

A Sustainable Approach to Carbon-neutral Fish Cold Storage Using Solar Thermal, Photovoltaic, Wind, and Tidal Energy



Arian Semedo and João Garcia

Abstract The preservation of perishable foods, particularly fish, requires careful management at every stage of the supply chain, from capture to consumption. Cold storage facilities are essential for maintaining optimal conditions, including precise control of temperature and humidity. However, these facilities often face significant challenges due to their high energy consumption, leading to increased operational costs. To address this issue, adopting energy-efficient strategies, such as advanced refrigeration technologies and real-time monitoring through automation, is crucial. This study examines an innovative cold storage system in Tarrafal, Santiago, Cape Verde, that integrates wind, solar, and tidal energy sources. The key objectives are to evaluate energy efficiency, financial viability, and environmental impact under four solutions. In solution 1, two R134a refrigeration units operate on conventional grid power. Solution 2 utilizes a transcritical CO₂ system, also powered by the grid. Solution 3 combines CO₂ refrigeration with independent renewable energy, and Solution 4 uses CO₂ refrigeration alongside seawater heat exchange and autonomous renewable energy. The results strongly favor Solution 4, showing emissions of 15,880 kg CO₂eq and a return on investment within five years. This solution reduces emissions by over 90% through autonomous energy generation. Although requiring higher upfront investment, Solution 3 also proves financially viable, significantly contributing to long-term energy sustainability. The renewable energy production in this solution cuts emissions by over 600,000 kg CO₂ compared to traditional systems, underscoring the environmental benefits of integrating local renewable energy sources.

A. Semedo (✉)

Department of Mechanical and Industrial Engineering (DEMI), Faculdade de Ciências E Tecnologias, Universidade Nova de Lisboa, Caparica, Portugal
e-mail: aa.semedo@campus.fct.unl.pt

A. Semedo · J. Garcia

UnIRE, ISEL, Polytechnic University of Lisbon, Lisbon, Portugal

J. Garcia

Lisbon Superior Institute of Engineering, Lisbon, Portugal

MARE-IPS, Marine and Environmental Sciences Centre, Escola Superior de Tecnologia, Instituto Politécnico de Setúbal, Setúbal, Portugal

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1 Motivation

The pursuit of sustainability in CO₂-based refrigeration systems has become a global imperative, particularly considering the environmental commitments made by various nations under the Kyoto, Paris, and Montreal Protocols. These international agreements have established guidelines for the reduction of greenhouse gas emissions and the progressive elimination of substances harmful to the ozone layer, thereby driving the adoption of more efficient and environmentally responsible technologies. In this context, the implementation of energy-efficient refrigeration systems based on alternative cycles, such as absorption systems [1], has emerged as a viable solution. The integration of renewable energy sources, including solar, wind, and tidal energy, plays a crucial role in mitigating environmental impacts and enhancing operational efficiency [2]. The advancement of these solutions directly reflects the objectives set forth in environmental treaties, underscoring the need for technological innovation and adaptation within the refrigeration sector. This study investigates the technical and economic feasibility of incorporating sustainable technologies into refrigeration systems, with a focus on reducing CO₂ emissions and energy consumption. Given the increasing regulatory pressure and international commitments to decarbonization, analyzing strategies to enhance the sustainability of these systems has become essential. To this end, a comparative assessment of four alternatives for implementing an integrated system in a refrigerated storage facility located in Tarrafal, Santiago, Cape Verde, is presented. The analysis of the proposed solutions aims to identify the most effective approach to aligning thermodynamic performance with environmental responsibility, while meeting the requirements established by global climate agreements.

2 Sustainable Solutions Using Renewables

Renewable energy sources play a crucial role in the transition toward a more sustainable future, particularly in sectors such as refrigeration, which have traditionally relied on conventional energy sources. Wind energy, a clean and widely available source, has emerged as a prominent solution for electricity generation from the force of the wind. Wind turbines are employed to capture the kinetic energy of the wind through blades, which, when driven by drag and lift forces, transfer the generated motion to a rotor connected to a generator via a gearbox, thereby converting mechanical energy into electrical energy [2]. The electricity produced can either be fed directly into the electrical grid or stored in batteries for future use, offering a flexible solution for various applications. In the refrigeration sector, wind energy systems are commonly utilized due to their ability to provide a reliable and renewable

energy supply. Recent studies, such as that by Vaughan et al. [3], have investigated the feasibility of integrating wind energy into refrigeration systems, specifically for powering refrigeration units in apple storage. The results demonstrated significant improvements in system reliability and a notable reduction in environmental impact. Similarly, Roselli et al. [4] conducted a study on the use of wind energy systems for heating, cooling, and supplying electricity to office buildings in two Italian cities, highlighting the effective integration of wind energy into climate control systems as a viable solution to meet global environmental goals and international guidelines. In addition to wind energy, the integration of photovoltaic solar energy into refrigeration systems represents a substantial advancement, enabling the reduction of reliance on conventional electrical grids. Hameed et al. [5] demonstrated the viability of solar energy for refrigeration in Baghdad, showcasing its effectiveness in enhancing energy efficiency and reducing operational costs. Furthermore, Yvon et al. [6] highlighted the successful integration of solar energy with vapor compression refrigeration systems, optimizing the performance of these systems in terms of energy consumption. The photovoltaic systems employed for such purposes typically consist of solar panels that generate electricity, solar inverters that convert direct current (DC) to alternating current (AC), and energy storage solutions such as solar batteries. The efficiency of these systems is contingent upon the performance of each individual component, making it crucial to ensure the optimization of all elements involved to achieve optimal performance. Another promising resource is tidal energy, which captures the kinetic energy of ocean currents. Similar to wind energy systems, turbines are used to convert tidal energy into electricity. Research conducted by Fandi et al. [7] explored the feasibility of this technology, although its application within the refrigeration sector still requires further development to reach a commercially viable stage.

3 CO₂ as Refrigerant

In this study, all the refrigeration systems examined operate based on the vapor compression principle, utilizing the inverted Rankine cycle. Amid growing environmental concerns and the impetus from international agreements aimed at reducing the impact of harmful substances, carbon dioxide (CO₂) has emerged as a more sustainable and environmentally responsible alternative. CO₂ is increasingly being considered as a substitute for traditional refrigerants, such as R134a, which have been widely used in refrigeration systems. The case study presented in this work emphasizes this transition to CO₂, as it offers a lower global warming potential and aligns with efforts to mitigate climate change [8]. Natural refrigerants, including CO₂, are gaining prominence as long-term, sustainable solutions due to their non-flammable and non-toxic properties, making them particularly suitable for vapor compression cycles. A notable advantage of CO₂ is its natural abundance, ensuring a consistent and reliable supply. Furthermore, its minimal contribution to the greenhouse effect, in contrast to conventional refrigerants, positions CO₂ as an environmentally responsible alternative [9]. These attributes make CO₂ a prime candidate for

Table 1 Cooling capacity derived from thermal load analysis

Thermal load	FC (Freezer chamber)	RC (Refrigerated chamber)	B (Buffer)
Conduction (W)	1230	470	2080
Product (W)	4020	770	4130
Internal (W)	470	440	820
Infiltrations (W)	1610	190	1030
Cooling Effect (W)	12,100	3100	13,300

An examination of the values presented in Table 1 reveals that the thermal loads fall within the expected range for refrigerated environments, as outlined in existing literature [10, 11]. This suggests that the thermal loads align with anticipated values, ensuring the proper dimensioning of the refrigeration system for each specific area.

5 Analyzed Solutions

Assessing the heat loads in each refrigerated compartment is crucial for accurately dimensioning the refrigeration system across different proposed solutions for comparison. This evaluation guarantees that optimal temperature and storage conditions are upheld throughout all sections, thereby enhancing the system’s overall energy performance. Mathematical formulations play a key role in quantifying the thermal loads associated with refrigeration units in cooled environments, enabling a thorough examination of cooling demands. This assessment considers variables such as material thermal conductivity and variations in temperature.

Four distinct refrigeration system configurations were examined. In the initial solution, a refrigeration arrangement comprising two independent units, both utilizing R134a as the refrigerant, was assessed. One unit is designated for storing frozen items, while the other is allocated for chilled products. The energy required to operate the refrigeration facility is drawn from the public electricity grid (see Fig. 2).

In Solution 2, the electricity necessary to power the refrigeration storage facility is obtained from the public energy network. This setup features a transcritical booster cooling system that employs CO₂ as the working fluid (see Fig. 3).

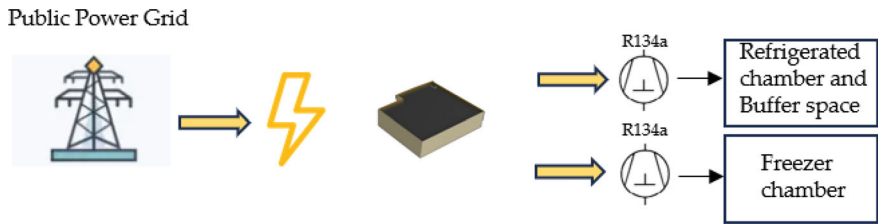


Fig. 2 Scheme for solution 1

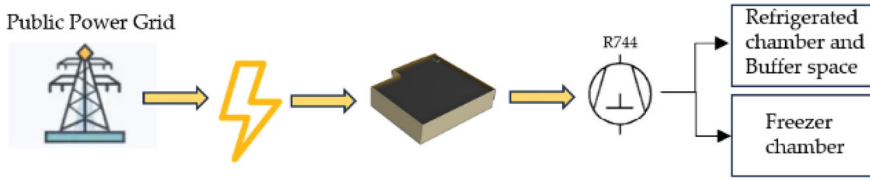


Fig. 3 Scheme for solution 2

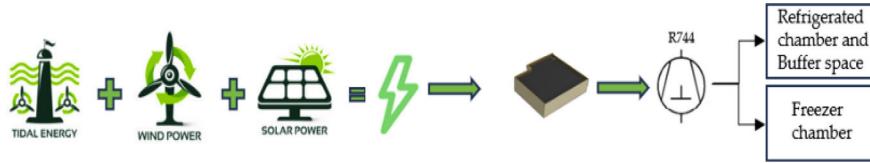


Fig. 4 Scheme for solution 3

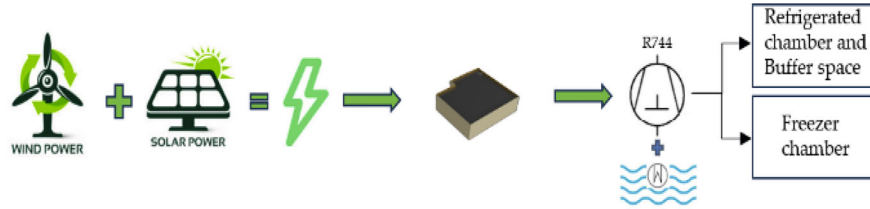


Fig. 5 Scheme for solution 4

In Solution 3, a transcritical booster cooling system using CO_2 as the refrigerant was evaluated. To supply the required electrical power for the refrigeration storage facility, renewable energy sources, including wind power, photovoltaic solar energy, and tidal energy, are utilized (Fig. 4).

In Solution 4, a subcritical booster refrigeration system utilizing CO_2 as the refrigerant was examined. It was established that cooling is accomplished by transferring heat through a heat exchanger with seawater located near the refrigeration facility. This solution also employs renewable energy sources, such as wind power and solar photovoltaic energy, to produce the necessary electrical power for the operation of the refrigeration warehouse (see Fig. 5).

6 Results

Table 2 displays the findings of the analysis on the coefficient of performance (COP) across the four proposed installation types.

Table 2 Comparison of cooling system configurations

Solutions study	Cooling power (kW)	Heat recover (kW)	Efficiency COP	Electrical demand of the system (kWe)	Annual energy usage (kWh)
Solution 1	28.480	0	1.99	54,264.000	475,352.000
Solution 2	28.480	10.320	1.30	69,952.000	613,200.000
Solution 3	28.480	10.320	1.30	69,952.000	613,200.000
Solution 4	28.480	10.320	3.02	50,801.000	445,016.000

The examination of the table shows that Solution 4 achieves the highest coefficient of performance (COP) at 3.02, reflecting better efficiency in converting electrical energy into refrigeration. It also stands out for having the lowest total electrical power demand, indicating a more effective and eco-friendly approach. On the other hand, Solution 1 demonstrates a considerably lower COP due to the lack of heat recovery. Solutions 2 and 3 also show reduced efficiency. These results are consistent with prior research, such as the studies by Sengupta et al. [12]. These findings underscore the significance of energy efficiency, especially through strategies like heat recovery. In conclusion, Solution 4 is considered the most effective, offering improved energy efficiency and lower electricity consumption for the same cooling capacity.

Table 3 presents the results concerning the financial feasibility of the four solutions over a 10-year period, factoring in initial investment, yearly energy expenses, generated savings, and the effect of inflation. The initial investment includes the total cost of the refrigeration infrastructure, along with the autonomous energy generation system. Yearly savings stem from the use of the autonomous energy generation systems, eliminating the need to purchase electricity from the public grid.

The financial feasibility of investments in Solutions 3 and 4 is superior, thanks to the integration of independent renewable energy generation systems. Although the upfront costs are considerable, with Solution 3 requiring -€769,172.00 and Solution 4 needing -€715,000.00, both solutions achieve positive cumulative balances after a decade, amounting to €1,500,000.00 and €935,000.00, respectively. Solution 3 is particularly notable for its quicker return on investment, recovering the initial expenditure in just 4 years, largely due to substantial annual energy savings. In contrast, Solution 4 has a 5-year payback period but offers a more stable initial

Table 3 Resume for financial viability

Solutions study	Initial capital Outlay (€)	10-Year energy savings (€)	Cumulative balance (€) after 10 years	ReturnPeriod (years)
Solution 1	-€ 45, 000.00	-€1,760,000.00	-€ 1,621,000.00	∞
Solution 2	-€ 64, 600.00	-€ 2, 270,000.00	-€ 2, 330,000.00	∞
Solution 3	-€ 769, 172.00	€ 2,270,000.00	€ 1, 500,000.00	4
Solution 4	-€ 715, 000.00	€ 1,650,000.00	€ 935, 000.00	5

investment. On the other hand, Solutions 1 and 2 show negative cumulative balances, as they depend entirely on electricity from the public grid, resulting in negative cash flows over time, with balances of -€1,760,000.00 and -€2,270,000.00, respectively. These solutions also have an infinite payback period due to the absence of energy savings.

Table 4 shows the outcomes of the comparative evaluation of CO₂ emissions from the power supply systems that provide energy to the refrigeration units across the four solutions studied. It compares the CO₂ emissions produced by the various solutions, considering whether the electricity comes from renewable energy sources or the public power grid. The CO₂ emission values were computed and totaled for each energy source, determining the overall emissions for each solution by summing the contributions from all sources. Data from Cabo Verde's public power grid, along with information on wind power systems, solar photovoltaic energy systems, and tidal turbines, were employed for these calculations [13–15].

Upon reviewing the data in Table 4, it becomes apparent that Solution 2, which depends solely on electricity from the public grid, results in significant CO₂ emissions, totaling 382,246.31 kgCO₂ eq. In contrast, Solution 3, which incorporates an independent energy generation system using wind, solar, and tidal sources, leads to a notable reduction in emissions, amounting to 21,549.32 kg CO₂ eq. Furthermore, in Solution 4, emissions are further reduced to 15,882.00 kgCO₂ eq, a level similar to that observed in Solution 3. When analyzing the total CO₂ emissions for each solution, it is clear that Solutions 3 and 4, which feature independent energy generation systems, are the most environmentally friendly, offering a significant reduction in emissions compared to those depending on the public grid (Solutions 1 and 2). The use of an autonomous energy generation system results in a 90% decrease in CO₂ emissions compared to relying on grid electricity. This analysis emphasizes the importance of investing in renewable energy sources, such as wind and solar power, to cut CO₂ emissions, promote more ambitious environmental goals, and reduce dependence on fossil fuels.

Table 4 CO₂ Emissions across the various analyzed solutions

Solutions study	CO ₂ emissions from grid power (kg CO ₂ eq./kWh)	CO ₂ emissions from wind energy (kg CO ₂ eq./kWh)	CO ₂ emissions from solar power (kg CO ₂ eq./kWh)	CO ₂ emissions from tidal energy (kg CO ₂ eq./kWh)	Total CO ₂ emissions (kg CO ₂ eq.)
Solutions 1	0.623	–	–	–	296,316.940
Solutions 2	0.623	–	–	–	382,246.310
Solutions 3	–	0.034	0.050	0.034	21,549.320
Solutions 4	–	0.034	0.050	–	15,882.00

7 Conclusions

The current study demonstrates that a subcritical booster refrigeration system using CO₂ as a refrigerant (Solution 4) represents the most advantageous option when compared to the other alternatives. This conclusion is based on its favorable attributes, including a lower initial investment, shorter payback period, high coefficient of performance, and substantial reduction in CO₂ emissions, particularly in comparison to Solution 2. The findings related to Solution 1 were less promising due to its reliance on R134a, a refrigerant with a high global warming potential, coupled with an infinite payback period and high CO₂ emissions. Solutions 2 and 3 exhibited both financial and environmental pros and cons. While Solution 3 proved more financially viable, Solution 4 emerged as the most comprehensive and optimal choice across all evaluated parameters. The financial analysis further supports the viability of Solution 3, despite its higher initial cost. Additionally, the significant reduction in CO₂ emissions underscores the advantages of autonomous renewable energy generation systems. In conclusion, the integration of sustainable practices, including the adoption of renewable energy systems such as solar, wind, and tidal energy, is essential for progressing towards environmental sustainability. This approach aligns with international environmental agreements such as the Kyoto Protocol, the Paris Agreement, and the Montreal Protocol. These global accords emphasize the need for substantial reductions in greenhouse gas emissions and the transition to clean, renewable energy sources to mitigate climate change, promote global environmental health, and achieve long-term socio-economic development. Based on these findings, it is recommended that strategies be implemented to promote and disseminate the conclusions of this study to government authorities and business organizations. To this end, it is suggested that technical presentations and workshops be conducted for policymakers, energy sector associations, and industry representatives, with the objective of raising awareness of the benefits associated with the adoption of sustainable technologies.

References

1. Garcia, J., Rosa, A.: Theoretical study of an intermittent water-ammonia absorption solar system for small power ice production. *Sustainability* **11**(12), 3346. <https://doi.org/10.3390/su11123346>
2. Sathyajith, M.: Wind energy fundamentals. In: *Resource Analysis and Economics*. Kerala (2006)
3. Vaughan, D.H., Moses, H.L., Blanton, J.C., Baldwin, J.D.: Design of wind-powered cold storage facility design of wind-powered cold storage facility (1978). <https://scholarsmine.mst.edu/cgi/viewcontent.cgi?article=1350&context=umr-mec>
4. Roselli, C., Sasso, M., Tariello, F.: A wind electric-driven combined heating, cooling, and electricity system for an office building in two Italian cities y. *Energies (Basel)* **13**(4). <https://doi.org/10.3390/en13040895>
5. Hameed, V.M., Hussein, M.A.: Studying the performance of refrigeration units powered by solar panel. *Iraqi J. Chem. Pet. Eng.* **14**(1), 39–46 (2013). www.iasj.net

6. Yvon, R., Kameni Nematchoua, M., Chrysostome, R.: Performance modelling of an electric vapor compression solar refrigeration system (SE-VCR) case for Madagascar. *Int. J. Front. Life Sci. Res.* **1**(2), 028–051. <https://doi.org/10.53294/ijflsr.2021.1.2.0057>
7. Fandi, O.M., Dol, S.S., Alavi, M.: Review of renewable energy applications and feasibility of tidal energy in the United Arab Emirates **3**(2), 165–174 (2022). <https://doi.org/10.22044/rera.2022.11747.1107>.
8. Maouris, G., Sarabia Escriba, E.J., Acha, S., Shah, N., Markides, C.N.: CO₂ refrigeration system heat recovery and thermal storage modelling for space heating provision in supermarkets: an integrated approach. *Appl. Energy*. **264** (2020). <https://doi.org/10.1016/j.apenergy.2020.114722>.
9. Sarabia Escriba, E.J et al.: Modelling of a real CO₂ booster installation and evaluation of control strategies for heat recovery applications in supermarkets. *Int. J. Refrig* **107**, 288–300 (2019). <https://doi.org/10.1016/j.ijrefrig.2019.08.005>.
10. Benardos, A., Brachos, G.: Thermal loads analysis of an underground cold storage facility in Attica (2007). <https://www.researchgate.net/publication/290746456>
11. Garcia, J., Semedo, A.: Sustainable CO₂ refrigeration system for fish cold storage facility using a renewable integrated system with solar, wind and tidal energy for Cape Verde—Analyzing Scenarios. *Sustainability* **16**(10), 4259 (2024). <https://doi.org/10.3390/su16104259>
12. Sengupta, A., Gullo, P., Dasgupta, M.S., Khorshidi, V.: Performance analysis of an R744 supermarket refrigeration system integrated with an organic Rankine cycle. *Energies (Basel)* **16**(22). <https://doi.org/10.3390/en16227478>
13. Electra.: Financial statements 2022. Mindelo (2023). <https://www.bcv.cv/pt/Supervisao/Mercado%20de%20Capitais/Sistema/Emitentes/Presta%C3%A7%C3%A3o%20de%20Contas/Paginas/RCELECTRA.aspx>. Accessed 01 Nov 2023
14. Nugent, D., Sovacool, B.K.: Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: a critical meta-survey. *Energy Policy* **65**, 229–244 (2014). <https://doi.org/10.1016/j.enpol.2013.10.048>
15. Coutinho, G.L., Vianna, J.N.: 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* **4**, e45077 (2020). <https://doi.org/10.18225/lalca.v4i0.5077>.