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TOWARDS CARBON-NEUTRAL FISH COLD STORAGE: A SUSTAINABLE APPROACH THROUGH RENEWABLE ENERGY

João Garcia[1,2,3] *, Arian Semedo[1]

1: Instituto Superior de Engenharia de Lisboa R. Conselheiro Emídio Navarro 1, Lisbon, Portugal
e-mail: joao.garcia@isel.pt
2: UnIRE, ISEL, Polytechnic University of Lisbon, Rua Conselheiro Emídio Navarro 1, Lisbon
3: MARE-IPS, Marine and Environmental Sciences Centre, Escola Superior de Tecnologia, Instituto Politécnico de Setúbal, Campus do IPS – Estefanilha, 2910-761, Setúbal, Portugal
e-mail: ariansemedo1997@hotmail.com

Abstract: *Preserving perishable foods, particularly fish, demands meticulous attention throughout the entire supply chain, from capture to consumption. The critical role of cold storage facilities in maintaining optimal conditions, encompassing temperature and humidity regulation, is indispensable. Nevertheless, these facilities pose a considerable challenge due to their substantial electrical energy consumption, which significantly contributes to operational costs. In addressing this challenge, the implementation of energy-efficient strategies, including the utilization of advanced equipment and real-time monitoring facilitated by automation technologies, becomes imperative. This research investigates an innovative integrated cold storage system situated in Tarrafal, Santiago, Cape Verde, which harmoniously incorporates wind, solar, and tidal energy sources. The primary objectives are to evaluate the energy efficiency, financial viability, and environmental impact across four distinct hypothesis. Hypothesis 1 entails the deployment of two R134a refrigeration units powered by the conventional public grid, while Hypothesis 2 adopts a transcritical CO_2 system reliant on grid electricity, Hypothesis 3 integrates CO_2 technology with autonomous renewable energy sources and Hypothesis 4 leverages CO_2 for refrigeration coupled with seawater heat exchange and autonomous renewable energy generation. The research findings strongly favor Hypothesis 4, demonstrating emissions of 15880 kg CO_2eq with an impressive 5-year return on investment. The autonomous electricity production associated with this hypothesis markedly reduces emissions by more than 90%. Despite an initial higher investment, Hypothesis 3 showcases financial viability, contributing significantly to long-term energy sustainability. The autonomous energy production in this scenario results in a noteworthy reduction of more than 600000 kgCO_2 compared to conventional systems, underscoring the positive impact of integrating local renewable energy sources.*

Keywords: Sustainable refrigeration, Fish Cold Storage, CO_2 refrigeration, Renewable Energy.

1. INTRODUCTION

The innovation towards sustainability in CO_2 refrigeration systems, through the utilization of renewable energies such as solar, wind, and tidal energy, has be-come increasingly relevant in the current context characterized by significant socio-economic and environmental challenges. This study aims to explore and analyze the feasibility and benefits of integrating sustainable technologies into refrigeration systems, with a focus on reducing environmental impact and im-proving energy efficiency. In the current hypothesis, where the need for sustainable hypothesis is urgent, particularly in the refrigeration sector, the introduction of innovations that harness renewable energy sources assumes a strategic priority. The growing awareness of environmental challenges and the pressure to reduce greenhouse gas emissions have driven research in this area, prompting the adoption of more sustainable approaches. In this regard, the present study conducts a comparative analysis among four hypothesis related to the installation of an integrated system in a refrigerated storage unit located in Tarrafal, Santiago, Cape Verde. These hypothesis involve the evaluation of sustainable technologies and their impacts, both from a technical and financial perspective, aiming to identify the best option for reducing energy consumption and CO_2 emissions in the specific context of this installation.

2.RENEWABLE ENERGY

2.1. Wind energy

Wind energy is a renewable and clean source of energy, widely available and derived from the force of the wind. These turbines capture the kinetic energy of the wind through blades moved by drag and lift forces, transferring this movement to a rotor. The rotor, in turn, is connected to a generator through a gearbox, which converts mechanical energy into electrical energy [1]. The produced energy can be integrated into the electrical grid or stored in batteries for later use. Wind energy systems are widely used in refrigeration facilities, ensuring a continuous supply of energy. Vaughan et al [2] examined the feasibility of integrating wind energy with refrigeration systems, achieved by supplying electrical power to refrigeration systems using a wind turbine for apple storage, showing promising results in terms of reliability and reduction of environmental impact. On the other hand, Roselli et al [3] presented a study on a wind-driven system for heating, cooling, and electricity for an office building in two Italian cities, emphasizing the effective integration of wind energy into heating and cooling systems, constituting a significant solution to meet global environmental goals and guidelines.

2.2. Photovoltaic solar energy

The implementation of photovoltaic solar energy in refrigeration systems represents a significant advancement in the sector. Hameed et al. [4] demonstrated the feasibility of this form of energy in refrigeration in Baghdad, emphasizing its effectiveness in reducing dependence on conventional grids. Additionally, Yvon et al. [5] highlighted the positive integration of solar energy with vapor com-pression refrigeration systems.
The considered photovoltaic system is a conventional system composed of solar panels for electricity generation, solar inverters for converting direct current (DC) into alternating current (AC), and energy storage systems such as solar batteries. The efficiency of this system depends on the effectiveness of each of its individual components.

2.3. Tidal energy

Tidal energy is a renewable energy source that harnesses the kinetic energy of oceanic waters. Turbines convert this energy into electricity, akin to wind energy systems. Studies, such as the one conducted by Fandi et al [6], have investigated the viability of this energy form; however, its application in refrigeration sectors still requires further developments.

3. VAPOR COMPRESSION SYSTEM

Within the scope of this study, all analyzed refrigeration systems follow the principle of vapor compression, adopting the inverted Rankine cycle. In response to increasing environmental concerns and international agreements, carbon dioxide (CO_2) emerges as a sustainable alternative in refrigeration, replacing other refrigerants such as R134a in the case study[7]. Natural refrigerants, like CO_2, stand out as long-term options due to their non-flammability and non-toxicity, being ideal for vapor compression cycles. Additionally, their abundance in nature and lack of contribution to the greenhouse effect make them environmentally responsible choices[8]. This technological advancement reflects a commitment to sustainable solutions in the refrigeration

industry, aligned with global demands for more ecological practices.

3.1. Loads for refrigerated spaces

Determining the thermal loads of each refrigerated space has played a crucial role in the proper sizing of the refrigeration system in the various proposed study hypothesis for comparison. This process ensures the maintenance of the ideal temperature and storage conditions in all areas, thereby contributing to the optimization of the system's energy efficiency. Equations play a crucial role in determining the refrigeration equipment for refrigerated spaces by assessing the involved thermal loads. They enable a comprehensive analysis of cooling requirements, considering factors such as the thermal conductivity of materials and temperature fluctuations. By considering these thermal loads, it is possible to design an effective refrigeration system tailored to the specific demands of each refrigerated environment. The considered thermal loads include thermal conductivity, which considers the thickness and temperature difference between both sides of the wall, crucial elements in determining the thermal load resulting from conduction. Additionally, the thermal load due to the temperature difference between the product and the ambient temperature in the chamber is relevant. The presence of occupants, equipment, and lighting in the refrigerated space contributes to three distinct sources of heat. Infiltrations of air from the door into the chamber are responsible for resulting thermal loads. The layout of the warehouse includes a chamber for frozen products (F), one for refrigerated products (R), and a buffer area (B) for receiving and dispatching goods.

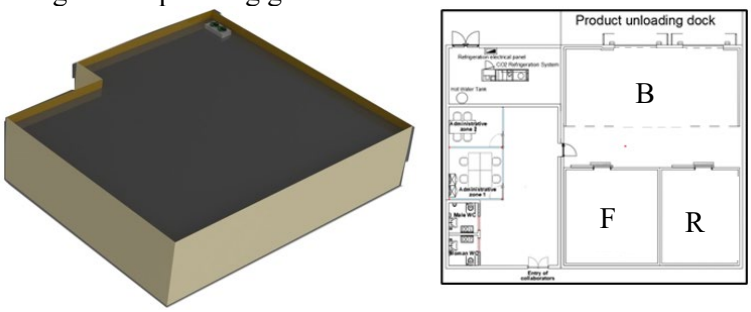

Figure 1. Layout for the facility.

Table 1 displays the results of the four types of thermal loads calculated for each refrigerated space.

Table 1. Thermal loads and refrigeration capacity of refrigerated spaces.

Thermal Load	F	R	B
- Thermal load from conduction (W)	1230	470	2080
Thermal load from product (W)	4020	770	4130
Internal thermal load (W)	470	440	820
Thermal load from infiltrations (W)	1610	190	1030
Cooling Power (W)	12100	3100	13300

Analyzing the values presented in table 1, it is noted that the loads fall within a range considered typical for refrigerated spaces [9], [10] .This observation suggests that the thermal loads are aligned with the expectations for the proper sizing of the refrigeration system for each specific space.

4. EVALUATED HYPOTHESIS

Hypothesis 1

In hypothesis 1, a refrigeration system with two distinct units, both using the refrigerant R134a, was studied. One unit is intended for storing frozen products, while the other is for refrigerated products. The electrical energy required for the operation of the refrigeration warehouse is supplied by the public electrical grid (Figure 2).

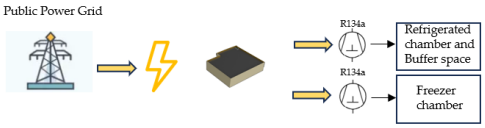

Figure 2-Hypothesis 1

Hypothesis 2

In hypothesis 2, the electrical energy required for the operation of the refrigeration warehouse is supplied by the public electrical grid. A transcritical booster refrigeration system using CO_2 was considered. (Figure 3).

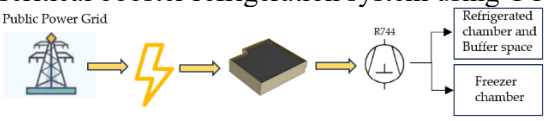

Figure 3. Hypothesis 2

Hypothesis 3

In hypothesis 3, a transcritical booster refrigeration system utilizing refrigerant CO_2 was considered. Renewable sources such as wind energy, photovoltaic solar energy, and marine currents (Figure 4) are employed in the generation of essential electrical energy for the operation of the refrigeration warehouse.

Figure 4. Hypothesis 3

Hypothesis 4

In hypothesis 3, a subcritical booster refrigeration system using refrigerant CO_2 was considered. Therefore, it was determined that the refrigerant cooling is achieved through heat exchange with seawater near the refrigeration warehouse. In this solution, renewable sources such as wind energy and photovoltaic solar energy are employed in the generation of essential electrical energy for the operation of the refrigeration warehouse. (Figure 5).

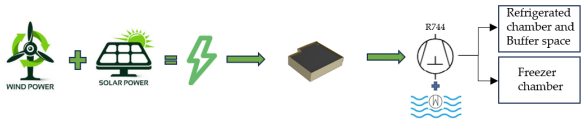

Figure 5. Hypothesis 4.

4.1.COP Results

This section presents the results regarding the study of the COP among the four proposed types of installations. Table 2 provides a summary of key information related to cooling capacity, heat recovery, electrical power of the installation, and annual energy consumption for each analyzed case.

Table 2. Comparative Analysis of Refrigeration Systems

Hypothesis Study	Cooling Capacity (W)	Heat Recover (W)	COP	Electrical Power of the Installation (We)	Total Annual Energy Consumption (Wh)
Hypothesis 1	28480	0	1.99	54264000	475352000
Hypothesis 2	28480	10320	1.30	69952000	613200000
Hypothesis 3	28480	10320	1.30	69952000	613200000
Hypothesis 4	28480	10320	3.02	50801000	445016000

The analysis of the table reveals that hypothesis 4 presents the highest COP of 3.02, indicating superior efficiency in utilizing electrical energy for refrigeration. Additionally, it stands out for having the lowest total electrical power of the installation, suggesting a more efficient and sustainable approach. In contrast, hypothesis 1 shows a significantly lower COP due to the absence of heat recovery. Hypothesis 2 and 3 also demonstrate inferior efficiency. These findings are consistent with previous studies, such as those conducted by Sengupta et al.[11]. Such conclusions underscore the importance of energy efficiency, particularly through the implementation of measures like heat recovery. In summary, hypothesis 4 is considered the most efficient, demonstrating higher energy efficiency and lower electricity consumption for the same thermal capacity.

4.2. Costs and payback results

The study analyzed the financial viability of four hypothesis over a period of 10 years, considering initial investment, annual energy costs, generated savings, and the impact of inflation. The initial investment encompassed the total cost of refrigeration facilities, including the autonomous energy generation system. Annual savings resulted from the use of autonomous energy generation systems, avoiding the purchase of electricity from the public grid.

Table 3. Financial Study for different hypothesis

Hypothesis Study	Initial Investment (€)	Energy savings (€) after 10 years	Accumulated Balance (€) after 10 years	Payback Period
Hypothesis 1	-€ 45 000.00	-€ 1 760 000.00	-€ 1 621 000.00	∞
Hypothesis 2	-€ 64 600.00	-€ 2 270 000.00	-€ 2 330 000.00	∞
Hypothesis 3	-€ 769 172.00	€ 2 270 000.00	€ 1 500 000.00	4
Hypothesis 4	-€ 715 000.00	€ 1 650 000.00	€ 935 000.00	5

Upon analyzing table 3, it is evident that hypothesis requiring higher initial investments (3 and 4) demonstrate better financial viability due to the implementation of autonomous renewable energy production systems. Despite the significant initial investments of -€769172.00 in hypothesis 3 and -€715000.00 in hypothesis 4, both yield positive accumulated balances after 10 years, totaling €1 500 000.00 and €935 000.00, respectively. hypothesis 3 stands out for its shorter investment payback period, just 4 years, attributed to annual energy savings. Although hypothesis 4 has a 5 years investment payback period, it represents a safer initial investment. On the other hand, hypothesis 1 and 2 incur negative accumulated balances, relying on electricity from the public grid, resulting in negative cash flows over time, with accumulated balances of -€ 1 760 000.00 and -€ 2 270 000.00, respectively. Hypothesis 1 and 2 have an infinite investment payback period due to the absence of energy savings.

4.3. CO_2 Emissions results

Table 4 represents the results of the comparative analysis of CO_2 emissions from the electrical power systems providing energy to the refrigeration facilities across the four examined hypothesis. Table 4 compares CO_2 emissions resulting from four different hypothesis, considering the origin of electricity from both renewable energy systems and the public electrical grid. CO_2 emission values were calculated and summed for each type of electrical energy source, determining the total emissions for each hypothesis by aggregating the contributions of each source. Data from Cabo Verde's public electrical grid, as well as information on wind systems, solar photovoltaic systems, and tidal turbines, were used for this calculation[12], [13], [14].

Table 4. CO_2 Emissions in Different Hypothesis Studied

Hypothesis Study	CO_2 Emission Grid Electricity (gCO_2 eq./kWh)	CO_2 Emission Wind System (gCO_2 eq./kWh)	CO_2 Emission Solar Photovolt-aic System (gCO_2 eq./kWh)	CO_2 Emission Tidal Turbines (gCO_2 eq./kWh)	Total Emission (gCO_2 eq.)
Hypothesis 1	623	-	-	-	296316940
Hypothesis 2	623	-	-	-	382246310
Hypothesis 3	-	34	50	34	21549320
Hypothesis 4	-	34	50	-	15882000

Upon analyzing the results presented in Table 4, it is observed that in hypothesis 2, where there is an exclusive dependence on electricity from the public electrical grid, considerable CO_2 emissions are recorded, totaling 382246310 gCO_2 eq. On the other hand, in hypothesis 3, the implementation of an autonomous system for electricity generation through wind, solar, and tidal energy leads to a significant reduction in emissions, totaling 21549320 gCO_2 eq. In hypothesis 4, emissions are further reduced, totaling 15882000 gCO_2 eq, a value close to that recorded in hypothesis 3.

When analyzing the total CO_2 emissions in each solution, it is evident that autonomous electricity generation systems (hypothesis 3 and 4) are the most environmentally sustainable, offering a significant reduction compared to dependence on the public electrical grid (hypothesis 1 and 2). The adoption of an autonomous electricity generation system resulted in a 90% reduction in CO_2 emissions compared to electricity sourced from the public electrical grid. This analysis highlights the crucial importance of investing in renewable energy sources, such as wind and solar energy, to reduce CO_2 emissions and contribute to more ambitious environmental objectives, reducing dependence on fossil fuels.

5. CONCLUSIONS

Present study shows that hypothesis 4 has emerged as the most favorable option among the comparative hypothesis, primarily due to advantageous criteria such as lower initial investment, a short payback period, high coefficient of performance, and a significant reduction in CO_2 emissions compared to hypothesis 2. Results associated with hypothesis 1 were discouraging due to its use of R134a, which has a high global warming potential, along with an infinite payback period and high CO_2 emissions. Both hypothesis 2 and 3 presented financial and environmental advantages and disadvantages, with hypothesis 3 being more financially favorable, while hypothesis 4 emerged as the best overall option. Financial analysis confirms the viability of hypothesis 3, despite its higher initial investment, while the reduction in CO_2 emissions is emphasized as an advantage of autonomous electricity production systems from renewable sources. In summary, the adoption of sustainable practices, such as the implementation of autonomous renewable energy systems like solar, wind, and tidal energy, represents a significant step toward sustainability and socio-economic development.

6. REFERENCES

[1] M. Sathyajith, Wind Energy Fundamentals, Resource Analysis and Economics. Kerala, 2006.

[2] D. H. Vaughan, H. L. Moses, J. C. Blanton, and J. D. Baldwin, "Design of wind-powered cold storage facility design of wind-powered cold storage facility," Oct. 1978. [Online]. Available: https://scholarsmine.mst.edu/umr-mechhttps://scholarsmine.mst.edu/umr-mec/351

[3] C. Roselli, M. Sasso, and F. Tariello, "A wind electric-driven combined heating, cooling, and electricity system for an office building in two Italian cities y," Energies (Basel), vol. 13, no. 4, 2020, doi: 10.3390/en13040895.

[4] V. M. Hameed and M. A. Hussein, "Studying the performance of refrigeration units powered by solar panel," Iraqi Journal of Chemical and Petroleum Engineering, vol. 14, no. 1, pp. 39–46, 2013, [Online]. Available: www.iasj.net

[5] Rakotondrazano Yvon, Modeste Kameni Nematchoua, and Raminosoa Chrysostome, "Performance modelling of an electric vapor compression solar refrigeration system (SE-VCR) case for Madagascar," International Journal of Frontiers in Life Science Research, vol. 1, no. 2, pp. 028–051, Dec. 2021, doi: 10.53294/ijflsr.2021.1.2.0057.

[6] O. M. Fandi, S. S. Dol, and M. Alavi, "Review of renewable energy applications and feasibility of tidal energy in the United Arab Emirates," vol. 3, no. 2, pp. 165–174, 2022, doi: 10.22044/rera.2022.11747.1107.

[7] G. Maouris, E. J. Sarabia Escriva, S. Acha, N. Shah, and C. N. Markides, "CO_2 refrigeration system heat recovery and thermal storage modelling for space heating provision in supermarkets: An integrated approach," Appl Energy, vol. 264, Apr. 2020, doi: 10.1016/j.apenergy.2020.114722.

[8] E. J. Sarabia Escriva et al., "Modelling of a real CO_2 booster installation and evaluation of control strategies for heat recovery applications in supermarkets," International Journal of Refrigeration, vol. 107, pp. 288–300, Nov. 2019, doi: 10.1016/j.ijrefrig.2019.08.005.

[9] A. Benardos and G. Brachos, "Thermal loads analysis of an underground cold storage facility in Attica," 2007. [Online]. Available: https://www.researchgate.net/publication/290746456

[10] J. Garcia and A. Semedo, "Sustainable CO_2 refrigeration system for fish cold storage facility using a renewable integrated system with solar, wind and tidal energy for Cape Verde—Analyzing Scenarios," Sustainability, vol. 16, no. 10, p. 4259, May 2024, doi: 10.3390/su16104259.

[11] A. Sengupta, P. Gullo, M. S. Dasgupta, and V. Khorshidi, "Performance analysis of an r744 supermarket refrigeration system integrated with an organic Rankine cycle," Energies (Basel), vol. 16, no. 22, Nov. 2023, doi: 10.3390/en16227478.

[12] S. Electra, "Financial statements 2022," Mindelo, 2023. Accessed: Nov. 01, 2023. [Online]. Available: https://www.bcv.cv/pt/Supervisao/Mercado%20de%20Capitais/Sistema/Emitentes/Presta%C3%A7%C3%A3o%20de%20Contas/Paginas/RCELECTRA.aspx

[13] D. Nugent and B. K. Sovacool, "Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey," Energy Policy, vol. 65, pp. 229–244, Feb. 2014, doi: 10.1016/j.enpol.2013.10.048.

[14] G. L. Coutinho and J. N. Vianna, "Greenhouse Gas Emissions Avoided in Cape Verde: Estimation in a Scenario of Renewable Energy Sources Adoption in 2025," LALCA: Revista Latino-Americana em Avaliação do Ciclo de Vida, vol. 4, p. e45077, Jun. 2020, doi: 10.18225/lalca.v4i0.5077.