Article
Journal Electrical Engineering
June 2022, Vol.6 No.16 33-41

Evaluation of a refrigerated container using photovoltaic solar energy for its implementation in the Mayan train

Evaluación de un contenedor refrigerado mediante energía solar fotovoltaica para su implementación en el tren Maya

VALLE-HERNANDEZ, Julio†*, CANSECO-SANDOVAL, Karen, APARICIO-BURGOS José Esteban and TORRES-MENDOZA, Galilea

Universidad Autónoma del Estado de Hidalgo, Escuela Superior de Apan.

ID 1st Author: *Julio, Valle-Hernández* / **ORC ID:** 0000-0001-8957-0066, **Research ID Thomson:** O-7339-2018, **CVU CONACYT ID:** 210743

ID 1st Co-author: *Karen, Canseco-Sandoval* / **ORC ID:** 0000-0002-6353-1824, **Research ID Thomson:** AGB-0910-2022

ID 2nd Co-author: *José Esteban, Aparicio-Burgos* / **ORC ID:** 0000-0002-7611-7825, **Research ID Thomson:** C-5019-2017, **CVU CONACYT ID:** 224034

ID 3rd Co-author: *Galilea, Torres-Mendoza* / **ORC ID:** 0000-0003-4542-5144

DOI: 10.35429/JEE.2022.16.6.33.41 Received January 25, 2022; Accepted June 30, 2022

Abstract

In this work, the energy evaluation of a refrigerated container is carried out for the transport of perishable products produced in the Southeast of Mexico, through the Mayan Train, for this design meat, products were considered. The design of the container is carried out through the selection of materials for its construction, the calculation of thermal loads, which are obtained from the climatic conditions of the place, and the properties of the meat that will be transported. Therefore, the refrigeration system used for this design is a simple vapor compression system, using R152a as refrigerant. For the sizing of the autonomous photovoltaic system, the amount of energy supplied is determined from the area available in the container, and the analysis of irradiation, over the last 10 years, in the states proposed by the Mayan Train route; Quintana Roo, Yucatan, Campeche, Chiapas and Tabasco. As a result, the power of the compressor, the COP coefficient of performance was obtained and a comparison is made with the energy required by the refrigeration cycle, along the proposed route.

Meat, Solar energy, Photovoltaic system, Refrigerated container, Mayan Train, Energy performance

Resumen

En este trabajo se realiza la evaluación energética de un contenedor frigorífico para el transporte de productos perecederos producidos en el Sureste de México, por medio del Tren Maya, para este diseño se consideraron cárnicos. El diseño del contenedor se realiza mediante la selección de materiales para su construcción, el cálculo de cargas térmicas, que se obtienen a partir de las condiciones climáticas del lugar, y las propiedades de los cárnicos que se transportaran. Por lo tanto, el sistema de refrigeración ocupado para este diseño es un sistema de compresión a vapor simple, que utiliza R152a como refrigerante. Para el dimensionamiento del sistema fotovoltaico autónomo se determina la cantidad de energía suministrada a partir del área disponible en el contenedor, y el análisis de la irradiación, a lo largo de los últimos 10 años, en los estados propuestos por la ruta del Tren Maya; Quintana Roo, Yucatán, Campeche, Chiapas y Tabasco. Como resultado se obtiene la potencia del compresor, el coeficiente de desempeño COP y se realiza una comparación con la energía requerida por el ciclo de refrigeración, a lo largo de la ruta propuesta.

Cárnicos, Energía solar, Sistema fotovoltaico, Contenedor refrigerado, Tren Maya, Eficiencia energética

Citation: VALLE-HERNANDEZ, Julio, CANSECO-SANDOVAL, Karen, APARICIO-BURGOS José Esteban and TORRES-MENDOZA, Galilea. Evaluation of a refrigerated container using photovoltaic solar energy for its implementation in the Mayan train. Journal Electrical Engineering. 2022. 6-16:33-41.

* Correspondence to Author (E-mail: julio_valle@uaeh.edu.mx)
† Researcher contributing as first author.

Article
Journal Electrical Engineering
June 2022, Vol.6 No.16 33-41

Introduction

The Mayan Train is a project that aims to boost the growth of the economy in the southeast of Mexico, as it will allow the transport of a greater quantity of products from the region, but it is important that this transport is profitable over the years.

The proposed route to be covered by the train includes the states of Tabasco, Chiapas, Quintana Roo, Campeche and Yucatan, 70% of the transport will be cargo. Part of this cargo will be perishable foodstuffs.

Perishable foods are those that deteriorate due to the presence of factors such as pressure, temperature and humidity. Therefore, it is important to transport them in refrigerated containers, where the main objective is to ensure the quality and safety of the product.

Although vapour compression refrigeration systems have good efficiencies, they require a large amount of energy for their operation, when the thermal load of refrigeration is high, which generates a high cost. An alternative to reduce these costs could be the use of solar energy, by means of photovoltaic systems, which could partially or totally satisfy the electrical energy required by the compressor in the refrigeration system.

The aim of this work is to estimate the amount of energy that could be generated by a photovoltaic system installed on a refrigerated container to supply the power required by the compressor, and to analyse whether it is possible to satisfy the demand for electrical energy required by the refrigeration system along the route of the Tren Maya.

The energy evaluation of the system is based on sizing the container and selecting the construction materials, calculating the thermal loads and obtaining the power required by the compressor, as well as the performance coefficient of the refrigeration system. Similarly, the sizing of the photovoltaic system is obtained, based on the available space on the roof of the railway container, obtaining the electrical energy generated along the route.

Finally, the electrical energy generated is compared with the electrical energy required, determining what fraction of the energy required by the system is satisfied.

Methodology

To establish the design of the refrigerated container, factors such as the product to be transported, four types of meat, the ambient temperature of the five states, as well as the speed at which the Mayan train travels were considered.

The design of the refrigerated container takes into account the temperature and humidity of the four products to be transported, in separate containers, using a compression refrigeration system. The sizing of the container was based on the quantity of product to be stored and in accordance with Mexican and international standards for rail transport of perishable foodstuffs.

To calculate the heat extracted from the refrigeration system in the container, the different thermal loads were calculated; by product, by solar radiation, by lighting and by infiltration, proposing efficient insulation for the system.

From the thermal loads, the work of the compressor is obtained, considering its electrical efficiency, and this will be the energy that the photovoltaic system needs to supply.

In the sizing of the photovoltaic system, parameters such as: type of panel, panel efficiency, power and the solar resource of the route proposed by the Mayan train were considered.

Finally, the compressor power is obtained and the amount of energy that can be supplied to the refrigeration cycle is determined, as well as the energy required by the compressor. This is done for each of the containers that will transport the meat products. The calculations of the thermal loads, the required electrical energy of the refrigeration system and the energy supplied by the photovoltaic panels were obtained in Microsoft Excel spreadsheets.

ISSN-2523-2517

Description of the methodology

Thermodynamic properties of the products to be preserved

In the Southeast of Mexico, different types of perishable products are produced, mainly meat products (Ministry of Agriculture and Rural Development), which require refrigeration to conserve their organoleptic characteristics during transport, which is why it is necessary to design a refrigerated train container. The design of this container must consider the thermodynamic properties of the products to be transported. Table 1 describes the thermodynamic properties of the four types of meat that will be transported separately in the different containers (Codex Alimentarius 2005).

Meat	Temperature (°C)	Relative humidity (%)	C.P (KJ/KgK)
Poultry	0	85	3.01
Pork	-1.1	85	2.72
Beef	-0.5	95	3.01
Fish	-0.50	80	3.42

Table 1 Thermodynamic properties of the different types of meat
Source: (Cold engineering theory and practice 2005).

Selection of container structure

Based on the standard for rail containers (ISO 668, 2013) the container dimensions shown in table 2 were selected.

	Door (m)	Size (m)
Length	2.28	13.71
Width	------	2.556
High	2.195	2.896

Table 2 Container dimensions
Source: (ISO 668)

Choice of materials used

In accordance with the heavy use of rail transport, suitable materials were selected to withstand both the speed at which the train travels (160 km/h) and the quantity of product to be stored.

Table 3 shows the properties of the materials proposed for the construction of the container.

Material	Thickness (m)	Conductivity [W/mK]
Aluminium.	0.003	152
Polyurethane foam.	0.0762	0.28
Wood.	0.0508	0.12

Table 3 Properties of the construction materials
Source: Own elaboration

Calculation of thermal loads

The thermal load is the amount of heat that must be extracted from the refrigerated container to cool and maintain an optimum temperature that guarantees the quality of the product (Sánchez, 2009).

The thermal loads taken into account for the design are as follows:

- Thermal load through the walls.

The thermal load through the walls is the heat transfer that occurs through the different walls, due to the difference in temperature between the inside and outside of the chamber. The temperature inside the container was considered to be -5 °C, and the outside temperature equal to the average ambient temperature along the route. Equation (1) gives the thermal load through the walls, and equation (2) the overall heat transfer coefficient.

$$Q_{a.m} = U * A * \Delta T \quad (1)$$

$$U = \frac{1}{\frac{1}{h_1}+\frac{e}{k}\dots\dots\dots+\frac{1}{h_2}} \quad (2)$$

Where:

$Q_{a.m.}$: Thermal load through the walls.

U: Overall heat transfer coefficient.

A: Area of the enclosure.

ΔT: Difference between the outside and inside air temperatures of the container.

h_1: Convective coefficient inside the chamber.

h_2: Convective coefficient of the outside of the chamber.

e: Thickness of the materials

k: Thermal conductivity of the materials

Thermal load due to lighting

The thermal load produced by the lighting inside the container, considering 23W lamps, is calculated using the following equation:

$$Q_{lamp} = \#_{lamparas} * P \quad (3)$$

Where:

Ql_{amp}: Thermal load per lighting

$\#_{lamps}$: Number of lamps

P: Power of each lamp

Heat load per infiltration

The thermal load due to infiltration is generated by the technical air renovations Q_1, and the equivalent air renovations Q_2, this is calculated by the following equation:

$$Q_{inf} = Q_1 + Q_2 \quad (4)$$

The following mathematical expression is used to calculate Q_1:

$$Q_1 = m * \Delta h \quad (5)$$

$$m = V * \rho * n \quad (6)$$

Where:

m: Mass of air

Δh: Enthalpy difference of the air, inside and outside the chamber

V: Volume of infiltrated air

ρ: air density

n: number of technical air changes

The infiltrated heat Q_2 due to the equivalent air renewals is calculated from the air mass and its enthalpy difference, inside and outside, as shown in the following equation:

$$Q_2 = \ m * \Delta h \quad (7)$$

The enthalpies of indoor and outdoor air are obtained by means of the psychrometric chart, and for the calculation of the air mass the door opening time is considered (θ).

$$m = V * \rho * \theta \quad (8)$$

The volume of infiltrated air is calculated by the following mathematical expression:

$$V = \frac{a*H}{4}\sqrt{0.072} * H * \Delta T \quad (9)$$

Where:

m: Mass of air
Δh: Enthalpy difference of the air, inside and outside the chamber
V: Volume of air
ρ: Mean air density
θ: Door opening time
a: Door width
H: Door height
ΔT: Outside air temperature difference

Heat load generated by the product

This is the heat given up by the product, at a temperature higher than the refrigeration temperature, until it reaches its storage temperature.

To guarantee the safety of the meat products, they must be transported in different containers, so the thermal loads are calculated separately for each product, considering the temperature at which the meat enters the container (pre-cooling temperature), the temperature inside the container and the time it will take for the meat products to reach their optimum storage temperature, which is calculated using the following mathematical expression:

$$Q_{sencible} = \frac{m*Cp*\Delta T}{t} \quad (10)$$

Where:

m: Mass quantity of the product

Cp: Specific heat of the product

ΔT: Temperature difference, initial and final of the product.

Total thermal load

Since no more than one type of meat can be transported in the same container, the total thermal load is obtained for each of the four cases presented:

Case 1 pork.

Case 2 beef.

Case 3 poultry meat.

Case 4 fish meat.

For each of the cases, the sum of all the thermal loads mentioned above is added up, giving the total thermal load as a result.

Obtaining the power required for the refrigeration cycle

The refrigeration cycle selected for this design is the simple compression cycle (Cengel and & Boles, M, 2001), the proposed refrigerant is R-152a, the thermodynamic properties of each state of the cycle were obtained from the National Institute of Standards and Technology (NST, 2022).

Table 4 shows the thermodynamic states of the refrigeration cycle.

State	T(°C)	P(kPa)	h(KJ/Kg)	S (KJ/Kg K)	Phase
1	-8	196.14	501.56	0.5107	Saturated steam
2	49	909.26	543.54	0.5107	Superheated vapour
3	40	909.26	271.35		Saturated liquid
4	-8	196.14	271.35		Mixture

Table 4 Thermodynamic states of the refrigeration cycle
Source: own elaboration

The mass flow is calculated by the following equation:

$$\dot{m} = \frac{Q_L}{(h_1 - h_4)} \quad (11)$$

Where:

m: Mass flow rate

Q_L: Total heat load

(h_1-h_4): Enthalpy difference

The compressor power is calculated as:

$$W_{comp} = \dot{m}(h_2 - h_1) \quad (12)$$

Where:

W_{comp}: Compressor work

m: Mass flow rate

(h_2-h_1): Enthalpy difference

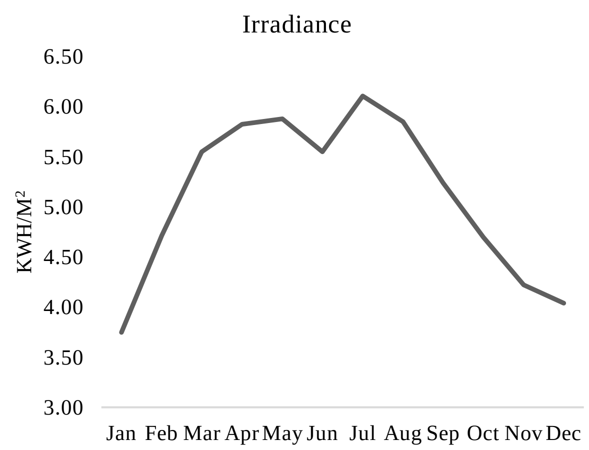
$$COP = \frac{Q_{total}}{W_{compresor}} \quad (13)$$

Analysis of the solar irradiation of the different places along the route of the Mayan Train

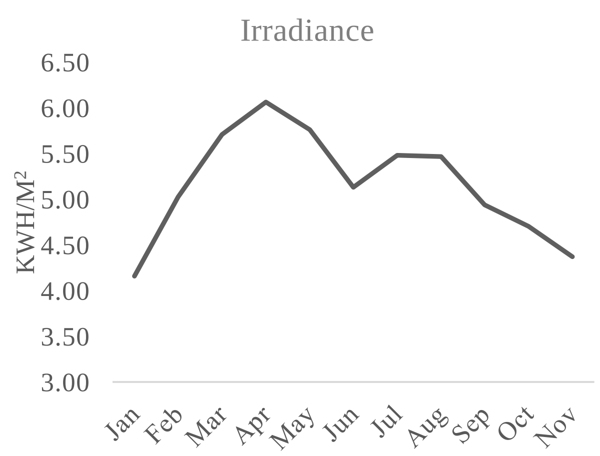
An analysis is made of the irradiation during 10 years (2010-2020) of the states through which the Mayan Train will pass, this data is obtained from the Power | Data Access Viewer page (NASA, 2022).

The graphs below show the average irradiation for the states of Tabasco, Chiapas, Yucatán, Campeche and Quintana Roo in KWh/m^2.

The calculation of the COP performance coefficient is equal to the heat extracted from the system, total heat loads, divided by the compressor power.

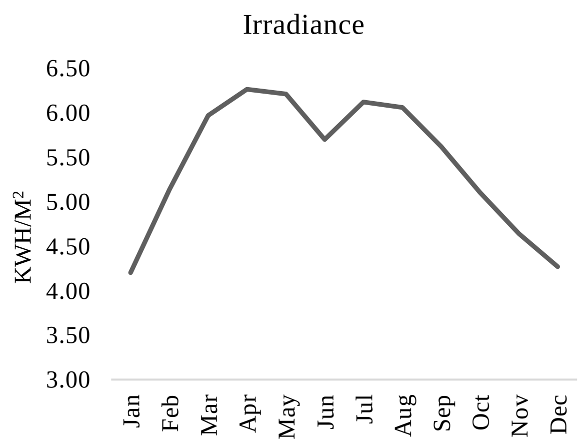


Graphic 1 Irradiance data for Tabasco
Source: NASA

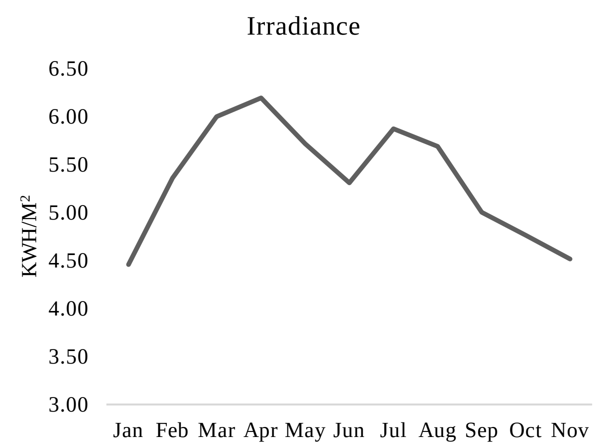


Graphic 2 Irradiance data for Quintana Roo
Source: NASA

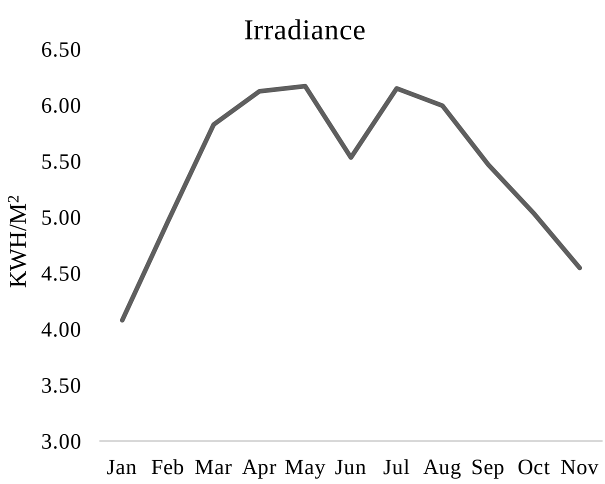
ISSN-2523-2517



Graphic 3 Irradiance data Campeche
Source: NASA



Graphic 4 Irradiance data Chiapas
Source: NASA



Graphic 5 Irradiance data for Yucatan
Source: NASA

Dimensioning of the Photovoltaic System

Figure 1 shows a diagram of the components of the photovoltaic system used for this design, which will be installed on the roof of the container.

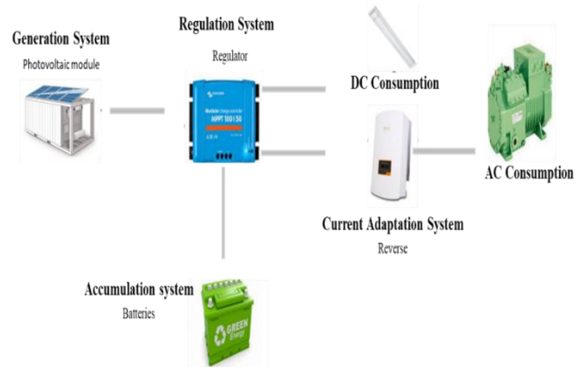


Figure 1 Solar photovoltaic system
Source: Own elaboration

Energy supplied by the panels

The daily energy supplied by each photovoltaic panel depends on the electrical power of the panel, and the average solar resource on the train route.

Energy supplied by the panels

The daily energy supplied by each photovoltaic panel depends on the electrical power of the panel, and the average solar resource on the train route.

$$E_s = P * R.S \tag{14}$$

Where:

E_s: Energy supplied.

P: Panel power.

R.S: Solar resource.

To obtain the solar resource it is necessary to know the average solar irradiation of the states that comprise the route, data obtained from the NASA website "The Power Project".

$$R.S = \frac{Irradiation\ Wh/m^2}{1000\ W/m^2} \tag{15}$$

Selection of the proposed solar panel for the design

The length and width of the container was considered in order to propose the solar panel to be used in the system, with the aim of covering most of the roof of the container.

ISSN-2523-2517

The characteristics of the solar photovoltaic panel selected are detailed in table 5.

Features	
Maximum power	540 W
Module efficiency	20.90%
Dimensions	2279 x 1134 x35
Weight	28.6 kg
Maximum system voltage	1250 V

Table 5 Solar panel characteristics

Electrical energy required

For the electrical consumption, the efficiency of the compressor is considered, which is between 80 and 90%; for this design, an efficiency of 80% was considered.

Considering that the compressor works between 60% and 70% of the operating time of the chamber, 66% of the working time is proposed for this design, which is equivalent to 6 hours and 30 minutes of a route of 9 hours and 52 minutes. Therefore, the electrical energy required by the compressor is obtained from the following equation:

$$Electricity = \frac{P_c * H_T}{\eta_{Electricity}} \quad (16)$$

Where:

$\eta_{electric}$: Compressor efficiency.

P_c: Compressor power.

H_T: Compressor working hours.

Results

Total thermal loads

The total thermal loads for each product are shown in table 6. It can be seen that the highest thermal load is in the month of May, as this month has the most extreme climatic conditions.

Total thermal loads [Watts]				
Months	Case 1	Case 2	Case 3	Case 4
Jan	31377.50	45336.67	32533.087	40993.74
Feb	31661.29	45620.47	32816.88	41277.53
Mar	32552.88	46512.06	33708.47	42169.13
Apr	31321.08	45280.26	32476.67	40937.32
May	32353.40	46312.57	33508.99	41969.64
Jun	31610.63	45569.81	32766.23	41226.88
Jul	32132.46	46091.64	33288.05	41748.70
Aug	30406.24	44365.43	31561.84	40022.49
Sept	31548.33	45507.50	32703.92	41164.57
Oct	30176.98	44136.16	31332.57	39793.22
Nov	30962.35	44921.53	32117.94	40578.60
Dec	32014.07	45973.25	33169.66	41630.32

Table 6 Total thermal loads per month and per product
Source: Own elaboration

Analysis of compressor power requirements

The power required by the compressor, the coefficient of performance (COP) and the maximum thermal load of each of the containers are shown in table 8. It can be seen that the greatest compressor power is for the beef container, as it is the container with the greatest weight.

Parameters	Poultry	Pig	Bovine	Fish
Mass flow (Kg/s)	0.15	0.14	0.20	0.18
Compressor power [KW]	6.11	5.90	8.45	7.65
QH [KW]	39.62	38.25	54.76	49.62
QL [KW]	33.51	32.35	46.31	41.97
COP	5.48	5.48	5.48	5.49

Table 7 Compressor power
Source: Own elaboration

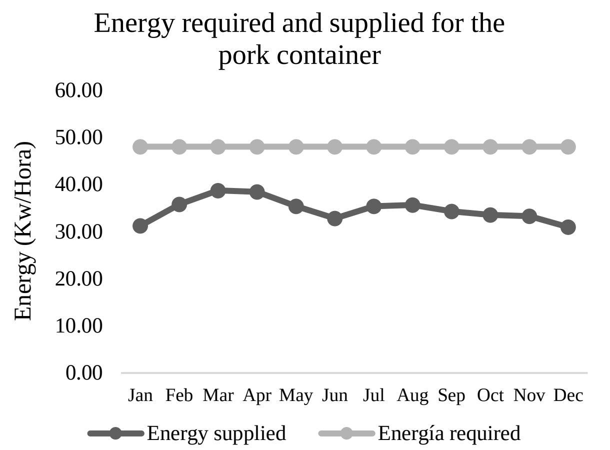
Analysis of the photovoltaic system

Table 8 shows the electrical energy required by the refrigeration chamber, the energy supplied by the photovoltaic system and the hours of solar energy supply. Twelve photovoltaic panels were considered, with the characteristics described above, and an average solar resource of 4.76 hours.

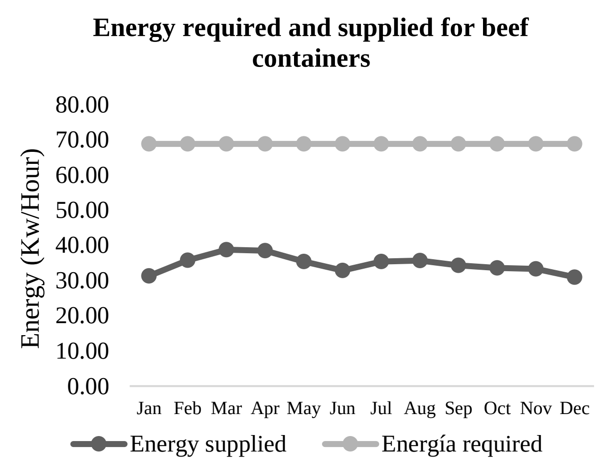
Product in container	Electrical energy required (KWh)	Electrical energy supplied (KWh)	Hours of supply
Pork Meat	48.04	30.56	5.2
Bovine Meat	68.81	30.56	3.6
Poultry Meat	49.75	30.65	5.0
Fish Meat	62.29	30.56	4.0

Table 8 Electrical energy required and supplied
Source: Own elaboration

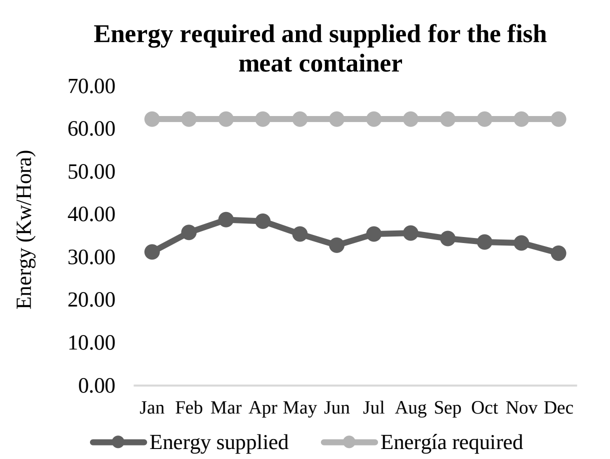
The following graphs show the amount of energy supplied by the twelve panels during the year, for each of the containers, making a comparison with the energy required by the system.



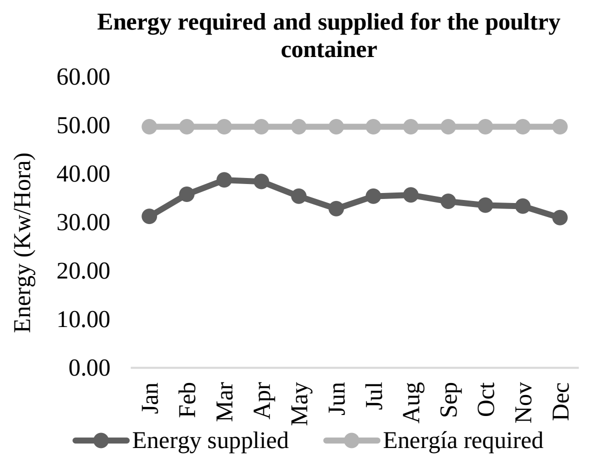
Graphic 6 Energy required and supplied for the pork container
Source: Own elaboration



Graphic 7 Energy required and supplied for beef containers
Source: Own elaboration



Graphic 8 Energy required and supplied for the fish meat container
Source: Own elaboration



Graphic 9 Energy required and supplied for the poultry container
Source: Own elaboration

Conclusions

This work shows a proposal for the design of a refrigerated container for the train Maya, which allows four types of meat to be transported, for which the average climatic conditions of the train route were considered. The results show that the refrigerated container that requires a larger compressor is the 10.92 KW beef container, due to its greater weight; the COP for all cases is the same, as the refrigeration system is equivalent in all cases.

Similarly, it can be seen that the energy supplied by the photovoltaic system to the different containers in none of the cases satisfies the energy demand 100%, however, approximately 50% of the train route can be satisfied. The container that is supplied most of the route is the pork container, as it is the compressor that requires the least power, 5.90 KW, as it is the one with the smallest weight to be refrigerated.

In general, the use of a photovoltaic system as a source of electrical energy for the railway container refrigeration process is feasible and viable, considering both the economic savings in fuel and the reduction of greenhouse gases in the environment.

ISSN-2523-2517

Article Journal Electrical Engineering
June 2022, Vol.6 No.16 33-41

References

I. Pereira, V. D. F., Doria, E. C. B., Carvalho Júnior, B. D. C., Neves Filho, L. D. C., & Silveira Júnior, V. (2010). Evaluation of temperatures in a refrigerated container for chilled and frozen food transport. *Food Science and Technology*, *30*, 158-165. https://doi.org/10.1590/S0101-20612010000100024

II. Filina-Dawidowicz, L., & Filin, S. (2019). Innovative energy-saving technology in refrigerated containers transportation. *Energy efficiency*, *12*(5), 1151-1165. https://doi.org/10.1007/s12053-018-9729-2

III. Vázquez, A. S. (2022). III. 3. Oportunidades de inversión extranjera en el sector energético cubano. *FUTURO ENERGÉTICO EN CUBA*, 196.

IV. Zhang, Y., Mao, Y., Li, K., Luo, X., & Hopkins, D. L. (2019). Effect of carcass chilling on the palatability traits and safety of fresh red meat. *Comprehensive Reviews in Food Science and Food Safety*, *18*(6), 1676-1704. https://doi.org/10.1111/1541-4337.12497

V. Cengel & Boles, M. (2001) *Termodinámica*, 7ma edición En Y. A Cengel, México. Libro impreso

VI. *Power | Data Access Viewer NASA* (2022) https://power.larc.nasa.gov/data-access-viewer/

VII. Covarrubias Cuevas, Pérez Moreno at. al (2019) *Diseño de una cámara frigorífica. México.* https://e-archivo.uc3m.es/bitstream/handle/10016/22946/PFC_david_torres_cicuendez_2014.pdf. (23-08-2022=

VIII. Alonso Albella (2019), *Sistemas fotovoltaicos. Colombia* https://static.eoi.es/savia/documents/componente45335.pdf, Recuperado 19/03/2022

IX. ISO 668 (2013) Series 1 freight conteiners – Clasificación, dimensiones and ratings. https://www.sis.se/api/document/preview/916460/ (23-08-2022)

X. Sánchez T (2009) Ingeniería del frío, teoría y práctica. España. Libro impreso

XI. National Institute of Standards and Tecnology (2022), Libro del Web de Química del NIST, SRD 69. https://doi.org/10.18434/T4D303

XII. Comisión del Codex Alimentarius (2005, marzo). Composición de la carne. Nuevo León, México. https://www.fao.org/3/a0369s/a0369s.pdf.