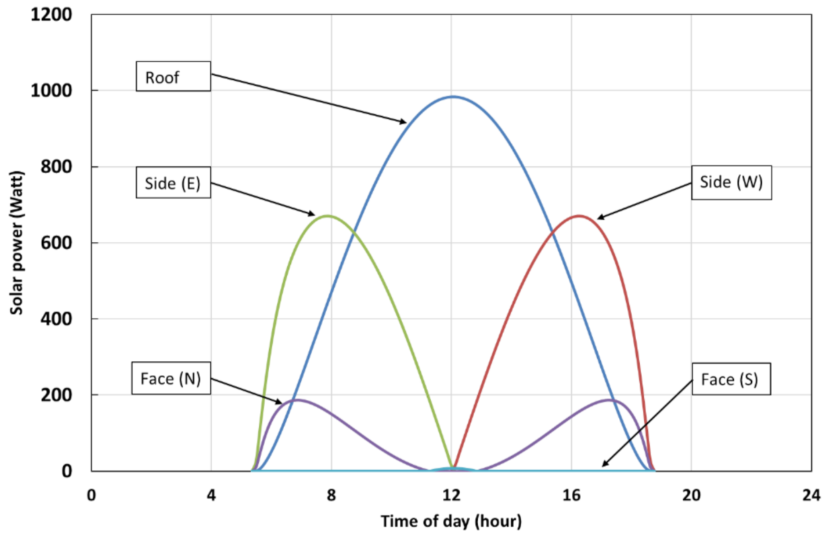

Figure 6. Solar radiation incident on the walls of the container over a summer's day. Side (E) indicates the container side wall normal to the east, Side (W) indicates the container side wall normal to the west, Face (N) indicates the container face wall normal to the north, Face (S) indicates the container face normal to the south, and Roof indicates the roof wall of the container, which is normal to up.

It must be noted that the most solar radiation is received on the roof of the container and then each side in turn. The north-pointing face receives up to 20% of the maximum value of the solar radiation the roof is exposed to. The incident solar radiation the container walls are exposed to changes significantly during wintertime, when the solar elevation angle is significantly reduced, as shown in Figure 7.

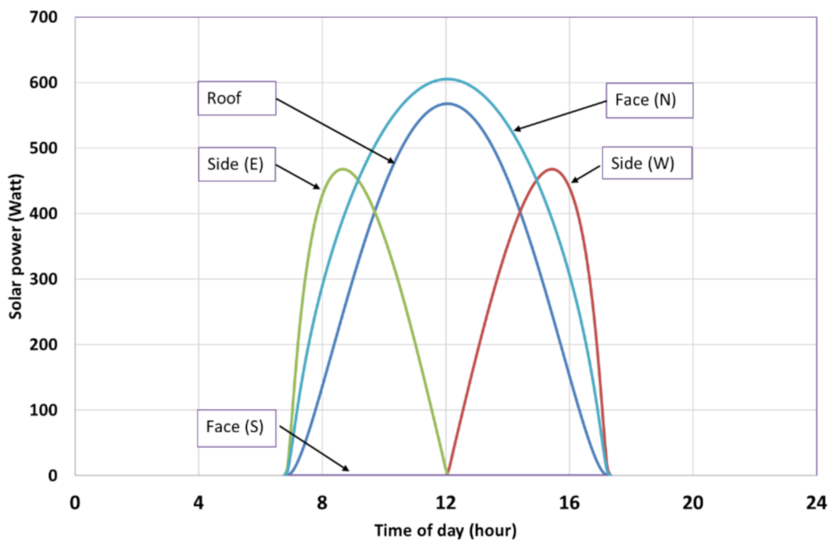

Figure 7. Solar radiation incident on the walls of the container over a winter's day. Side (E) indicates the container side wall normal to the east, Side (W) indicates the container side wall normal to the west, Face (N) indicates the container face wall normal to the north, Face (S) indicates the container face normal to the south, and Roof indicates the roof wall of the container, which is normal to up.

The incident solar radiation on the container walls follows a similar pattern to that in summer, except for the significant exposure of the north-pointing face and the reduction in the solar radiation onto the roof of the container as result of the limited sun elevation angle. The total incident solar radiation on the container walls for summer and winter is shown in Figure 8.

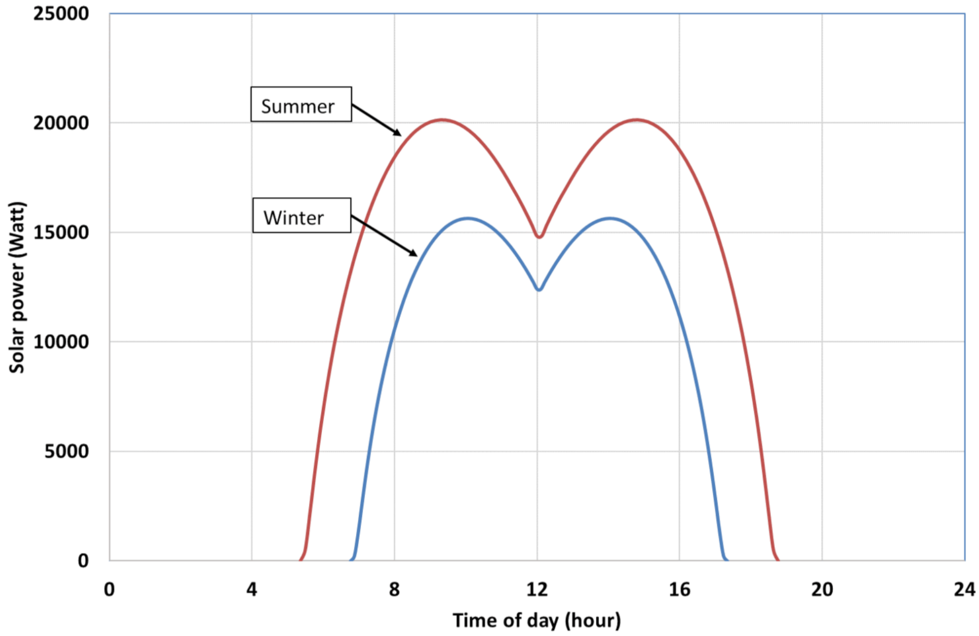

Figure 8. Total incident solar radiation on the container walls for mid-summer and mid-winter.

The incident solar power on the walls of the steel container causes a temperature increase in the steel walls of the container, as shown in Figure 9.

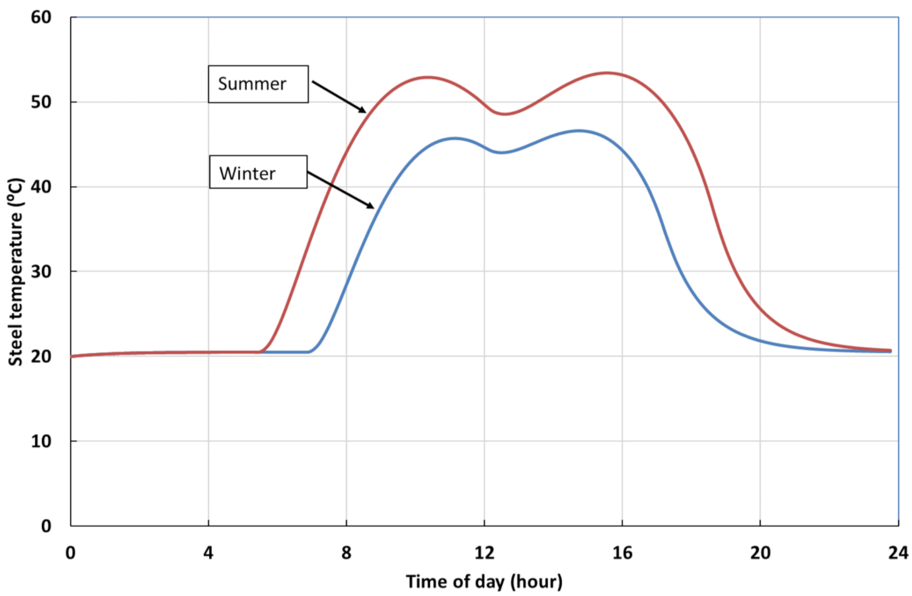

Figure 9. Steel container wall temperature for mid-summer and mid-winter.

From Figures 8 and 9, it can be seen how the geographical orientation of the container plays a significant role in the solar heat absorption of the container, resulting in the high temperatures of the steel walls of the container.

3.3. Solar Panel Mounting Consideration

It is ideal in these applications to mount the solar panel array on top of the steel shipping container. This not only makes for a more contained solution, but also aids in the security of the solar panels. The benefit of mounting the solar array on top of the container is the shading afforded to the roof surface of the container, which significantly reduces the solar heat absorption and reduces the temperature of the roof steel wall. The effect of the shading as a result of mounting the solar panels on the roof of the container is shown in Figure 10.

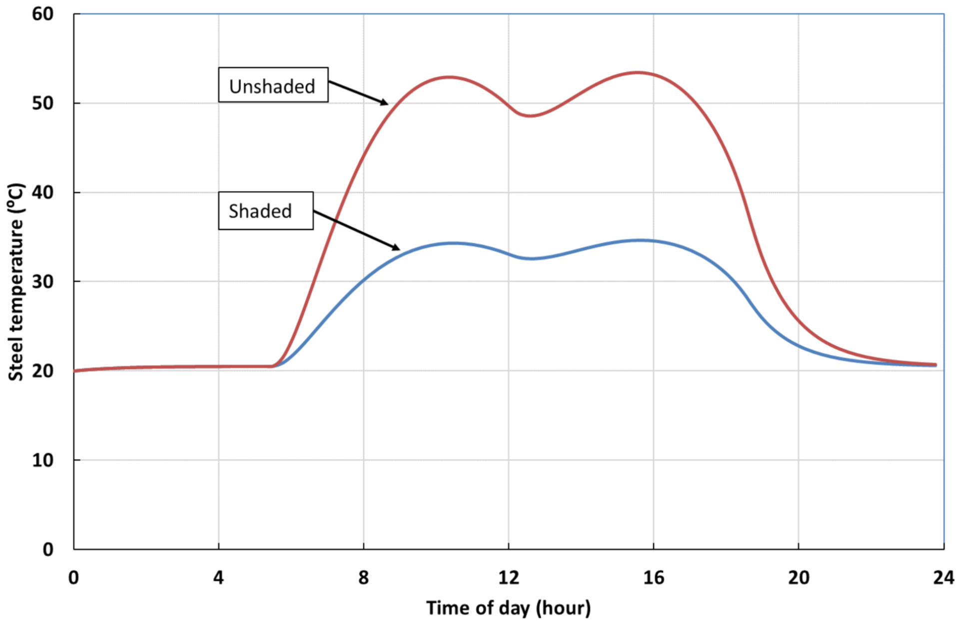

Figure 10. Container steel wall temperature in mid-summer shaded by the solar array mounted on top of the container vs. unshaded, where the solar panel array is mounted away from the container.

Mounting the solar panel array on top of the container results in a reduction in the steel temperature of the roof surface, which in turn results in a lower power requirement for the refrigeration compressor to maintain the inside of the cold storage at a constant of 5° Celsius, as shown on Figure 11.

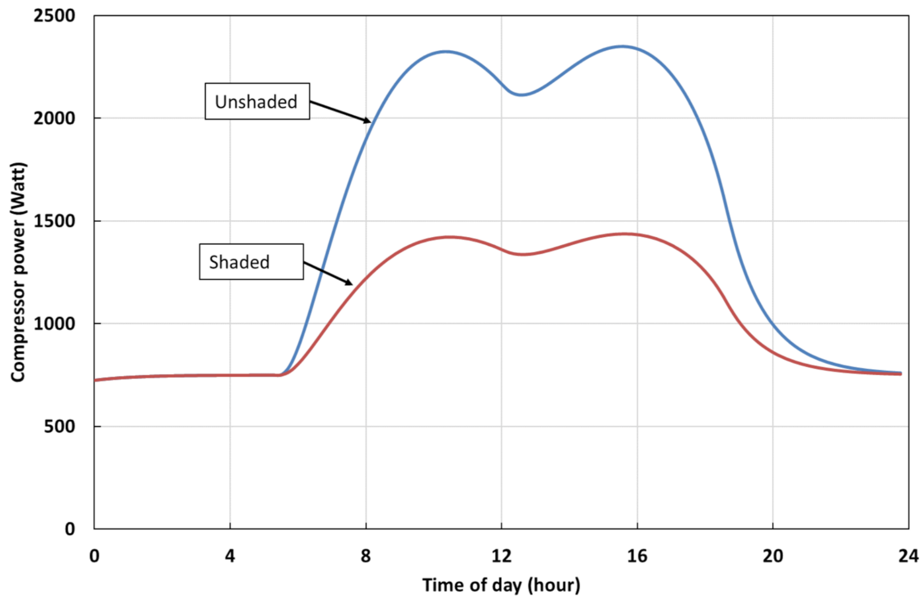

Figure 11. Compressor power required to maintain a constant 5 °C temperature inside the cold storage unit. Shaded by the solar array vs. unshaded container.

Mounting the PV array on top of the container can significantly shade the container, resulting in a reduction in the steel wall temperature of the cold storage container.

3.4. Insolation Material Thickness Consideration

The steel shipping container is insulated on the inside walls using thermal insulation material, such as polystyrene sheeting. The importance of the thickness of the insulating material is demonstrated in Figure 12, which shows the reduction in thermal power required by the refrigeration compressor for a shaded container with insulation thickness materials of 50 mm and 100 mm.

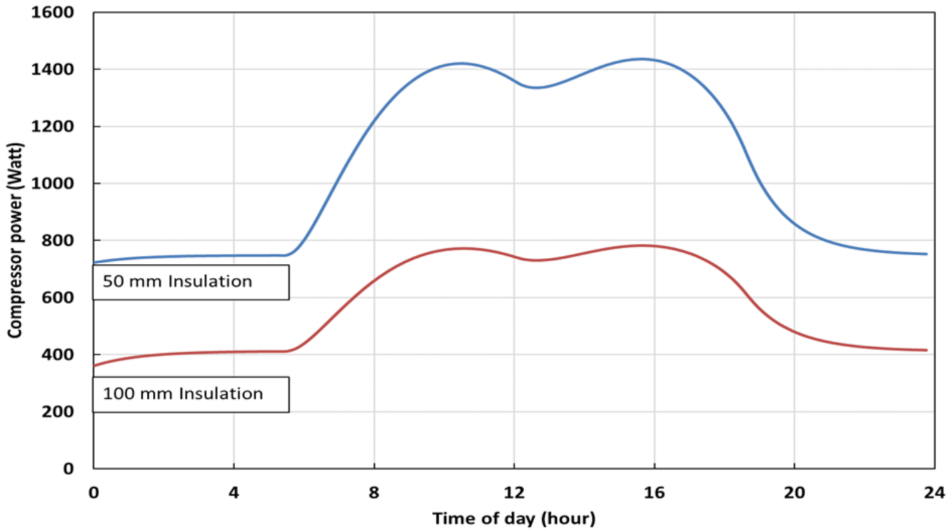

Figure 12. Required compressor thermal power for insulation materials 50 mm thick and 100 mm thick in summer with a shaded container.

By doubling the thickness of the insulation material, the heat load of the refrigeration compressor can be halved, as shown in Figure 12. Insulation material is a relatively inexpensive material, which makes this one of the primary design considerations.

3.5. Geographical Orientation Consideration

The geographical orientation of the container faces, based around the principal north–south axis and the east–west axis, leads to significant differences in the solar radiation absorbed by the steel container. Since the container is rectangular, different face or end alignments result in different values of heat absorption from the exposed solar thermal radiation, as shown in Figure 13.

The corresponding thermal power requirement of the refrigeration compressor is demonstrated in Figure 14.

The Face (E) orientation requires less compressor power to keep the inside of the cold storage at 5 °C than the Side (E) orientation in the winter. The best solution would be the Face (E) orientation with additional shading, which would limit the amount of solar radiation absorbed when the side wall is mostly facing the Sun during midday. The resulting thermal power requirement for the refrigeration compressor is shown in Figure 15.

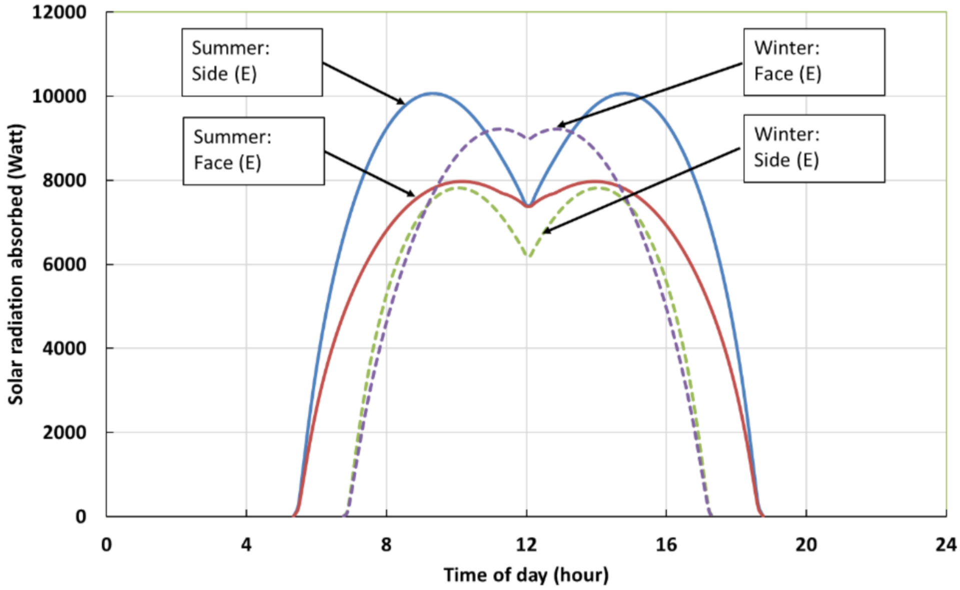

Figure 13. Solar radiation absorbed by the container in mid-summer and mid-winter for orthogonal orientations. Side (E) indicates the container side wall normal to the east, Side (W) indicates the container side wall normal to the west, Face (N) indicates the container face wall normal to the north, Face (S) indicates the container face normal to the south, and Roof indicates the roof wall of the container, which is normal to up.

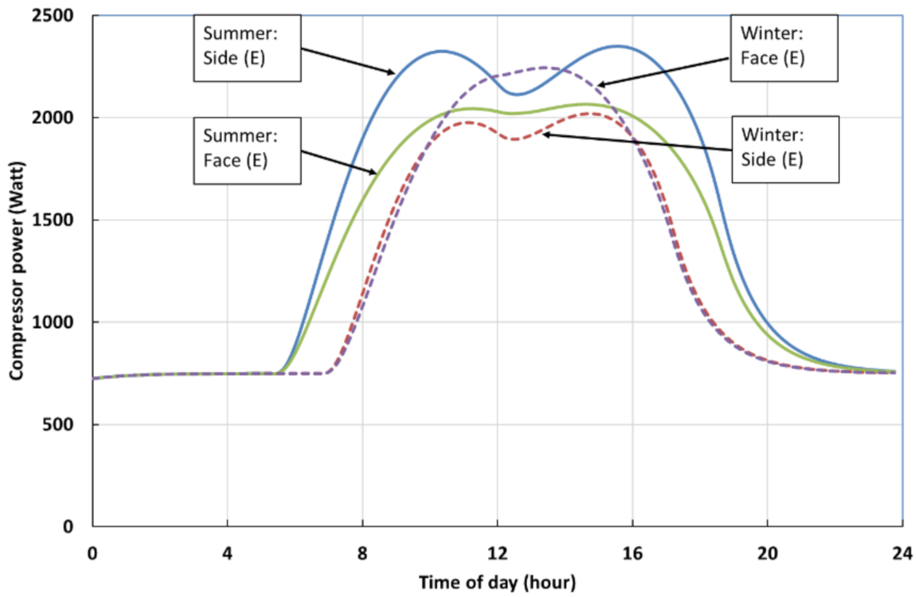

Figure 14. Compressor power required to maintain the cold storage at 5 °C for orthogonal container orientations in mid-summer and mid-winter. Side (E) indicates the container side wall normal to the east, Side (W) indicates the container side wall normal to the west, Face (N) indicates the container face wall normal to the north, Face (S) indicates the container face normal to the south, and Roof indicates the roof wall of the container, which is normal to up.

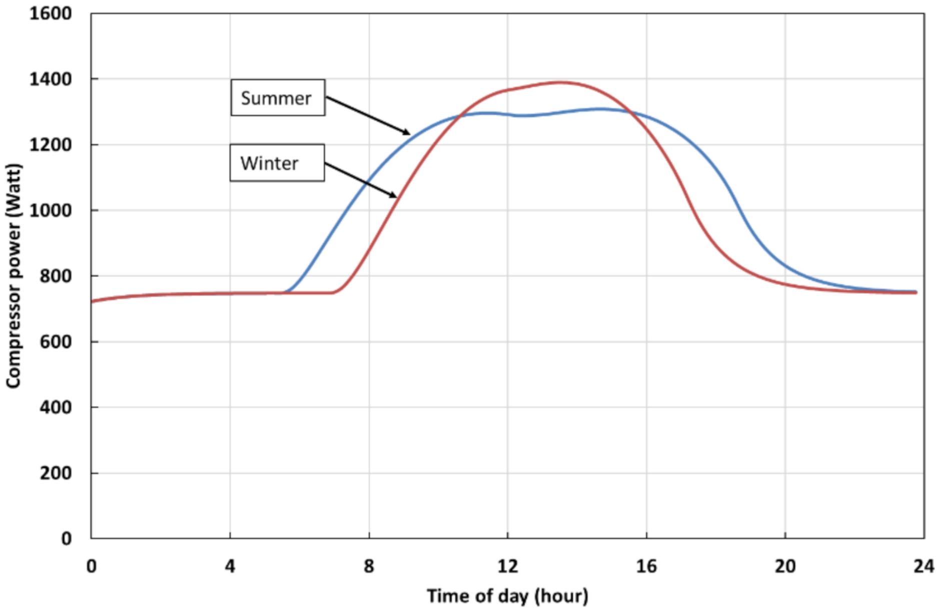

Figure 15. Compressor thermal power required to keep the cold storage temperature at 5 °C in mid-summer and mid-winter for a cold storage container orientated with the container face wall, normal to east, with all the container walls shaded.

3.6. Photovoltaic Panels Tilt Consideration

The ideal solution would be to mount the PV panels directly on top of the cold storage container in a flat configuration with the PV panels horizontally mounted parallel to the roof of the container. Flat mounting the PV panels would be structurally simple; however, unfortunately, it would not be energy yield optimal as a result of the Earth's declination angle of 23.5° as it orbits the Sun. Shown in Figure 16 is the solar elevation and azimuth angles for mid-summer and mid-winter for a PV array geolocated at 23° S latitude. The solar elevation angle is reduced to a maximum of 44° at midday during mid-winter conditions, increasing to 90° at midday during mid-summer conditions. The reduced solar elevation angle results in a reduction of the solar energy yield as the incidence angle between the solar radiation and the horizontal is limited to 46° in mid-winter. The decrease in the incidence solar angle on the PV array leads to a reduction of the solar energy yield. This reduction in the solar energy yield on a flat PV array is at a maximum when the Sun's position is in the opposing hemisphere to the solar installation.

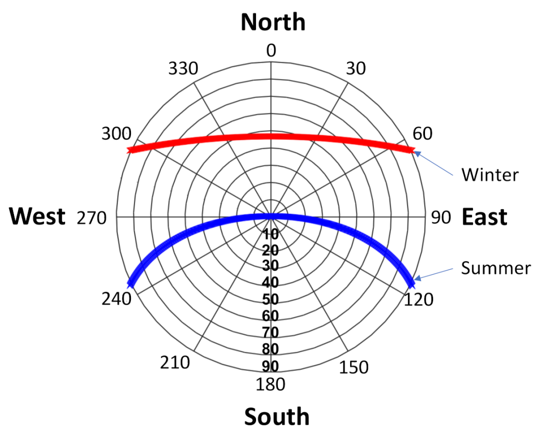

Figure 16. The Sun's elevation and azimuth angles during winter and summer for a solar PV installation at a 23.5° S latitude.

Figure 17 shows the configuration of a horizontally mounted PV panel (A) at a southern latitude of 23.5°. The Sun's angle in relation to the PV array is indicated with the angle α. For a horizontally mounted PV array, the PV array tilt angle β = 0°. It can be seen in Figure 17 how the solar incidence angle for a horizontal PV array is decreased according to the latitude angle of the PV array. The solar incidence angle on the PV array can be increased by mounting the PV array tilted from the horizontal to the north, with a tilt angle β, thereby increasing the solar incidence angle and, subsequently, the solar energy yield of the PV array.

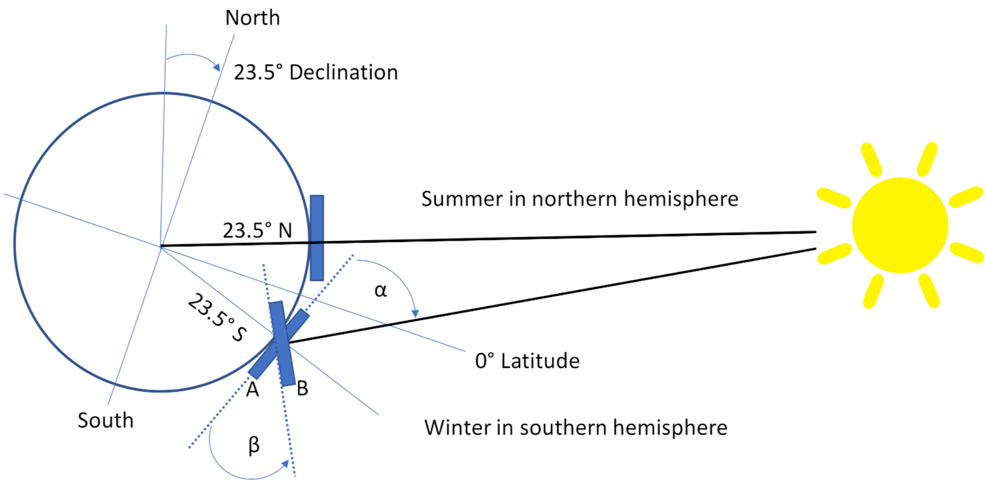

Figure 17. Solar incidence angle on a PV array in winter conditions, where the PV array is in the southern hemisphere and the Sun's orbit is in the northern hemisphere. (A) Local horizontally mounted PV array. (B) Locally tilt-mounted PV array.

In Figure 18, the available electrical power on a clear day for every square meter of the installed PV array located at the winter solstice latitude of 23.5° S is plotted for a flat-mounted array versus an array tilted at 23.5° towards the north, for mid-summer and mid-winter conditions. The peak electrical power available at midday in summer is about 186 W/m^2 compared to 108 W/m^2 for mid-winter. These computations are based on basic solar radiation algorithms, which exclude any thermal heating effects of the panels. The total energy available from a flat-mounted solar array in mid-summer is about 5.1 MJ/m^2 per day compared to 2.4 MJ/m^2 per day in mid-winter, which is a significant reduction of 54%. The benefit of tilting the PV array is clearly demonstrated in Figure 18. By tilting the PV array 23.5° to the north, the peak electrical power is increased by 34% in mid-winter compared to the flat array. The increased power comes at a cost of reducing the peak summer power by only 8%.

The significance of tilting the PV array is highlighted even more when comparing the increased yield in energy availability over the period of a day. If we consider the worst-case scenario of a refrigeration compressor load of 100 W/m^2 of installed PV array in mid-winter, the compressor will only start at about 11:00, when the electrical power produced exceeds the compressor load (Figure 18, point D), and stops at 13:00 (Figure 18, point E) for the flat-mounted PV array. Compared to the tilted PV array, the compressor would be able to produce full load at about 09:00 (Figure 18, point C) and run till about 15:00 (Figure 18, point F). The flat 1 m^2 PV array would only be able to supply 100 W × 2 h = 0.72MJ compared to the tilted 1 m^2 PV array, which would be able to supply 100 W × 6 h = 2.16 MJ, which is an increase of 200%. This increase in available energy is substantial for a minimal reduction in available energy in summer, which is, in any case, more than what is available under the winter conditions.

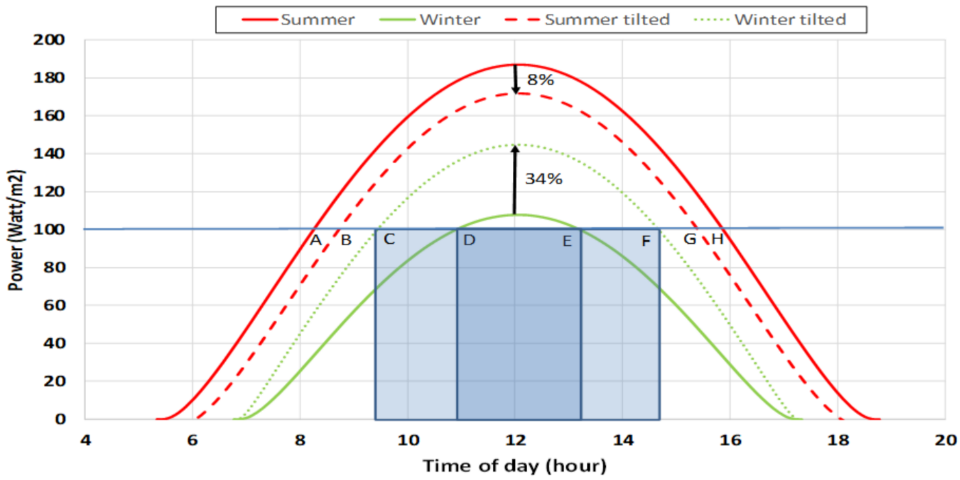

Figure 18. Available electrical power per unit of installed PV panels for a flat-mounted PV array versus a 23.5° northward-tilted PV array.

Table 3 shows the PV panel maximum power yield per unit as a function of the tilt angle comparing mid-summer and mid-winter values.

Table 3. PV panel maximum power yield per unit as a function of the tilt angle comparing mid-summer and mid-winter values.

PV Array Tilt Angle (deg)	Mid-Summer (W/m^2)	Mid-Winter (W/m^2)
0	187	108
10	184	126
20	176	141
30	163	150
35	154	154
40	144	157
50	121	157
60	94	153

The design consideration to be evaluated is whether the increase in solar energy yield justifies the increase in the complexity of mounting the solar panels at a tilt angle.

3.7. Excess Energy Collected during the Day for utilization at Night

Figure 19 shows the available solar power for an installation at 23.5° S latitude with panels tilted 23.5° towards the north. As can be seen for a constant load, excess energy (Figure 19, area B) will be available when the solar yield exceeds the load requirement. The excess solar power is available for storage in an energy storage bank, such as a battery. The excess energy stored in daytime can be used to run the compressor at a reduced load during nighttime, as discussed in the next section. When the compressor power level for nighttime operations has been established, the amount of energy required for nighttime running that must be stored during the day daytime can be determined, and the overall size of the PV array can be determined. The amount of excess energy available for storage in summer (area A) is about 25% and in winter (area B) about 16% of the total energy collected over the period of a day. Unfortunately, the utilization of the available excess solar energy would require more electronic devices, which complexifies the electrical power solution, which must be compared to the cost of installing additional PV panels to supply the energy requirements for the nighttime operation.

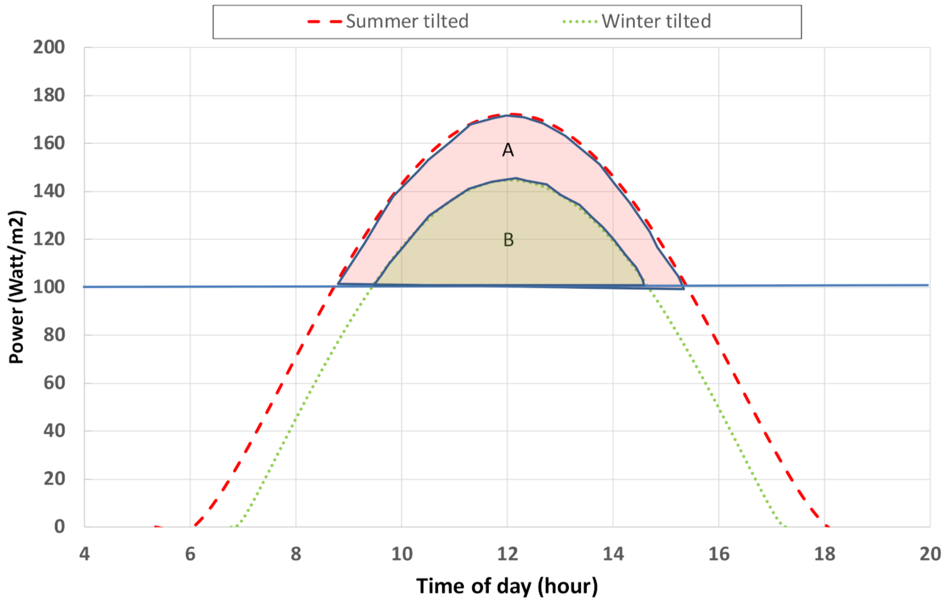

Figure 19. Excess available solar energy for a constant compressor load.

3.8. Dynamic Behavior

The dynamic thermal behavior of the cold storage unit is modelled using an electrical equivalent circuit [20]. The electrical equivalent circuit is shown in Figure 20. The intention of the electrical equivalent circuit is not to model the exact thermal behavior of the cold storage, but rather to obtain trend information, as well as the dynamic relationship among the thermal components of the cold storage. The model is based on a lumped parameter model with heat flow rate Q reproduced by a current source, heat capacity by a capacitor, and thermal resistance by a resistor. Component values were chosen to duplicate the temperature behavior of the steel container wall that are based on the experimental measurements obtained from the case application.

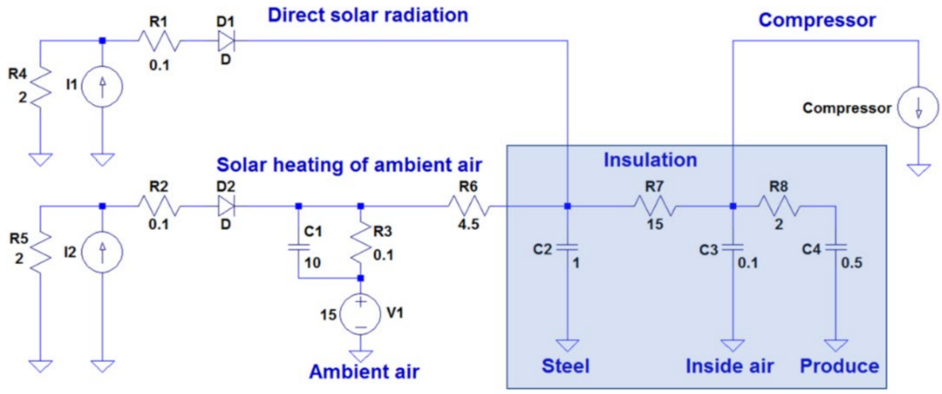

Figure 20. The dynamic thermal behavior of the cold storage modelled using an electrical equivalent circuit.

The heat capacity from the steel wall of the container is modelled using the capacitor C1. The steel wall of the container is heated by direct solar radiation as well as thermal heat transfer from the ambient air to the steel wall of the container. The heat transfer as a result of the direct solar radiation on the steel surface is modelled by the current source I1. The daily solar radiation profile is obtained via the half-wave rectification of the sinusoidal current using diode D1. The resistor R4 is used to provide a current path for the current source when blocked by the diode D1. Thermal conduction from the ambient air, which is driven by solar radiation from current source I2, is modelled by the voltage source V1 and the parallel RC network formed by R3 and C1. The RC network allows us to model the rise in ambient air temperature during the day, with a minimum value set by the voltage source. The thermal heat transfer from the ambient air to the steel wall of the container is modelled by a sinusoidal current source I2, which is half-wave rectified by diode D2 to obtain the daily solar radiation profile. The ambient air temperature is obtained from the rectified current from current source I2 and the charging capacitor C1, of which the voltage on C1 represents the ambient air temperature. The minimum ambient air temperature is set by the voltage source V1. The dissipation of the air temperature is obtained by the resistor R3. The thermal heat transfer from the ambient air to the steel container wall is controlled by the resistor R6. The thermal conduction through the insulation material between the steel wall of the container and air inside the cold storage is simulated by resistor R7. The heat capacity of the air inside the cold storage is simulated with capacitor C3 and the thermal heat transfer to the produce inside the cold storage with resistor R8. The thermal heat capacity of the produce inside the cold storage is modelled by capacitor C4. The voltage on capacitor C4 is an indication of the temperature of the produce inside the cold storage. The cooling compressor of the cold storage is modelled as a current source, which removes heat from the air inside the cold storage. The dynamic switching behavior of the compressor can be modelled by the waveform of the compressor current source.

The produce temperature profile is shown in Figure 21 over a period of 48 h, when the container steel wall temperature can rise to a maximum 50 °C. The compressor is powered from the available solar power, which rises from about 06:00 in the morning to the maximum value required by the compressor at around 09:00 in the morning, and which reduces from about 15:00 downward to no power at sunset at 18:00. During the on-time of the compressor, the produce temperature is reduced from 15 °C to just above 5 °C. It is desirable not to cool the produce down to below 5 °C, as freezing can start. As a result of the heat capacity of the steel and the ambient outside air, the maximum container steel wall temperature is reached at around 14:00, which coincides with the period of high solar yield, resulting in the produce temperature being maintained close to 5 °C. As result of the heat capacity of the steel and the ambient surroundings, the container steel wall temperature drops off considerably slower than the reduction in available solar power, resulting in a large temperature gradient between the container steel and the produce at a time when there is insufficient solar power available to prevent the produce temperature rising above 10 °C. As can be seen from the graph in Figure 21, the critical time is the period after the solar power has reduced at sunset, where the steel container wall is at a high residual temperature, resulting in a rapid rise in produce temperature until the temperature of the produce approaches the temperature of the steel wall, which is at the nighttime minimum ambient temperature of 15 °C.

The produce temperature rises during the nighttime, necessitating the running of the compressor also at night. The running of the compressor at night is associated with a large cost increase, as a battery bank with additional power electronics need to be provided, together with an increased number of PV panels to collect the energy for nighttime use. By driving the compressor from a variable speed drive, the power consumption of the compressor can be controlled to a reduced level, which limits the size of the required battery bank.

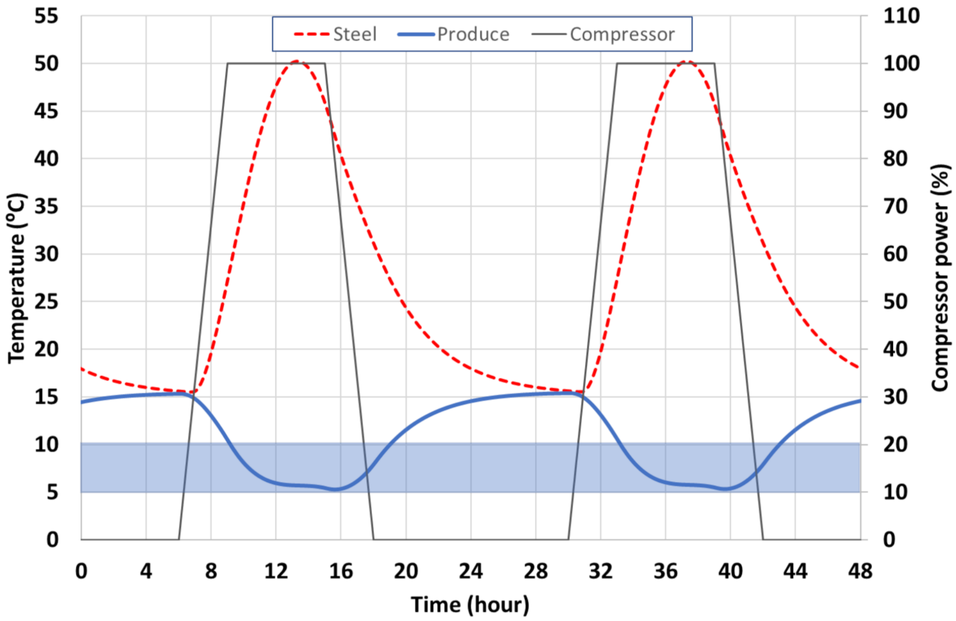

Figure 21. Produce temperature over a period of 48 h.

Figure 22 shows that the produce temperature can be maintained below 10 °C by running the compressor for an additional 7 h at night from 18:00 till 01:00 at a 33% power level. After shutting down the compressor at 01:00, the produce temperature rises slowly to just below 10 °C before the day cycle starts. The compressor switching is controlled by a thermostat that is set to switch the compressor on when the temperature exceeds 7 °C and switch the compressor off when the temperature is below 5 °C. During the first part of the day cycle, the compressor is repeatedly switched on and off by the thermostat, since the container steel wall has not warmed up to the point where the compressor must run continuously to keep the produce temperature within the 5 °C to 10 °C band.

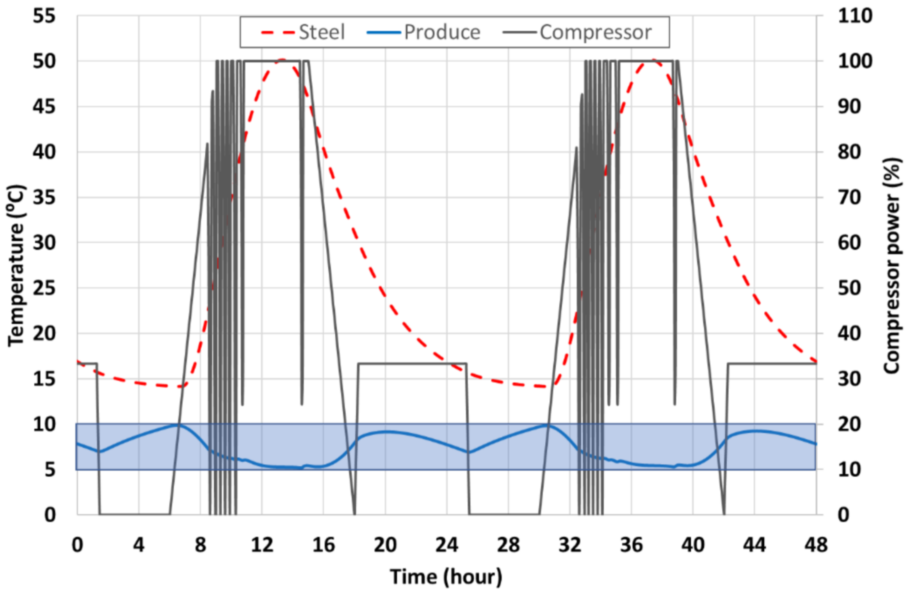

Figure 22. Produce temperature when running the compressor for an additional 7 h at night at a 33% power level.

The compressor must be kept running at night for as short a time as possible at the lowest power level possible to reduce the amount of electrical energy that must be collected and stored during the daytime. The battery storage of electrical power is not only expensive, but also requires the regular maintenance of the battery bank, which is undesirable. The consequence of this solution is that the cold storage is operated in the upper region of the allowed temperature band during the night and at the lower region during the daytime.

Reducing the size of the battery bank is a key design consideration in the design of PV-powered cold storage solutions. One of the design parameters that can be controlled reasonably easily and relatively inexpensively is the insulation between the steel container wall and the inside air. The largest rise in produce temperature occurs when there is no longer solar power available to drive the compressor at the point when the container steel wall is still relatively warm. To reduce the amount of heat transfer from the warm steel container wall to the air inside the cold storage unit, the thermal insulating properties of the insulation material can be increased. The effect of increasing the thermal resistance of the insulation material by 66% results in the heat transfer response shown in Figure 23.

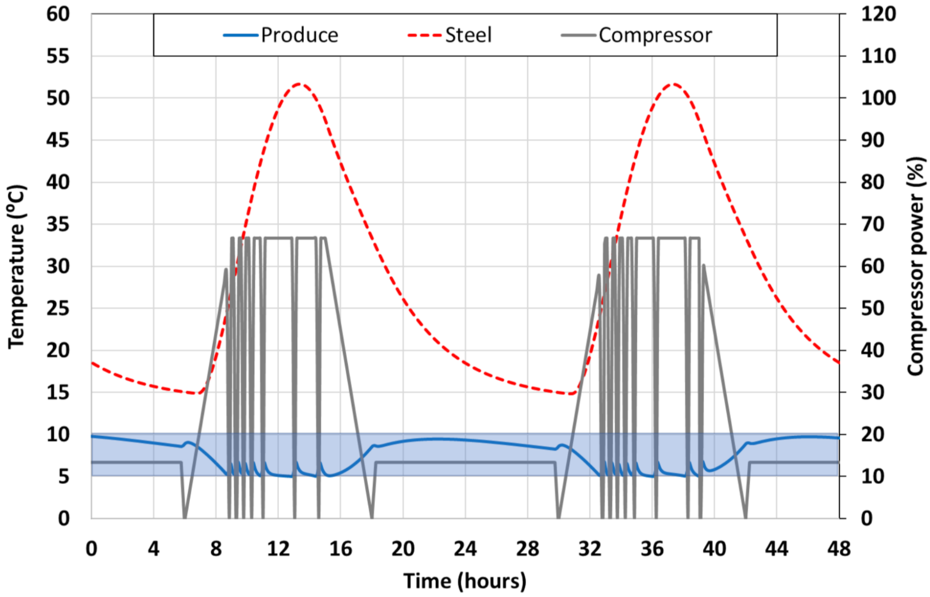

Figure 23. Produce temperature with a 66% increase in the insulation properties of the insulation layer.

By increasing the thermal resistance of the insulation layer by 66%, the daytime operating power level of the compressor can be reduced by 33% to 66%, and running at night can be achieved at a 14% power level for 12 h from 18:00 till 06:00. An important aspect to notice is that the amount of power not required in the daytime running of the compressor as result of the better insulation would be sufficient when collected and stored in the battery bank to run the compressor for the nighttime operation.

4. Discussion

From the results presented in the previous sections, strong consideration should be given to mounting the PV array at a tilt angle that would significantly increase the available electrical energy in winter conditions. The mounting of the PV array comes at the cost of construction complexity compared to the flat mounting of the PV array. Mounting the PV panels at a tilt angle on the roof of the shipping container would also cause shading effects if the tilted panels were not spaced far apart, which in turn would reduce the number of solar panels that can be fitted on the roof of the shipping container. Therefore, another design consideration would be to mount the solar panels on a terrestrial structure, not on the roof top of the container, to tilt the panels to generate optimal efficiency. Additional measures must then be taken regarding the security of the solar panels, as the roof top mounting has some security benefits. The amount of energy required to be stored during daytime to allow the compressor to run at a reduced load at nighttime can be determined by looking at Figure 23. When the cold storage is highly insulated, the daytime load power level can be reduced by 33%, with a nighttime compressor load of about 14% of the daytime load, as shown in Figure 23. By taking these design concepts into consideration, the feasibility and effectiveness of rural PV-powered cold storage projects can be increased, as demonstrated by the results presented.

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