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Methodology for energy demand reduction of potato cold storage process

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Abstract

In order to maintain the quality of the potatoes over time, it is necessary to store them under certain storage conditions, which minimize losses both of quality and product, preferably without using chemical treatments. Conservation chambers consume a considerable amount of energy. Between 60% and 70% of the electricity consumed is used in refrigeration. Good insulation reduces the need for cooling the potato since its optimum storage temperature for consumption is around 4–7°C and relative humidity is 85%–90%. This research studies potatoes' cold storage process to minimize the cost in the product value chain and to ensure its competitiveness in the market. A model is developed to assess energy consumption and propose measures to reduce energy, environmental, and economic costs. All this to reduce their impact within the value chain of potato consumption.

Practical Applications: In this case study, different energy efficiency measures applied to the cold storage of potatoes have been implemented: replacement or improvement of the performance of refrigeration equipment, insulation and infiltrations in the refrigeration chamber, control of the product entry temperature, thermal conditioning through free-cooling, improvements in lighting equipment, technical management, and supervision of facilities, and thermographic control. The set of actions implemented has allowed to obtain a reduction in energy demand, standardized through the developed reference line, by 16.41% compared to previous years.

KEYWORDS
cold storage, cooling chamber, energy efficiency, energy saving, potato, renewable energy

1 | INTRODUCTION

Potato (*Solanum tuberosum* L. ssp. *tuberosum*) is a dicotyledonous tree belonging to the Solanaceae family. It is a herbaceous plant, vivacious, with an aerial and an underground cauline system in which the tubers are formed. Its importance lies in the fact that it is one of the main consumed foods worldwide, occupying the fourth place after rice, wheat, and corn, with the production of 2016 being 376,829,000.00 tons (FAO, 2018).

Potato tubers are plant storage organs that generally contain 80% water and 20% dry matter. This constitution rich in water implies greater issues associated with the biological processes that take place during storage, and with environmental factors such as light, temperature, humidity, and aeration. Depending on the variety, the tubers have a characteristic color and shape. When the potatoes are in their optimum state of harvesting, it is when the dry matter content is greater and less than that of sugars. In addition, the skin is already fully formed, which minimizes water loss and greater protection against microorganisms, favoring better and longer conservation.

According to Peters (1996), out of the 30% of the total production that can be damaged during harvest, 70% of the damages are caused during the harvest, while the remaining 30% are produced in transport and storage. This is due to the damage of the tubers in the collection, which increases the incidence of diseases and losses throughout storage; thus decreasing the value of the potato due to low quality.

1.1 | Storage conditions

Good potato conservation depends on storage conditions and duration but is also determined by factors such as variety, soil type, and climatology during cultivation (Bajema et al., 1998; Baritelle & Hyde, 2003; Mathew & Hyde, 1997). Good insulation reduces the need for cooling the potato since its optimum storage temperature for consumption is around 4–7°C and relative humidity of 85%–90% (Chourasia & Goswami, 2001; Montaldo, 1984).

Given the aforementioned, the most important processes that can cause losses during storage are:

1. *Respiration*: Provides the energy necessary to maintain the life of the potato as it turns sugars into carbonic gas and water. If the ventilation and temperature of the warehouse are not adequate, this carbonic gas and heat can cause fermentation ending in rotting and suffocation of the tubers. Damages such as bumps and wounds increase respiration, which makes it a very important factor to consider for storage (Bethke, 2014; Copp et al., 2000; Ellis et al., 2019; Kedia et al., 2021).
2. *Water loss*: It implies loss of weight and turgidity, due to evaporation and perspiration. This loss depends on factors such as the temperature of the potatoes, the relative humidity of the air, the degree of tubing, and the presence of sprouts. The conditions for a lower water loss are a relative humidity between 90% and 95% and a temperature of about 3–5°C (Broćić et al., 2016; Magdalena & Dariusz, 2018).
3. *Sprouting*: The sprouts cause a significant loss of weight, taking into account the evaporation of water through its surface. The way to control sprouting is by sprouting inhibitors and low-temperature storage (Blahovec et al., 2013; Lin et al., 2019; Şanlı & Karadoğan, 2019).
4. *Dissemination of diseases*: The causes of rot are especially important. The most relevant is *Erwinia carotovora* subsp. *carotovora* (Bhat et al., 2017; Salem & El-Shafea, 2018) and *Fusarium* (Bártová et al., 2018; Pour et al., 2019; Vatankhah et al., 2019). The permissible ranges in the storage of the potato are 5% in total; of which 0.1% are due to wet rot, 1% due to dry rot, and the remaining 4% due to mechanical damage (Shahgholi et al., 2020) and poorly formed tubers.
5. *Changes in the chemical composition*: Storage at temperatures below 7°C progressively increases the transformation of starch into sugar, a process that reverses when the temperature rises. The aging of the potato involves a similar process but, in this case, is irreversible. Therefore, it should be considered that a general rule for long-term preservation of potatoes is a temperature range between 5 and 6°C (Barichello et al., 1990; Raigond et al., 2018; Rastovski & Van Es, 1981; Sowokinos et al., 1987).

Storage techniques should seek minimum losses of both weight and quality, most of the time. To control these losses mentioned above, it is necessary to control temperature, humidity, and ventilation.

1.2 | Research context

In order to maintain the quality of the potatoes over time, since they are harvested in October and consumed throughout the year, it is necessary to store them under certain storage conditions, which minimize losses both of quality and product, preferably without using chemical treatments. For instance, Yilmaz and Yilmaz analyze the economic costs of a refrigerated storage system against a natural one used to conserve potatoes. They conclude that modern refrigeration plants guarantee a return on investment in a short period (Yilmaz & Yilmaz, 2020). Valencia-Flórez et al. research the effect of different cold storage processes on two different potato varieties. They highlight the need to adjust cold storage conditions depending on the variety, in order to achieve optimal conservation conditions (Valencia-Flórez et al., 2019).

Conservation chambers consume a considerable amount of energy. Between 60% and 70% of the electricity consumed is used in refrigeration (Evans, 2018; Sudhakar et al., 2019). For example, Pardo Martínez and Cotte Poveda analyze the different types of refrigeration systems used in the food industry in Colombia. They highlight the importance of modernizing the systems and increasing their efficiency to reduce consumption and their environmental impact (Pardo Martínez & Cotte Poveda, 2022). Along these lines, Winkler et al. study the possible effect of climate change on potato storage. They conclude that future changes in the refrigeration needs of this type of product will lead to an increase in energy consumption or a reduction in the storage time allowed (Winkler et al., 2018).

The cost of electric power is in a bullish environment, suffering significant price increases that penalize potato conservation costs. Therefore, energy efficiency saves financial resources while also reducing CO_2 emissions into the atmosphere.

Proper management during the operation phase of any installation is essential to ensure the profitability of the economic activity developed. Whether the operation has been designed and installed following criteria of efficiency in its use, or if it has not been so and other factors have prevailed, proper management of the operation and maintenance of the farm can help reduce operating costs.

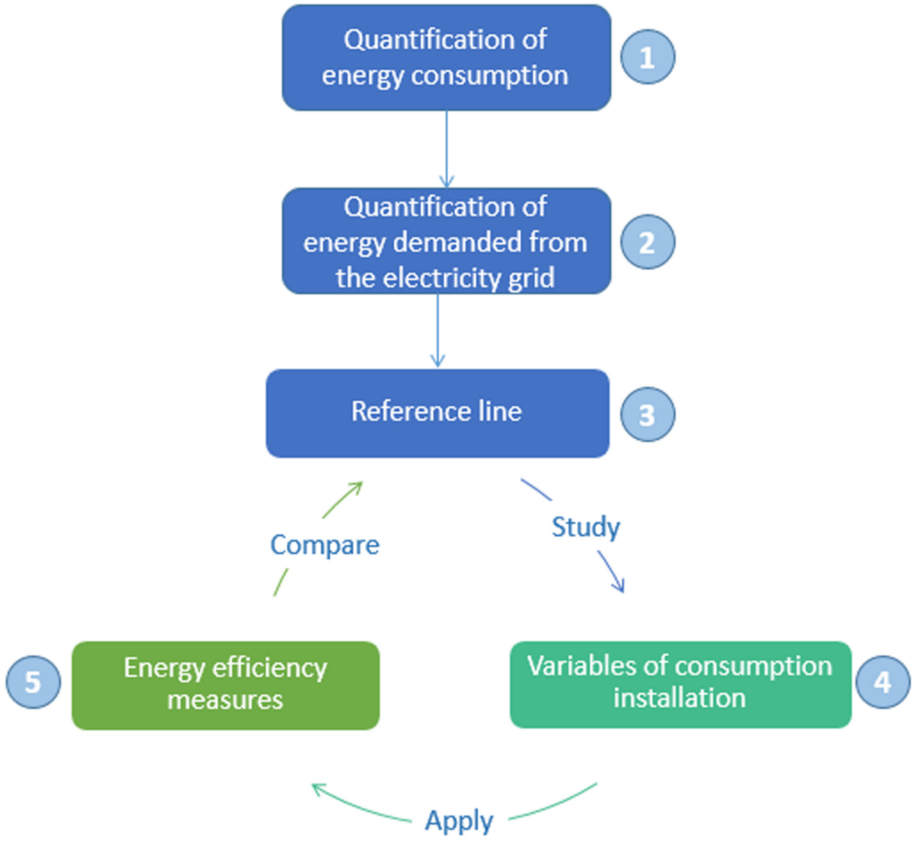

FIGURE 1 Research model

Industrial storage locations are usually facilities with long life periods, in which the replacement of equipment or facilities before the end of it, are usually not usual.

This research studies cold storage to minimize the cost in the product value chain and to ensure its competitiveness in the market. A model is developed to assess energy consumption and propose measures to reduce energy, environmental, and economic costs. All this to reduce their impact within the value chain of potato consumption.

2 | MATERIALS AND METHODS

The research model proposed in this paper has the following step-by-step procedures (Figure 1):

Step 1. Quantification of energy consumption. Any energy analysis process must begin by establishing the criteria for evaluating consumption in a way that is measurable and quantifiable.

Step 2. Energy demanded from the power grid. It is necessary to quantify the actual energy demanded from the network based on the quantification of consumption.

Step 3. Reference line. A mathematical model of the process (baseline) is developed through the information of the reference period to study. The model allows quantifying the reference energy consumption and comparing it with that demanded in the demonstration period of savings.

Step 4. Variables influencing consumption of the facility and energy efficiency measures. From the real information of the process, the strategies for the reduction of energy demand are established, all this by studying the different alternatives with real information of the process studied from a technical and economic point of view. Along with technical feasibility, other factors such as economic viability and sustainability of the process and the organization are analyzed. It is important not to lose sight that we are working on an industrial process optimization in which economic profitability is essential to determine the viability of any action.

Step 5. Energy efficiency measures. Finally, once all the alternatives in energy efficiency have been considered, the study of facilities based on renewable energies is proposed.

2.1 | Energy model to determine the energy demanded by a facility

The energy required for its conservation depends on different factors ranging from the product itself (including its characteristics and conditions) to the conditions of the refrigeration chamber, equipment used, and thermal conditions of the location.

The energy demand is calculated by the following expression:

$$P_{\text{ref}} = P_{\text{chamber}} + P_{\text{potatoes}} + P_{\text{equip}} + P_{\text{others}}, \tag{1}$$

where P_{chamber} represents the energy used to compensate for energy loss in the cooling chamber, both by conduction and by internal ventilation. P_{potatoes} represents the energy associated with the product to

TABLE 1 Calculation of the amount of energy used to compensate energy losses in the cooling chamber

$P_{\text{chamber}} = P_{\text{Transmission}} + P_{\text{air renewal}} + P_{\text{inf}}$ (2)	
$P_{\text{Transmission}} = \sum_{i=1}^{n} U_i \cdot A_i \cdot (T_{\text{inside}} - T_{\text{outside}})$ (3)	where: T_{inside}: Temperature inside the chamber T_{outside}: Temperature outside the chamber A_i: Enclosure surface of the conservation chamber U_i: Thermal conductivity coefficient of the enclosure
$P_{\text{air renewal}} = V \cdot \rho_{\text{air}} \cdot N \cdot \Delta h$ (4)	where: V: free volume of the cooling chamber ρ_{air}: air density N: number of renewals Δh: enthalpies of indoor and outdoor air Note: The free volume varies depending on the space occupied in the cooling chamber
$P_{inf} = 1.33 \cdot A_d \cdot \sqrt{D_h}$ (5)	where: A_d: infiltration surface ρ_0: outdoor air density ρ_i: indoor air density H_0: enthalpy of outside air H_i: enthalpy of indoor air

be refrigerated. P_{equip} represents the energy used to compensate for the energy associated with machinery, equipment (lighting, ventilation equipment, etc.), and where appropriate, people or equipment installed inside the ventilation chamber. P_{others} represents any other energy demand not contemplated in the previous sections. The calculations of the model elements are shown below:

Energy used to compensate for energy losses in the cooling chamber (P_{chamber}). This energy consumption includes the energy transmission through the walls of the chamber walls ($P_{\text{Transmission}}$), which occurs by the conduction that is determined by the temperatures on either side of the storage chamber. The exposed surface and the ability to conduct thermal energy from it. Added to the characteristics of the product stored, the generation of CO_2 is involved, which must be removed to ensure the presence of oxygen in the cooling chamber in suitable amounts. The renewal of the air ($P_{\text{air renewal}}$), either in a controlled way or through infiltrations in the chamber (P_{inf}), the opening of doors, and so on entails energy needs that must be considered (Table 1).

The thermal load generated by the potatoes (P_{potatoes}) is formed by the energy necessary for the refrigeration of the product ($P_{\text{ref pot}}$), the energy necessary for the refrigeration of the containers in which the product will be located inside the chamber ($P_{\text{ref cont}}$), and the thermal load generated by aerobic respiration ($P_{\text{aerobic resp}}$) by which the energy stored in the potato, in the form of sugars, is used in the maintenance of the potato. Glucose in reaction with circulating oxygen is converted to water, carbon dioxide, and energy. The energy generated can be related to the generation of carbon dioxide. According to Hardenburg et al. (1990), 2.55 calories (10,676 J) of energy are produced by the aerobic respiration of potatoes for every milligram of CO_2. Other authors relate it directly to the number of existing products, providing values of generated power between 1.7 and 47.0 mW/kg (Sastry et al., 1977). A third method proposed in the literature for measuring the respiration rate of potatoes is based on measuring the loss of the substrate represented by the loss of dry weight (Gross et al., 2016) (See Table 2).

The storage containers are standardized and have the following characteristics (See Table 3):

- P_{lighting} represents the energy used to compensate for the energy associated with the lighting inside the storage chamber that is used in the storage processes, mainly during the product withdrawal phases or specific inspection and maintenance tasks. The thermal energy associated with it varies strongly depending on the lighting technology used. It must then be included:

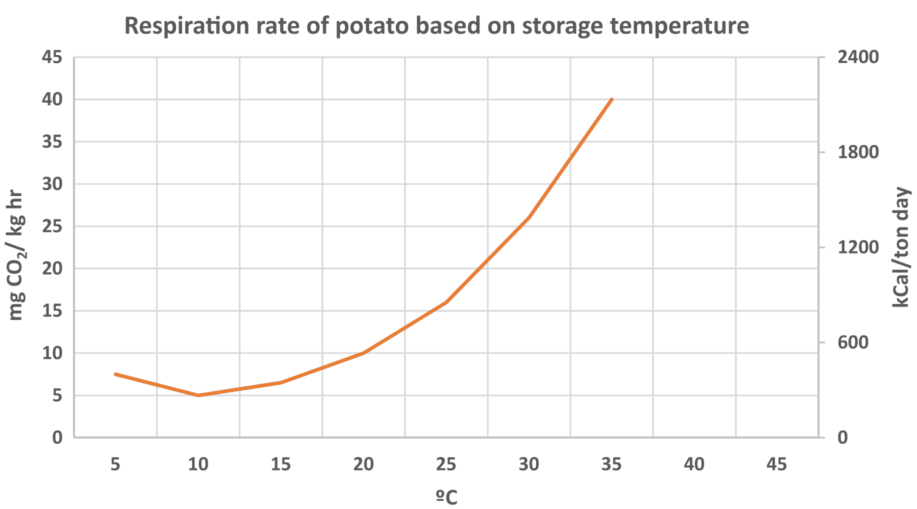

FIGURE 2 Potato respiration rate based on storage temperature. Source: Prepared by the author based on data from the Nederland's potato consultative foundation (NIVAP, 2019)

TABLE 2 Calculation of thermal load generated by potatoes

$P_{\text{potatoes}} = P_{\text{ref pot}} + P_{\text{ref cont}} + P_{\text{aerobic resp}}$ (6)	
$P_{\text{ref pot}} = m_{\text{pot}} \cdot c_{\text{p(pot)}} \cdot \frac{dT}{dt}$ (7)	where: m_{pot}: Mass of product to be refrigerated $c_{\text{p(pot)}}$: Specific heat of potatoes dT/dt: Temperature variation between the inlet and outlet of the refrigeration process product
$P_{\text{ref cont}} = m_{\text{cont}} \cdot c_{\text{p(cont)}} \cdot \frac{dT}{dt}$ (8)	where: $m_{\text{cont:}}$ container mass to be refrigerated $c_{\text{p(cont)}}$: specific heat of the container material dT/dt: temperature variation between the inlet and outlet of the refrigeration process product
CO_2 production	
$C_6H_{12}O_6 + 6O_2 + 6H_2O \rightarrow 6CO_2 + 12H_2O + 673\frac{\text{kcal}}{\text{mol}}$ (9)	See Figure 2, relation CO_2 production/storage temperature/$P_{\text{aerobic resp}}$

TABLE 3 Characteristic values of wooden containers used in the storage of potatoes

Wooden storage bins	Units	Value
Dimensions	m	Length = 1.6, width = 1.2, height = 1.05
Weight	kg	90
Storage capacity of the container	kg	1000
Specific heat of the container	kJ/kg °C	0.5

$$P_{\text{lighting}} = i \cdot S. \tag{10}$$

where i represents the power released by the lighting system per unit area and S represents the illuminated surface of the conservation chamber.

- P_{others} represents other parameters not contemplated in the previous points that have a greater or lesser influence on energy consumption. The existence of other energy sources that need to be compensated to maintain the conditions inside the conservation chamber is possible. Examples of this can be in the storage of the product (elevators, pallet trucks, etc.) by means of electrical or thermal machinery, or energy losses derived from having the access doors open, among others. In each case, the energy involved in the process will be studied and considered in the model.
- P_{man} is the thermal load generated by people inside the chamber. The energy released by a person varies depending on the temperature of the chamber and the activity developed. In this case, for a temperature between 0 and 5°C and an average activity is considered a power released per person (q) of 250 W.

$$P_{(\text{man.})=} q \cdot n \tag{11}$$

where q represents the power released per person and n represents the number of people inside the conservation chamber.

2.2 | Energy demanded from the electricity grid by the conservation chamber

The electrical power absorbed for the indicated thermal generation is obtained considering the performance of the generating equipment, as reflected in the following expression:

$$P_{\text{ref elect.}} = \frac{P_{\text{ref}}}{\text{EER}}, \tag{12}$$

where EER (energy efficiency ratio) is the ratio between the cooling capacity and the energy consumption used to obtain it. The higher the EER, the better the performance of the machine will be.

Conservation at controlled temperatures is conducted at a constant temperature according to the strategy set by the company, usually marked by the type of product, characteristics, destination, etc.

In the case of conducting the cooling and thermal process to maintain the temperature conditions with different equipment, the power supplied and the thermal performance of each equipment must be considered separately.

2.3 | Reference line: Measurement and verification of energy savings

The energy management of any facility is intended to ensure that the consumptions obtained conform to those planned according to the characteristics of the facility. Thus, it is essential to have real measures and information on everything that happens in the facility.

Considering the aforementioned, the capacity to determine the results and savings achieved with energy-saving measures is essential to demonstrate the savings achieved and enter into a process of improvement, or at least maintenance, of the energy yields obtained. The measurement and verification plans and the demonstration reports of the savings achieved allow us to unequivocally demonstrate and quantify the results achieved.

With the measurement and verification plan, a mathematical model of the process (baseline) is developed with information from

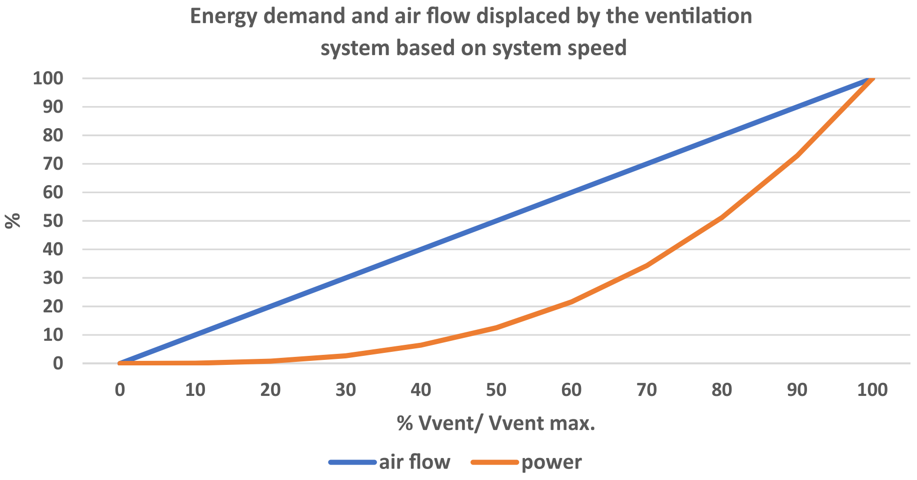

FIGURE 3 Energy demand and airflow displaced by the ventilation system depending on system speed

the reference period to study and quantify the energy consumption baseline and compare it to the demanded one in the demonstrative period of savings.

For the general case, considering the process and the thermal losses in the conductions, the reference equation is established under the following expression:

$$Q_{ref} = A_1 \cdot \frac{dT_i}{dt} + B_1 \cdot T_{inside} + C_1 \cdot T_{outside} + D_1 \cdot T_{chamber} + E_1 \cdot T_e + F_1, \quad (13)$$

where A_1, B_1, C_1, D_1, E_1, and F_1 are values to be adjusted based on the parameters and constants indicated above (product quantity, specific heat, surface and construction characteristics of the chamber, environmental conditions, existing conduits, their layout, etc.) and the characteristics of the process and the product stored.

To achieve an energy improvement of the conservation process or within a performance monitoring program, the savings obtained are calculated with the following expression:

$$\text{Savings} = P_{ref\ elec} - P_{demost} \pm adjustment, \quad (14)$$

where $P_{ref\ elec}$ represents the reference line of the energy consumed during the processes taken as a reference. P_{demost} represents the reference line of the energy consumed during the demonstration phase of the savings achieved and adjustment represents possible correction factors under circumstances or changes in the process that need to be considered.

2.4 | Variables that influence the consumption of the facility

Not only is the temperature of the warehouse important for storing potatoes, but the harvest conditions are determining factors for good storage. For example, if the potatoes at the time of harvest are wet, more energy for drying and subsequent storage will be needed.

Conservation by mechanical cooling generally uses a direct gas expansion system (DX) with a cooling fluid that surrounds a pipe circuit between the inside and outside of the warehouse. The fan draws air through the cold coils to provide cooling.

The efficiency of the cooling system is not fixed but varies depending on its type and design, the cooling temperature and room temperature, the amount of refrigerant, and the control and operational parameters.

During storage, it is not only necessary to ventilate to dry the wet potatoes that may come from the harvest but to keep the temperatures stable and thus avoid condensation. Figure 3 shows the relationship between energy demand and airflow displaced by the ventilation system as a function of system speed.

Condensation is a potential problem during storage as it can lead to skin problems and bacterial rot. For example, at 10°C, with a relative humidity of 95%, a temperature drop of 1.14°C will cause the air to reach its dew point. Hence, the importance of keeping the temperature constant throughout storage.

Efficiency in air movement is also important since when storing in boxes, air volume and speed are the key conductors of energy. Sometimes a low airspeed involves an inadequate mixture of air.

2.5 | Energy efficiency measures

Energy efficiency is a measure to reduce the amount of energy necessary for the proper preservation of the product. The use of technologies that enhance the efficiency of the process together with appropriate work methodologies based on the search for efficiency will reduce costs and enhance product quality.

The use of frequency inverters in ventilation and airspeed control is also interesting, allowing:

- A saving in energy costs, since its goal is to work at lower speeds.
- A better distribution of the anti-sprouts.
- Together with the humidifiers, it avoids product weight loss (long-term storage).

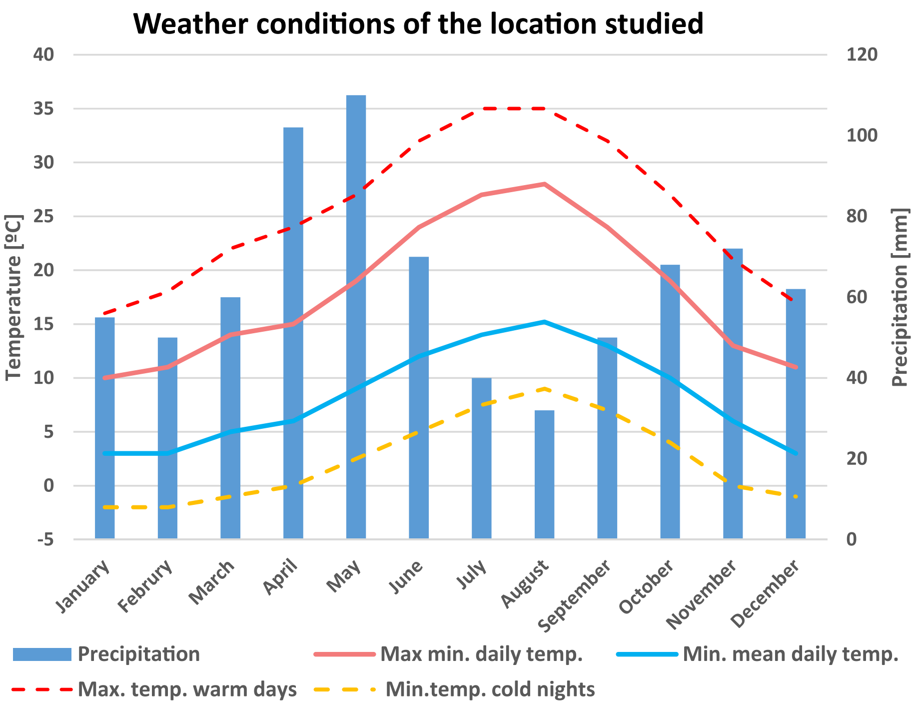

FIGURE 4 Weather conditions of the location studied

Other advantages, such as reduction of power peaks during startup or improvements in the performance and quality of the regulation and control of the system, are highly valued.

According to recent studies (Cunnington et al., 2010), a 20% reduction in air velocity produces an increase in ventilation time and an energy-saving of around 40%.

Energy-saving measures can directly affect the energy demanded by the electrical equipment, causing an increase in performance, or influencing other non-electric variables that motivate electricity consumption.

Some of the energy efficiency measures applied to cold potato conservation are as follows:

- Replacement or improvement of cooling equipment performance.
- Insulation and infiltration in the cooling chamber.
- Product entry temperature. A zone dedicated to stabilization before the product enters the refrigeration chamber.
- Thermal conditioning by free-cooling.
- Lighting.
- Technical management and supervision of the facilities
- Thermographic control

The monitoring of the operation and performance of the facilities, together with adequate maintenance and technical management of the facilities, is in general one of the main existing sources of savings (Foster et al., 2013).

The constant increase in energy demand, the associated costs and its high environmental impact, mainly derived from fossil fuels, forces the transition towards a new energy model.

Any installation based on renewable energies and sustainability concepts must first consider basing its pillars on energy efficiency: elimination of unnecessary energy use, reduction of the necessary energy use, selection of equipment, control systems, and equipment for good management of energy demand (Avgoustaki et al., 2020).

The elimination of energy inefficiencies in the operation phase of the facilities, as explained in the previous points, allows maintaining and improving the energy performance and cost associated with the potato conservation phase.

Once all this is considered, the bases for energy supply based on renewable energies are established. The adoption of renewable-energy-based facilities without considering demand reduction would only mask the inefficiency of the facility.

Renewable energies seek energy production through sources capable of regenerating by natural means. The origin of them is mainly due to the sun, manifesting itself under different phenomena (photoelectric, thermal, geothermal, etc.), water (hydraulic, tidal, etc.), wind, or biomass.

2.6 | Case study

The model is validated by applying it to a case study, where a potato conservation facility by cool storage is analyzed. The warehouse under study is located in the northeast area of La Rioja (Spain). The facility has an altitude of 650 m above sea level. Its weather conditions are shown in Figure 4.

Constructively, the warehouse considered acquires the form of an industrial building and is designed for a capacity of approximately 1.100 tons, distributed in drawers (1600 mm length $\times$ 1196 mm width $\times$ 1232 mm height and weight of approximately 31 kg). For adequate ventilation, 10% of the lateral surface are grooves and a maximum height of four stacks.

TABLE 4 Percentage assessment of the energy involved in each term of the energy model of the conservation chamber

Item	% energy demand
Thermal load due to transmission losses ($P_{Transmission}$)	44.15%
Thermal load due to air renewal ($P_{air\ renewal}$)	12.43%
Thermal load due to air infiltration losses (P_{inf})	5.43%
Thermal load due to potato cooling ($P_{ref\ pot}$)	24.47%
Thermal load due to container cooling ($P_{ref\ cont}$)	0.03%
Thermal load due to potato respiration ($P_{aerobic\ resp}$)	3.44%
Thermal load due to lighting ($P_{lighting}$)	0.38%
Thermal load due to personnel (P_{man})	0.73%
Other thermal loads (P_{others}), among which should be highlighted:	
Thermal load associated with the operation of the machinery.	8.18%
Thermal load due to other inputs and/or losses.	0.76%
Total	100.00%

TABLE 5 Variation of energy demand according to the management strategy of the facilities used

Technical management measure and supervision of facilities	Energy increase (%)
Non-use of the technical management measures of the facilities	3.00%
Annual maintenance of the facilities	0.00%
Monitoring system with plant staff attention	−0.45%
Monitoring system with staff attention in control center	−0.88%
Management monitoring system under ESCO strategies	−1.56%

Abbreviation: ESCO, Energy Service Company.

For the best distribution inside the chamber, the drawers should be considered to be stacked up to four stacks, leaving between each row a corridor of about 0.6 m (for staff access) and a space between 0.8 and 1.5 m between the top of the pile of drawers and the roof, for a correct distribution of the air inside.

3 | RESULTS AND DISCUSSION

3.1 | Energy study and reference line

The average energy cost associated with the storage of potatoes varies between 0.11 and 0.15 kWh/ton/day depending on the conditions of the storage chamber, capacity, and location.

The measurement and verification plan will be developed following option B (Celorrio et al., 2015, 2016, 2017) of the International Performance Measurement and Verification Protocol (IPMVP, 2017) developed by the Efficiency Valuation Organization according to the norm EVO 10000-1:2016.

TABLE 6 Energy demand for the cooling of potatoes and containers for different inlet temperatures

Temperature increase [°C]	Total [kWh]	Diff. [%]
4	−395	−157.14%
10	198	−71.43%
15	691	0.00%
20	1185	71.43%
25	1679	142.86%
30	2173	214.29%
35	2666	285.71%
40	3160	357.14%

For that purpose, all the variables involved in consumption have to be measured. In this case, the measurements include chamber temperatures, outer space, air conditions, etc. The thermal conductivity values of the chamber walls are considered based on the manufacturer's data.

A detailed energy analysis of the different options, knowing the actual operation of the facility, provides very interesting information for the improvement of processes and product quality as demonstrated. All this will be checked during the demonstration phase of savings through the measurement and verification plan adopted. Table 4 reflects the energy consumed by the facility (P_{ref}) and for each thermal load studied.

3.2 | Energy efficiency measures

In the case study, six measures have been used, which are developed in the next section.

3.2.1 | Measure 1: Technical management and supervision of facilities

Management and improvement from information is the main basis of efficiency in all aspects. It is difficult to improve without the necessary information to know in what situation the facility is, where to go, and the steps to be taken. In Table 5, energy savings obtained are collected through different technical management strategies and supervision of facilities.

The management strategies under the Energy Service Company (ESCO) imply a link between the company that owns it and the energy company (Guo et al., 2019; Khan et al., 2018; Sovetova et al., 2019). The remuneration received by the energy services company is subject to some degree to the results obtained.

TABLE 7 Variation in the energy transmitted through the walls in the cold storage chamber of potatoes according to the thickness of the walls of the storage chamber

T_{inside} [°C]	Pot. trans. [W]	Diff. [%]
40	−633	55.81%
60	−482	18.60%
80	−406	0.00%
100	−359	−11.63%
120	−331	−18.60%
150	−302	−25.58%
180	−284	−30.23%
200	−274	−32.56%

TABLE 8 Variation in the energy transmitted through the walls in the cold storage chamber of potatoes according to the thickness of the walls of the storage chamber for a conservation cycle

Thickness (mm)	Energy increase [%]
40	4.13%
60	1.38%
80	0.00%
100	−0.86%
120	−1.38%
150	−1.89%
180	−2.24%
200	−2.41%

3.2.2 | Measure 2: Product entry temperature—A zone dedicated to stabilization before the product is introduced into the chamber

The product supply to the conservation facility is conducted in different ways. The local product can be supplied directly with tractors, or transported from other areas supplied by trucks. They can have product air conditioning systems or not. This causes important variations in the temperature at which the product arrives.

Once the product has been prepared for storage, the product is deposited in an anteroom to the refrigeration chamber, which is naturally conditioned. This will allow reducing the thermal jump of the product and, consequently, the energy needed for its refrigeration.

The change in energy demand for cooling the potatoes according to the temperature thereof against the temperature allotted inside the chamber (8°C) is reflected in Table 6. The percentage variation is made based on a temperature of 15°C.

3.2.3 | Measure 3: Insulation of the cooling chamber

Incrementing the insulation of the chamber walls or reducing thermal bridges are some of the main points of action to reduce demand. This must be subject to a technical-economic analysis to achieve the highest possible economic performance, weighing energy, and economic criteria, throughout the entire life cycle of the facility.

The variation of the energy transmitted through the walls that make up the cold storage chamber, necessary for the cooling of the potatoes, for different thicknesses is represented in the following table for an ideal case. The temperature inside the storage chamber is set at 8°C and outside at 15°C. The percentage variation is conducted taking as reference a wall thickness of 80 mm thick of panel with polyurethane insulation (see Table 7).

Considering the energy demand in each case for an annual period, the variations in energy demand can be observed in Table 8.

The increase in thickness of the conservation chamber entails an economic cost over which it is necessary to conduct an analysis contemplating its entire life cycle analyzing the return on investment made.

It is important to conduct periodic thermographic analysis of the conservation chamber, oriented to the search for deficiencies, thermal bridges, etc., which can help avoid problems and large energy and economic costs in the conservation process.

3.2.4 | Measure 4: Thermal conditioning through free-cooling systems

Thermal variations of the facility location, between day and night, can help improve thermal performance. Temperature reduction in the chamber environment conservation reduces conduction losses and thus reduces the need for additional cooling.

One way to save energy is to take advantage of the outside temperature, with the system commercially called *free-cooling*. Since when the outside ambient temperature is lower than 10°C, the temperature of the outside air can be used to cool, ideally without the need for energy expenditure. The effectiveness of this airflow depends on the temperature difference between the exterior and interior of the warehouse and the efficiency of the fan that produces this flow.

The night ventilation helps reduce costs when it is conducted in a controlled manner and when the adequate conditions of the warehouse are created, or for an area of the same, in which the conservation chamber is located. Along with this, the economic costs of energy demanded from the grid at night are reduced compared to other times.

Another factor to consider in energy consumption during storage is air leaks. These may be due to poor insulation of the chamber, frequent openings of staff (doors), and maintenance.

Ventilation in the preservation chamber is necessary to maintain the optimal storage conditions of the products. The air, in the appropriate conditions, to eliminate contaminants, moisture, and so on, must be introduced at the temperature closest to the conservation chamber to avoid added energy needs. Impulsion and extraction facilities, associated with heat exchangers to reduce the thermal jump are suitable to reduce energy demand. Along with this, simpler ventilation strategies, although effective, can be based on a correct choice of ventilation periods, facility layout, and so on.

TABLE 9 Variation in energy demand by the refrigeration equipment based on its SEER energy efficiency ratio

SEER	Energy increase [%]
2.5	80.00%
3.5	28.57%
4,5	0.00%
5.5	−18.18%
6.5	−30.77%
7.5	−40.00%
8.5	−47.06%

Abbreviation: SEER, seasonal efficiency energy ratio.

Variables such as the weather conditions of the geographical location of the facility (temperature, humidity, etc.) and the conditions of the analyzed process are considered. In this case, the use of 62 days per year for an average of 4.75 h per day has been estimated.

3.2.5 | Measure 5: Performance of refrigeration equipment

Any refrigeration installation, regardless of its purpose and without entering into particular technologies or operating conditions or design, is conditioned by its energy efficiency.

At the equipment level, the energy efficiency in refrigeration is determined by the fabric ante through ratios such as EER or seasonal efficiency energy ratio (SEER). The use of equipment with a higher EER and/or SEER, together with an adequate design of the installation, allows reducing the energy demand of the process in a very important way.

Currently, energy efficiency is one of the main arguments of manufacturers, developing new technologies and equipment aimed at reducing energy demand. The variation of the energy achieved through the improved energy efficiency of equipment is reflected in Table 9.

3.2.6 | Measure 6: Thermographic control

The energy losses in the conservation chambers are manifested by an increase in temperature on the affected surface. The technology currently available allows the detection of such incidents by thermal cameras.

It is possible to detect and solve issues that are causing significant problems both in the stored product, for loss of its optimal storage conditions, and in refrigeration equipment, for overloading in the energy demand to compensate for such losses.

The proposed methodology allows a reduction of consumption by 15%, with a reduction of the energy demanded above 3000 kWh per year. This has allowed reducing the energy intensity from 0.13 kWh/ton to 0.1125 kWh/ton.

The approach and implementation of a measurement and verification process with the proposed energy model have allowed detecting opportunities for improvement and demand reduction. Applying a conversion factor of 0.28307 kg CO_2 per kWh demanded from the distribution grid, a reduction in emissions due to the energy demand of the potato storage chamber of 1 ton of CO_2 per year is obtained.

3.2.7 | Measure 7: Replacement of lighting systems

The change to LED lighting offers numerous advantages beyond economic savings. In the case of storage, it is a smaller heat source, provides uniform light, and with the possibility of regulating.

3.2.8 | Measure 8: Renewable energies—Photovoltaic generation

The potato storage chamber during its activity period carries an energy demand of 20.3 MWh/year and associated emissions of 5.75 tons of CO_2 per year.

In order to reduce these emissions and enhance the competitiveness of the conservation process, the energy supply is projected through a photovoltaic generation facility.

The facility is sized to supply photovoltaic energy to the conservation chamber in the months of greatest demand, coinciding with the months of lower photovoltaic production.

In the months without using the conservation chamber, the energy generated will be used in other parts of the organization.

The installation of the photovoltaic panels is proposed to be on the roofs of the industrial activity with a power of 70 kW. It will allow the generation of 90 MWh/year, avoiding the discharge into the atmosphere of more than 25 tons of CO_2 per year.

Along with this, to reduce the costs of cold potato preservation activity, an electrical generation facility has been developed using photovoltaic generation technology. Thanks to this, the facility allows reducing the environmental impact of the activity.

Figure 5 represents the total energy generation obtained through the photovoltaic solar facility, as well as its distribution between the energy demand of the conservation chamber and other consumptions of the organization.

Twenty-three percentage of the energy generated has been used to supply the total energy demanded by the conservation chamber. The remaining 77% of energy from renewable sources generated by solar photovoltaic installation, has been demanded in other consumptions of the organization.

3.3 | Summary of the improvements obtained

Table 10 shows the overall result of the improvement achieved through the implementation of the measures of energy efficiency, 1 to 7 in the first year of research. It is worth noting that, if measure

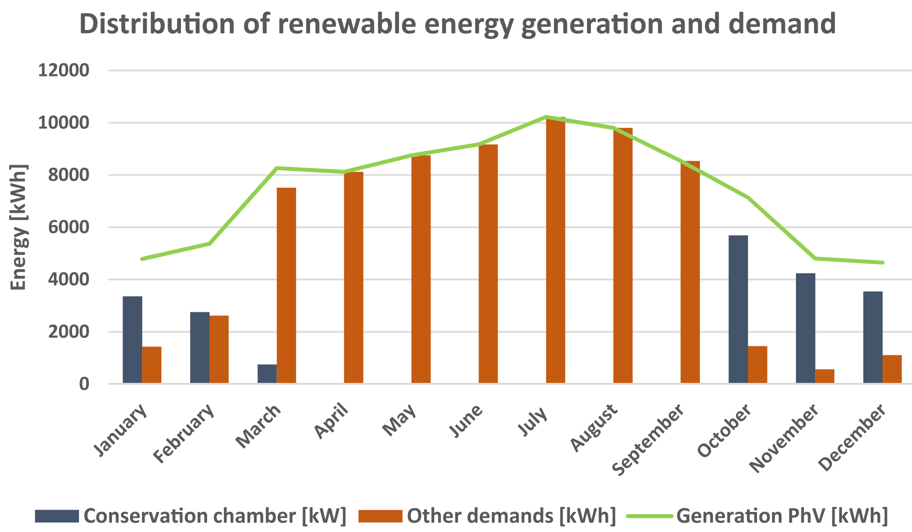

FIGURE 5 Electricity generation through a photovoltaic installation and distribution of consumptions for the conservation chamber and other demands

TABLE 10 Energy saving actions 1 to 7 and energy savings achieved

ESA [ID]	Description	Developed activities	Demand reduction [%]
1	Technical management and supervision of the facilities	Facility control Demand supervision	1.25% 0.47%
2	Product entry temperature. A zone dedicated to stabilization before product storage	I/O procedure	3.45%
3	Cooling chamber insulation	Enclosure review Change of enclosures	1.16%
4	Thermal conditioning through free-cooling system	Other measures	0.94%
5	Performance of refrigeration equipment	Performance review and adjustment	6.20%
6	Thermographic control	Thermographic study and leak detection	2.78%
7	Other performances	Replacement of lighting equipment	0.21%
Total reduction in energy demand			16.41%

8 is fully implemented, the improvement would be a 100% reduction in energy demand.

4 | CONCLUSIONS

The energy costs of cold storage are important in all sectors, having a special impact on sectors such as potato conservation. Therefore, the improvement of processes is paramount, in search of efficiency, which allows cost reduction. This is enhanced by the generation, through renewable power generation facilities, at the same point of demand. In the case of activities so close to the environment, such as agriculture and the first phases of the value chain, as it is the case, it allows a reduction in CO_2 emissions and the environmental impact associated with the conservation process.

Cold storage facilities, especially in warm and temperate climates, have a significant cost due to the energy demand associated with these particular climates. Additionally, the environmental impact associated with it must be considered.

This article studies cold preservation to minimize the added cost in the potato value chain to ensure its competitiveness in the market. In addition, a model is developed to evaluate energy consumption and to propose measures to reduce energy, environmental, and economic costs. All this has the final objective of reducing its impact within the value chain of potato consumption.

The energy modeling of the facility, along with the added value of mastering different technologies oriented towards energy efficiency and renewable generation, allows reducing conservation costs, while reducing their environmental impact.

In the case of the analyzed study, different energy efficiency measures applied to the cold storage of potatoes have been implemented: replacement or improvement of the performance of refrigeration equipment, insulation and infiltrations in the refrigeration chamber, control of the product entry temperature, thermal conditioning through free-cooling, improvements in lighting equipment, technical management and supervision of facilities, and thermographic control.

Finally, as a summary of the results, the set of actions implemented has allowed us to obtain a reduction in energy demand, standardized through the developed reference line, by 16.41% compared to previous years.

AUTHOR CONTRIBUTIONS

Conceptualization: M. Sáenz and J. I. Latorre-Biel; Data curation: M. Sáenz and J. I. Latorre-Biel; Formal analysis: J. Blanco and E. Jiménez; Funding acquisition: M. Sáenz and J. I. Latorre-Biel; Investigation: E. Martínez and E. Jiménez; Methodology: J. Blanco and E. Jiménez; Project administration: M. Sáenz and J. I. Latorre-Biel; Validation: J. Blanco; Visualization: E. Jiménez and F. Longo; Writing – original draft: M. Sáenz and J. I. Latorre-Biel; Writing – review and editing: F. Longo, J. Blanco, and E. Martínez. All authors have read and agreed to the published version of the manuscript.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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