# Techno-Economic Comparison of Renewable Energy-Driven Cooling Systems for Food Preservation in a Nigerian Farm

**Ammar MOUAKY***
*Green Energy Park, Benguerir, Morocco*
**Corresponding author, mouaky@greenenergypark.ma*

**Abstract.** *Food preservation is a critical challenge, particularly in developing countries. Among the available solutions, active cooling stands out as it maintains food quality without altering its flavor or texture. However, the widespread adoption of such technologies for food preservation, especially in developing regions, requires overcoming key challenges, including energy availability and cost. In response, researchers are increasingly investigating renewable energy-driven cooling systems, leveraging abundant resources like solar energy in these regions. In this context, this study compares the techno-economic performance of different variants of vapor compression cycle and absorption refrigeration technologies, designed to be integrated with a renewable energy system to meet cooling needs of a farm in Nigeria. The evaluation was based on two key indicators: technical performance, measured by the coefficient of performance, and economic performance, assessed using the levelized cost of cooling. The results showed that advanced cycles provided notable improvements over standard configurations from both technical and economic perspectives. Additionally, refrigerants with low global warming potential exhibited competitive performance compared to the reference refrigerant, R134a. Vapor compression cycle variants outperformed absorption refrigeration systems in both efficiency and economic viability. Furthermore, operating the cooling systems under variable conditions significantly reduced annual energy consumption compared to fixed operation.*

**Keywords**: Food preservation, Vapor compression cycle, Absorption refrigeration, Coefficient of performance, Levelized cost of cooling.

## Introduction

Feeding the world's growing population is a critical challenge that requires addressing food loss and waste (FLW), among other issues. In developing countries, food losses occur primarily before consumption due to financial, technical, and infrastructural constraints (Gustavsson et al., 2011). In addition, tackling this issue will enhance the sustainability of food systems (Dinu et al., 2020), thereby reducing the environmental impacts associated with this sector (Cepoi et al., 2020; Pătărlăgeanu et al., 2024).

There are numerous methods of food preservation, each tailored to specific types of food and desired outcomes. Among the existing alternatives, active refrigeration ensures precise temperature regulation, guaranteeing optimal food preservation without altering its flavor or texture (Aste et al., 2017).

Yet, optimizing the cost of active cooling technologies is essential to promote their adoption for food preservation in developing countries. The REPTES project, funded under the LEAP-RE program, aims to develop optimal renewable energy configurations to meet the energy and agricultural needs of African communities. Among the investigated case studies, one in Nigeria focuses on addressing the cooling needs for food preservation in a farm.

This study aims to answer the following question: Which cooling system configuration offers the most cost-effective and energy-efficient solution for food preservation in the context of

DOI: 10.2478/picbe-2025-0051

the considered farm? To address this question, various system configurations and operational strategies are evaluated.

We hypothesize that vapor compression cycle (VCC)-based systems will exhibit superior energy efficiency and lower levelized cost of cooling (LCOC) due to their higher coefficient of performance (COP). However, absorption refrigeration could become a viable alternative if a low-cost heat source is available. Additionally, we expect that adopting a variable operating strategy will further enhance the economic viability of refrigeration systems compared to fixed operating conditions.



With this aim, the COP of the variants considered were first compared under design conditions. Then, two operational scenarios were evaluated on an annual basis: the first scenario assumes fixed operating conditions based on design parameters, while the second one allows the system to operate under variable conditions adjusted to ambient temperature fluctuations. The variants were subsequently compared in terms of the LCOC. Finally, parametric studies were conducted to assess the impact of energy costs and determine the threshold values of the control system investment cost at which adopting variable operating conditions becomes economically viable.

## Literature review

Promoting the use of active cooling systems, particularly in low-income countries, requires addressing multiple challenges, including energy supply constraints. In this context, there is a growing interest in leveraging renewable energy sources, particularly solar energy, to power such systems due to its abundance in developing countries (Amjad et al., 2023)

Among the available cooling technologies, VCC is the most widely used option when coupled with a renewable electricity generation system. The basic cycle consists of four components: a compressor, a condenser, an expansion valve, and an evaporator. The cooling effect is achieved during the evaporation process, where the refrigerant absorbs heat from the refrigerated space before releasing it to the environment through the condenser (Cengel et al., 2020)

However, a critical concern associated with VCC systems is the environmental impact of the used refrigerants, particularly their global warming potential (GWP). With increasing regulatory pressures driven by climate change concerns, the transition toward more environmentally friendly alternatives has become imperative. As a result, research efforts have focused on identifying low-GWP refrigerants that maintain similar performance levels while minimizing environmental impact (McLinden et al., 2020).

Absorption refrigeration systems on the other hand present an alternative to VCC technology, especially when a low-cost heat source is available. Their configurations closely mirror VCC ones, except for considering a more complex setup involving chemical reactions instead of the compressor used in VCC. These systems operate by utilizing a refrigerant-absorbent pair. The most commonly used working pairs include ammonia/water and water/lithium bromide. The former is suitable for applications requiring lower temperatures, while the latter is widely used for cooling applications where temperatures remain above the freezing point of water (Sun, 2011).

To ensure the competitiveness of sustainable cooling solutions, researchers are increasingly focusing on comparative analyses of systems that incorporate both VCC and absorption refrigeration technologies (Mortadi & El Fadar, 2022).

In this context, this study contributes to ongoing research by providing a comparative assessment of VCC and absorption refrigeration systems powered by a renewable energy system for food preservation in a farm setting, considering both technical and economic aspects.

Specifically, it aims to enhance the existing literature by offering a detailed comparative analysis of the economic viability of VCC and absorption refrigeration systems under different operational strategies. Additionally, it examines various configurations for both technologies, including the integration of low-GWP refrigerants in VCC variants.



## Methodology

The cooling loads for the investigated case study include a continuous cooling capacity of 10.8 kW for cold rooms maintained between 0 to 4°C and a cooling capacity of 3.2 kW for a refrigerator operating between 4 to 5°C.

This study aims to compare different VCC and absorption refrigeration system variants from both technical and economic perspectives.

For the VCC variants, the analysis focuses on three aspects as depicted in Figure 1. First, the configuration of the compression cycle, distinguishing between single-stage and two-stage cycles. Two-stage cycles include intercooling and flash variants (Gardner, 2022). Second, the cooling cycle configuration, evaluating whether separate cycles are used for the cold room and refrigerator or if a single cycle satisfies both loads. Third, the type of refrigerant fluid, with R134a as the reference fluid, and five low-GWP alternatives: R1234ze(E), R1234yf, R513a, R513b, and R450a.

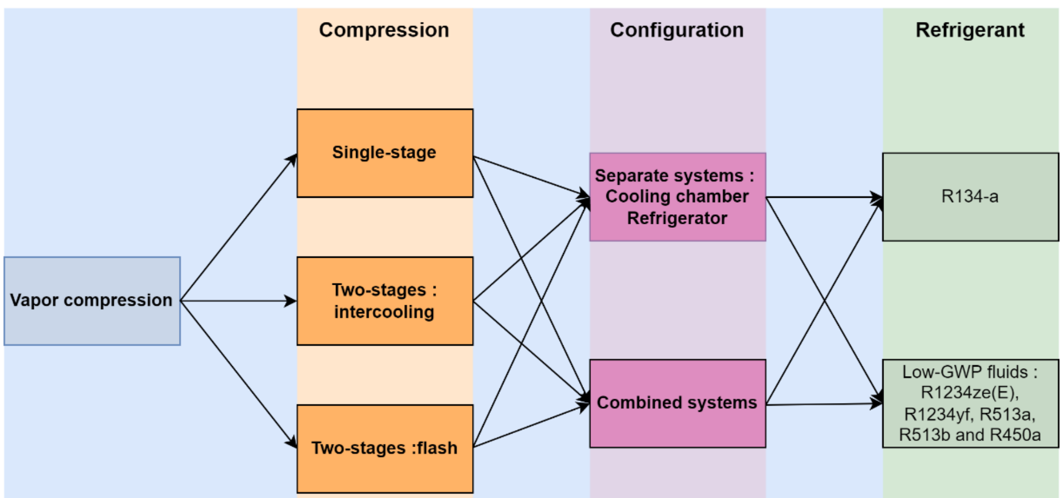


**Figure 1. Investigated VCC variants**

Source: Authors' own research contribution.

For the absorption refrigeration variants, the study investigates two main aspects as illustrated in Figure 2. First, the single-stage cycle variants, including a simple cycle, a cycle with a condensate precooler, and a cycle incorporating both a condensate precooler and rectifier heat integration (Herold et al., 2016). Second, the cooling cycle configuration, analyzing both separate and combined cycle options to meet the cooling demands of the two case studies. Regarding, the working pair, only $NH_3$ /$H_2O$ was considered

DOI: 10.2478/picbe-2025-0051, pp. 636-655, ISSN 2558-9652 |
Proceedings of the 19th International Conference on Business Excellence 2025

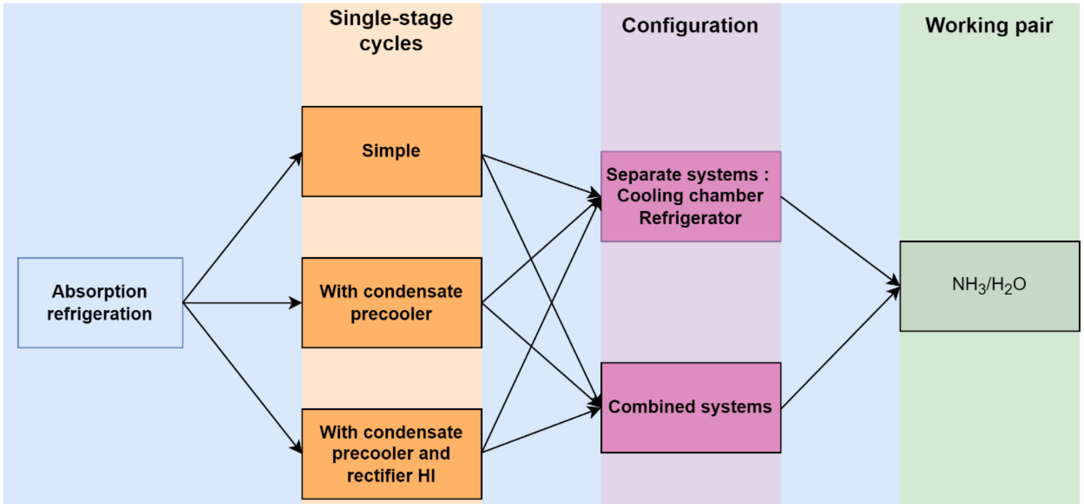


**Figure 2. Investigated absorption refrigeration variants**

Source: Authors' own research contribution.

The variants for both VCC and absorption refrigeration systems were modeled in Ebsilon® Professional, a software used for the simulation and validation of thermodynamic processes. The developed models enabled, first, the assessment of the technical performance of the variants under design conditions assuming as ambient temperature the maximum hourly temperature at the study site. Then, they were used to evaluate their annual performance, taking into account variable ambient temperature conditions. The results from the annual simulations were finally used as inputs for the economic assessment.

Tables 1 and 2 summarize the main assumptions considered during the simulation of the VCC and absorption refrigeration variants respectively.

**Table 1. Assumptions considered for the VCC variants simulations**

| Parameter | Value |
|---|---|
| Compressors' isentropic efficiency | 75% |
| Electric motors efficiency | 90% |
| Evaporation saturation temperature | 30°F below the cooling air setpoint temperature |
| Condensation pressure | 15°F above outdoor air temperature |

Source: (Gardner, 2022)

**Table 2. Assumptions considered for the absorption refrigeration variants simulations**

| Parameter | Value |
|---|---|
| Pump isentropic efficiency | 75% |
| Electric motors efficiency | 90% |
| Solution heat exchanger and condenser precooler efficiencies | 80% |
| Target refrigerant content in vapor outlet | 99.96% |
| Ammonia mass fraction at the outlet of the evaporator | 97.5% |
| Ammonia mass fraction difference between the desorber inlet and the absorber inlet | 10% |
| Temperature difference between the mixture at the inlet of the evaporator and the cooled air | 16.6 K |
| Absorber outlet temperature | 5°C above ambient temperature |
| High pressure of the cycle | 5°C above the boiling temperature at the ambient temperature |

Source: (Gardner, 2022; Herold et al., 2016)

The coefficient of performance is a widely used metric for evaluating the performance of cooling systems. It is defined as the ratio of the cooling effect delivered to the refrigerated space to the net work input required by the refrigeration cycle.

For the VCC variants, the cooling effect corresponds to the cooling capacity provided by the evaporator, while the work input includes the power consumption of the compressor(s) and the system's fans:

$$COP_{VCC} = \frac{Q_{evap}}{W_{net,in}}$$

Regarding the absorption refrigeration variant, the work input is primarily determined by the heat supplied to the generator:

$$COP_{abs} = \frac{Q_{evap}}{Q_{gen}}$$

For the economic evaluation, the levelized cost of cooling (€/kWh) is used as an indicator to estimate the cost of cooling.

In the case of VCC systems, LCOC is calculated as a function of the system CAPEX (€), OPEX (€), annual electricity consumption $C_{Elec}$ (kWh), annual cooling production $En_C$ (kWh) and capital recovery factor $crf$ (Leiva-Illanes et al., 2018) :

$$LCOC_{VCC} = \frac{CAPEX \cdot crf + OPEX + C_{Elec}}{En_C}$$

Where the capital recovery factor is calculated as function of the discount rate $(i)$ and the number of annuities $(n)$ using the following formula:

$$crf = \frac{i \cdot (1+i)^n}{(1+i)^n - 1}$$

The LCOC of the absorption refrigeration systems includes, in addition to the aforementioned parameters for the VCC, the annual heat consumption $C_{Heat}$ (kWh):

$$LCOC_{ABS} = \frac{CAPEX \cdot crf + OPEX + C_{Elec} + C_{Heat}}{En_C}$$

For the CAPEX calculation, the correlations presented in Tables 3 and 4 were used for the VCC and absorption refrigeration variants, respectively.

**Table 3. Assumptions considered for the VCC CAPEX estimation (costs in £, 1£ = 1.2 €)**

| Component | Cost correlation | Dependent variable |
|---|---|---|
| Condenser | $288 + 316 \cdot A_{cond}$ | $A_{cond}$ : Heat exchange area (m²) |
| Evaporator | $288 + 217 \cdot A_{evap}$ | $A_{evap}$ : Heat exchange area (m²) |
| Compressor | $162\,000 \cdot V_{comp,in}{}^{0.839}$ | $V_{comp,in}$ : Inlet volumetric flowrate (m3/s) |
| Fan | $578 \cdot A_{fan}$ | $A_{fan}$ : Frontal area (m²) |
| Expansion valve | 135 | - |
| Miscellaneous | 20% of the total cost | - |

Source:(Olympios et al., 2024).

**Table 4. Assumptions considered for the absorption refrigeration CAPEX estimation**

| Component | Cost correlation | Dependent variable |
| --- | --- | --- |
| Condenser | $8000 \cdot \left(\frac{A_{cond}}{100}\right)^{0.6} \cdot \left(\frac{CEPCI_{2022}}{CEPCI_{2000}}\right)$ (in \$, 1\$ =0.97 €) | $A_{cond}$ : Heat exchange area ($m^2$) |
| Evaporator | $16000 \cdot \left(\frac{A_{evap}}{100}\right)^{0.6} \cdot \left(\frac{CEPCI_{2022}}{CEPCI_{2000}}\right)$ (in \$) | $A_{evap}$ : Heat exchange area ($m^2$) |
| Absorber | $16500 \cdot \left(\frac{A_{abs}}{100}\right)^{0.6} \cdot \left(\frac{CEPCI_{2022}}{CEPCI_{2000}}\right)$ (in \$) | $A_{abs}$ : Heat exchange area ($m^2$) |
| Regenerator | $12000 \cdot \left(\frac{A_{reg}}{100}\right)^{0.6} \cdot \left(\frac{CEPCI_{2022}}{CEPCI_{2000}}\right)$ (in \$) | $A_{reg}$ : Heat exchange area ($m^2$) |
| Generator | $17500 \cdot \left(\frac{A_{gen}}{100}\right)^{0.6} \cdot \left(\frac{CEPCI_{2022}}{CEPCI_{2000}}\right)$ (in \$) | $A_{gen}$ : Heat exchange area ($m^2$) |
| Fan | $578 \cdot A_{fan}$ (in £, 1£ = 1.2 €) | $A_{fan}$ : Frontal area ($m^2$) |
| Pump | $578 \cdot \dot{W}_{pump}^{0.46}$ (in £) | $\dot{W}_{pump}$ : Work required (kW) |
| Miscellaneous | 20% of the total cost | |

Source :(Altun, 2022 ; Olympios et al., 2024).



Where $CEPCI_{2022}$ and $CEPCI_{2000}$ represent the Chemical Engineering Plant Cost Index values for the years 2022 (797.6) and 2000 (394.1), respectively (Tsogt et al., 2024).

OPEX is assumed to be equivalent to 2% of CAPEX. Additionally, the specific electricity and heat costs are set at 0.12 €/kWh and 0.05 €/kWh, respectively. $crf$ was determined using a discount rate of 0.03 and an annuity period of 20 years.

## Results and discussions

### *Performances in design conditions*

*Vapor compression cycle*

Figure 3 shows the COP values for the various VCC variants previously presented. Focusing on the 10.8 kW separated systems variants, the two-stage configurations notably enhance the COP, showing improvements of 14-20% across the different fluids. The results also vary depending on the refrigerant used, with a maximum relative difference of up to 8%.

R134a, the reference refrigerant, yields the best results for both the single-stage and two-stage intercooling variants. R450a and R1234ze(E) deliver comparable performances, with R450a slightly outperforming in the two-stage flash variant. It is also noteworthy that the flash variants generally show slightly better performance than the intercooling variants. These trends are consistent in the 3.2 kW separated systems, where performances are marginally better due to the different required cooling set-point temperatures.

Similar patterns are observed in the combined variants compared to the separated ones, though the combined systems exhibit lower COP values.

The primary differences between the single-stage and two-stage configurations, stem from two key factors. First, intercooling in two-stage variants reduces the compressor work per unit mass of refrigerant, leading to energy savings. Second, in two-stage configurations, the refrigerant exiting the second expansion valve has a significantly lower quality (i.e., a higher liquid fraction) compared to that in single-stage compression. As a result, in single-stage systems, less liquid is available for evaporation at the same cooling power, which reduces the overall cooling capacity.

Among the two-stage variants, the flash configuration achieves slightly better performance due to a lower mass flow rate circulating in the compressors.

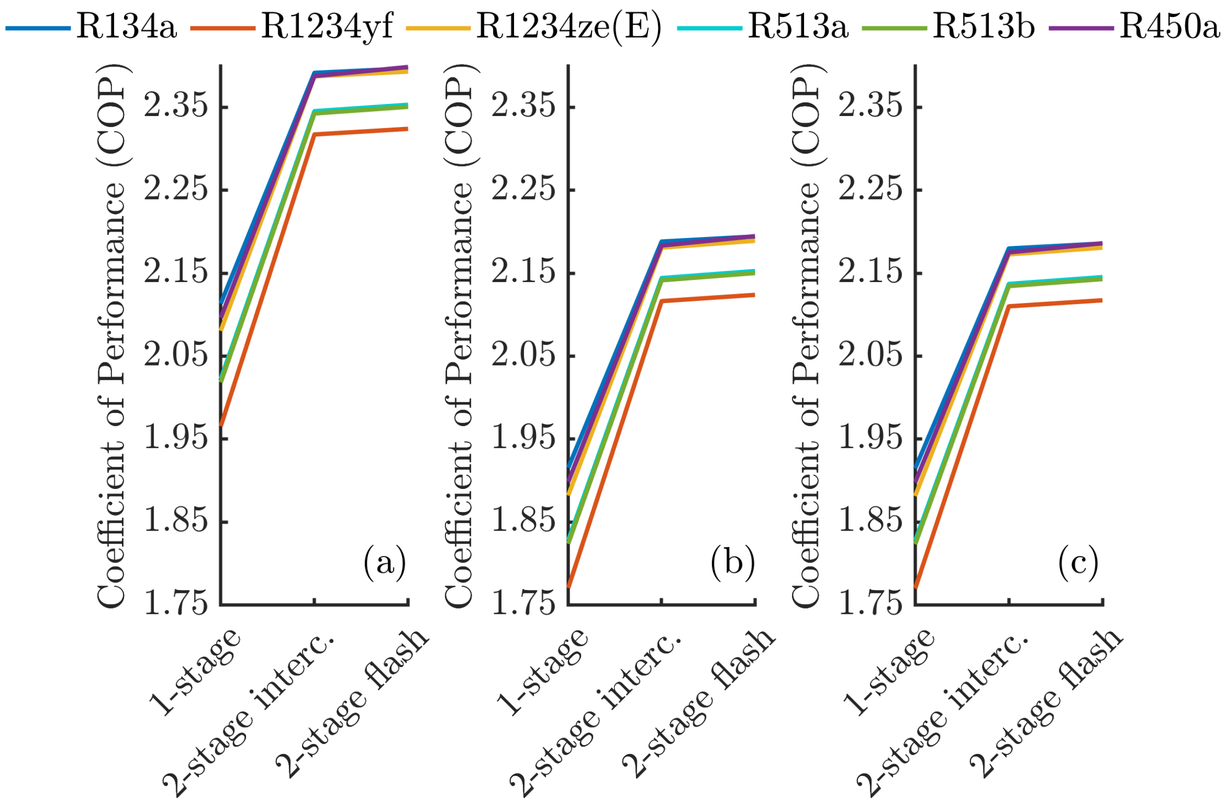


**Figure 3. COP values for the VCC variants investigated to meet the cooling loads (a): Separate system providing 3.2 kW, (b): Separate system providing 10.8 kW, (c): Combined system providing 3.2 kW + 10.8 kW**

Source: Authors' own research results.

*Absorption refrigeration*

Figure 4.a illustrates the variation in COP for the three investigated variants of the absorption refrigeration system providing cooling for the 10.8 kW load. The COP ranges from 0.385 for the simple variant to 0.45 for the variant that includes a condensate precooler and rectifier heat integration. A similar trend is observed in Figure 4.b, which represents the COP variation for the variants providing cooling for the 3.2 kW load, but with slightly different COP values ranging from 0.413 to 0.48. The difference in COP values between the two loads is attributed to the variation in the setpoint temperatures at which cooling is provided, as a decrease in the setpoint temperature leads to a reduction in the COP. Finally, for Figure 4.c, where a single system with two evaporators provides cooling for both loads, the COP values are comparable to those obtained in Figure 4.a.

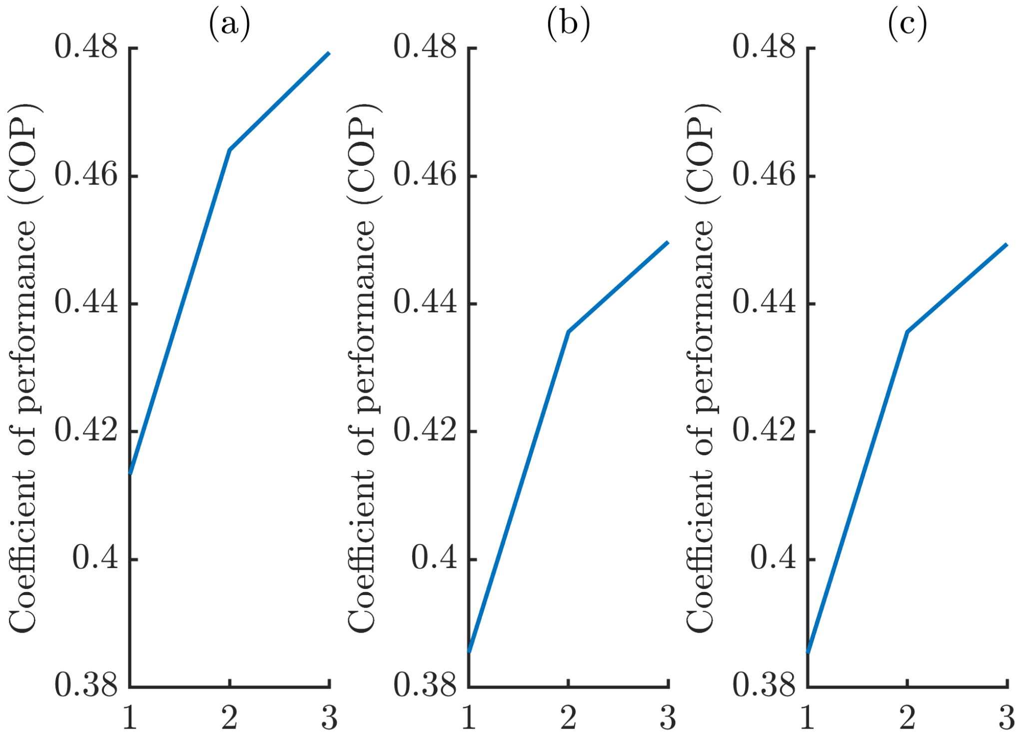




**Figure 4. COP values for the absorption refrigeration investigated variants to meet the cooling loads [1: Simple, 2: Condensate precooler, 3: Condensate precooler and rectifier heat integration] (a): Separate system providing 3.2 kW, (b): Separate system providing 10.8 kW, (c) Combined system providing 3.2 kW + 10.8 kW**

Source: Authors' own research results.

***Annual energy consumption under fixed and variable operating conditions***

The results presented under design conditions correspond to scenarios where the ambient temperature is set to the maximum hourly temperature observed at the study location. However, an alternative operational strategy involves varying the operating conditions based on the ambient temperature, which can lead to reduced energy consumption. To assess the potential energy savings of this strategy, calculations were performed for the various variants on an annual basis, using a one-hour time step.

*Vapor compression cycle*

Figure 5 compares the annual energy consumption for the variants meeting the 10.8 kW cooling demand using simple, two-stage intercooling, and two-stage flash configurations. Each configuration considers scenarios where operational conditions are fixed to those related to the maximum hourly temperature, as well as scenarios where condensation pressure varies based on ambient temperature. A notable observation from the figure is that two-stage variants achieve an energy consumption reduction of 10 to 16.5%, depending on the refrigerant used, compared to single-stage variants. Additionally, within each configuration, there is a clear benefit to adapting operational conditions to ambient temperature, which significantly reduces energy consumption. For the single-stage cycle, this adaptation leads to an energy reduction of approximately 11 to 12%, while for two-stage scenarios, the reduction ranges from 9.3 to 9.8%.

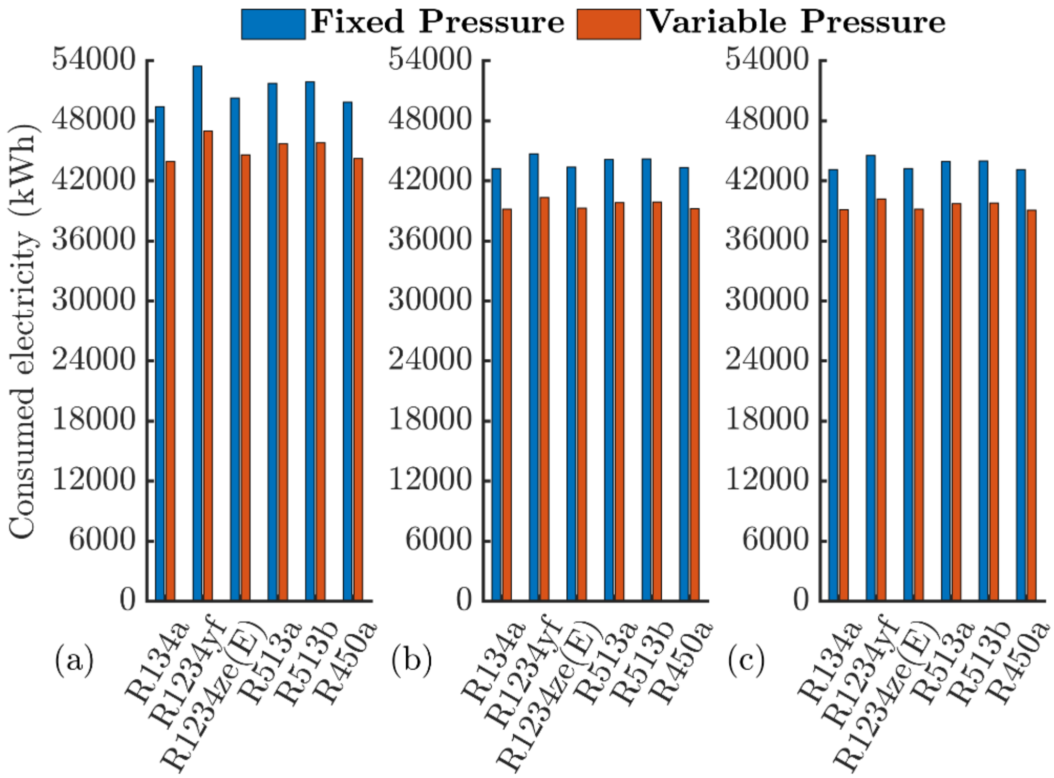


**Figure 5. Annual electricity consumption for 10.8 kW separate production variants: (a) Simple VCC, (b) Two-stage intercooling, (c) Two-stage flash**

Source: Authors' own research results.

Similar observations can be made for the other two cases (Figures 6 and 7). These cases also show comparable percentages of energy reduction through both adapting cycle operational conditions and employing two-stage variants, relative to fixed conditions and single-stage variants. Additionally, a comparison of the combined case against the sum of the two separate cases indicates that the combined variants result in a 2.2 to 2.9% increase in annual energy consumption.

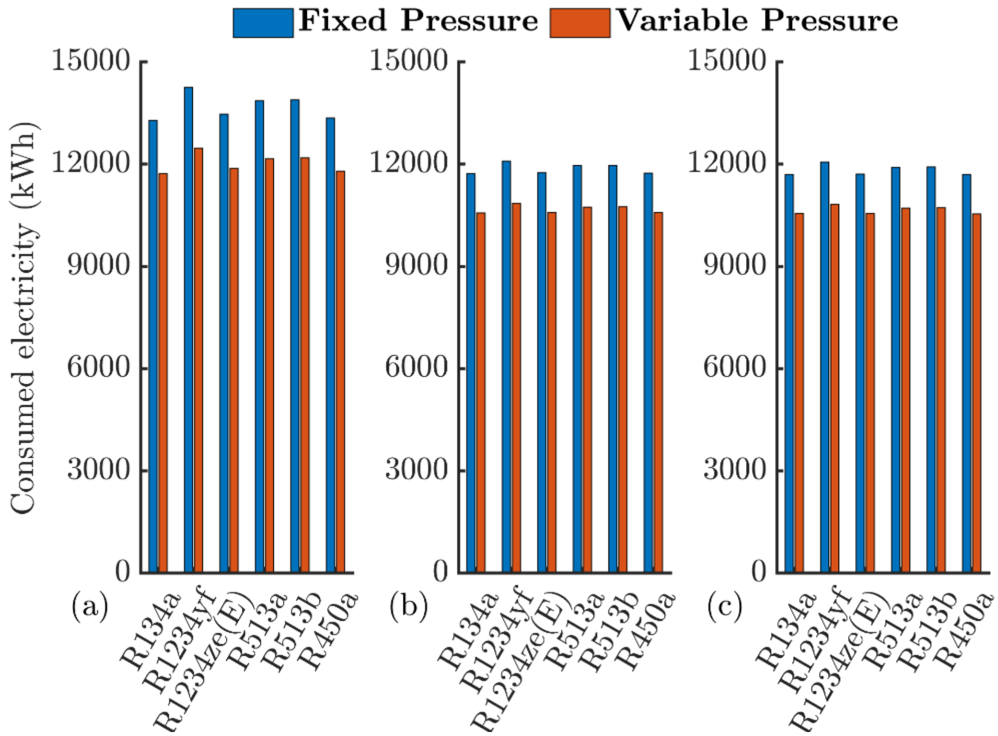


**Figure 6. Annual electricity consumption for 3.2 kW separate production variants: (a) Simple VCC, (b) Two-stage intercooling, (c) Two-stage flash**

Source: Authors' own research results.

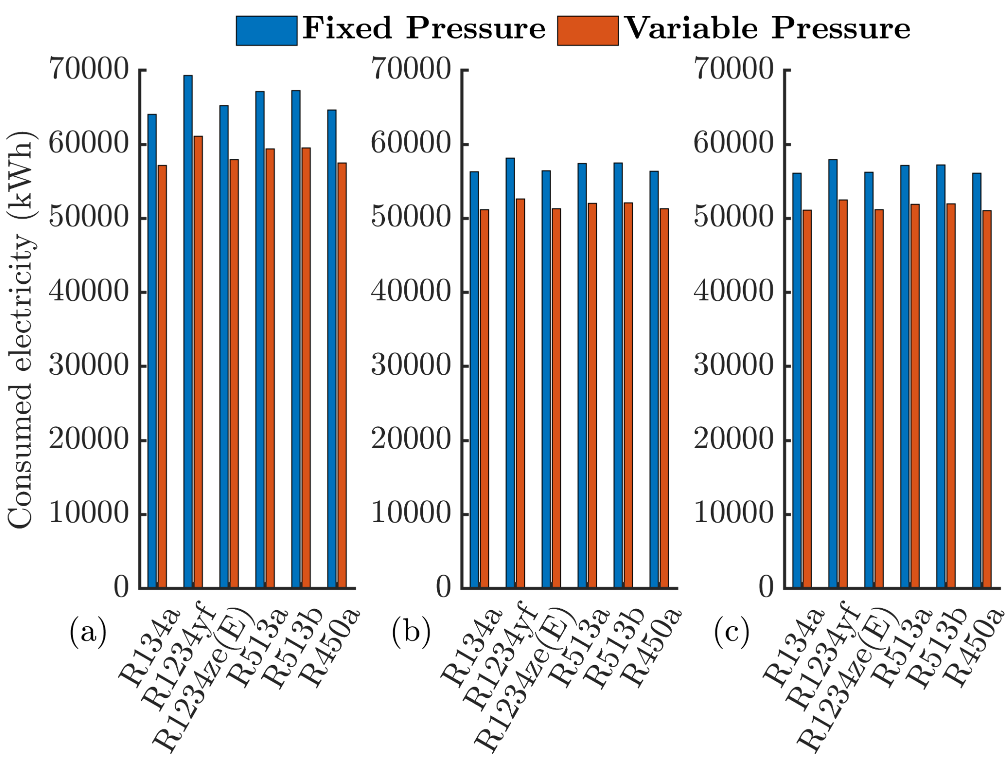


**Figure 7. Annual electricity consumption for combined 3.2 kW + 10. 8 kW combined production variants: (a) Simple VCC, (b) Two-stage intercooling, (c) Two-stage flash**

Source: Authors' own research results.

*Absorption refrigeration*
Figure 8 illustrates the generator annual energy consumption of the investigated variants for the absorption cooling technology.

For the 10.8 kW separate configuration, the annual energy consumption for the fixed simple variant is 245 508 kWh. The inclusion of a condensate precooler and the integration of a condensate precooler with rectifier heat recovery resulted in annual energy reductions of 11.53 and 14.31%, respectively. Conversely, adopting a variable pressure configuration achieved energy savings of 7 to 8.3% annually.



Similar trends and comparable percentage savings were also observed for the 3.2 kW and combined configuration variants.

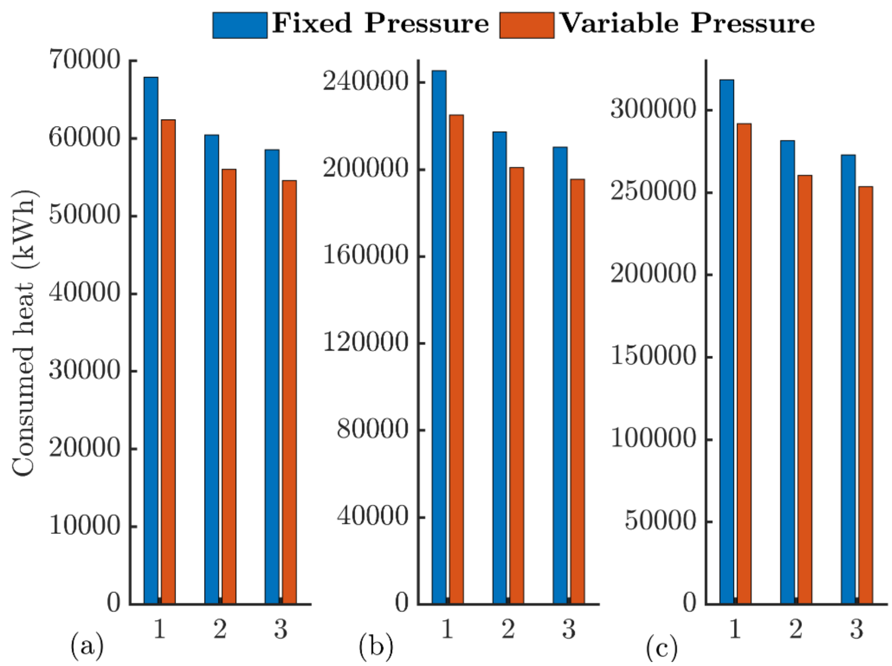


**Figure 8. Annual heat consumption for the investigated absorption refrigeration variants [1: Simple, 2: Condensate precooler, 3: Condensate precooler and rectifier heat integration] (a): Separate system providing 3.2 kW, (b): Separate system providing 10.8 kW, (c) Combined system providing 3.2 kW + 10.8 kW**

Source: Authors' own research results.

***Evaluation of the levelized cost of cooling***

*Vapor compression cycle*
Tables 5-7 present the LCOC estimates for the VCC system variants under fixed operating conditions.

The LCOC for the simple variants ranges between 0.0784 and 0.0878 €/kWh. For the two-stage intercooling variants, it ranges from 0.0727 to 0.0770 €/kWh, while for the two-stage flash variants, it ranges from 0.0726 to 0.0768 €/kWh.

Regarding the refrigerants, the highest LCOC values are associated with R1234yf, ranging from 0.0713 to 0.0878 €/kWh. This is primarily due to the higher power consumption of the variants using this refrigerant compared to the others. In contrast, the lowest LCOC values are observed for variants using R134a and R450a.

**Table 5. LCOC (in €/kWh) of the VCC 3.2 kW variants**

| Refrigerant | Simple | Two-stage intercooling | Two-stage flash |
|---|---|---|---|
| R134a | 0.0784 | 0.0727 | 0.0726 |
| R1234yf | 0.0832 | 0.0745 | 0.0744 |
| R1234ze(E) | 0.0809 | 0.0746 | 0.0744 |
| R513a | 0.0810 | 0.0735 | 0.0733 |
| R513b | 0.0811 | 0.0736 | 0.0734 |
| R450a | 0.0787 | 0.0728 | 0.0726 |

Source: Authors' own research results.

**Table 6. LCOC (in €/kWh) of the VCC 10.8 kW variants**

| Refrigerant | Simple | Two-stage intercooling | Two-stage flash |
|---|---|---|---|
| R134a | 0.0820 | 0.0748 | 0.0746 |
| R1234yf | 0.0877 | 0.0768 | 0.0766 |
| R1234ze(E) | 0.0847 | 0.0767 | 0.0764 |
| R513a | 0.0851 | 0.0758 | 0.0755 |
| R513b | 0.0853 | 0.0758 | 0.0756 |
| R450a | 0.0825 | 0.0749 | 0.0745 |

Source: Authors' own research results.

**Table 7. LCOC (in €/kWh) of the combined 3.2 kW + 10.8 kW VCC variants**

| Refrigerant | Simple | Two-stage intercooling | Two-stage flash |
|---|---|---|---|
| R134a | 0.0821 | 0.0750 | 0.0748 |
| R1234yf | 0.0878 | 0.0770 | 0.0768 |
| R1234ze(E) | 0.0847 | 0.0768 | 0.0766 |
| R513a | 0.0852 | 0.0760 | 0.0757 |
| R513b | 0.0853 | 0.0760 | 0.0758 |
| R450a | 0.0825 | 0.0750 | 0.0748 |

Source: Authors' own research results.

As mentioned earlier, integrating a control system with the VCC to adjust the cycle's operating conditions contributes to reducing electricity consumption. However, this comes with an associated purchase cost. In this context, the threshold values for the control system's purchase cost were determined, ensuring that the resulting LCOC remains equivalent to that of each corresponding fixed VCC variant (see Tables 8-10).

As capacity increases, the ratio of the threshold value to CAPEX rises from 20.24 to 34.76% for the 3.2 kW variants, reaching 28.85 to 50.43% for the combined variants. This indicates that the economic viability of implementing the control system improves with capacity. On the other hand, the results also showed that using the control system is more economically viable in simple variants compared to two-stage configurations.

**Table 8. Control system cost threshold value and its ratio to CAPEX for the VCC 3.2 kW variants**

| Refrigerant | Simple | | Two-stage intercooling | | Two-stage flash | |
|---|---|---|---|---|---|---|
| | Threshold (€) | Ratio (%) | Threshold (€) | Ratio (%) | Threshold (€) | Ratio (%) |
| R134a | 2132.10 | 30.79 | 1597.40 | 22.09 | 1583.43 | 21.91 |
| R1234yf | 2469.70 | 34.76 | 1705.23 | 23.32 | 1694.11 | 23.19 |
| R1234ze(E) | 2193.88 | 29.45 | 1589.85 | 20.34 | 1580.19 | 20.24 |
| R513a | 2340.26 | 33.65 | 1669.23 | 23.23 | 1647.18 | 22.94 |
| R513b | 2346.52 | 33.72 | 1665.56 | 23.17 | 1645.53 | 22.91 |
| R450a | 2149.21 | 31.13 | 1588.51 | 21.93 | 1587.55 | 21.95 |

Source: Authors' own research results.

**Table 9. Control system cost threshold value and its ratio to CAPEX for the VCC 10.8 kW variants**

| Refrigerant | Simple | | Two-stage intercooling | | Two-stage flash | |
|---|---|---|---|---|---|---|
| | Threshold (€) | Ratio (%) | Threshold (€) | Ratio (%) | Threshold (€) | Ratio (%) |
| R134a | 7501.06 | 35.76 | 5584.80 | 25.84 | 5533.26 | 25.63 |
| R1234yf | 8870.24 | 41.02 | 6040.90 | 27.64 | 5993.21 | 27.46 |
| R1234ze(E) | 7776.28 | 34.22 | 5643.33 | 24.06 | 5574.77 | 23.80 |
| R513a | 8296.51 | 39.32 | 5891.50 | 27.45 | 5809.88 | 27.10 |
| R513b | 8329.68 | 39.44 | 5901.88 | 27.48 | 5816.01 | 27.12 |
| R450a | 7670.93 | 36.75 | 5628.44 | 26.08 | 5558.84 | 25.82 |

Source: Authors' own research results.



**Table 10. Control system cost threshold value and its ratio to CAPEX for the combined 3.2 kW + 10.8 kW VCC variants**

| Refrigerant | Simple | | Two-stage intercooling | | Two-stage flash | |
|---|---|---|---|---|---|---|
| | Threshold (€) | Ratio (%) | Threshold (€) | Ratio (%) | Threshold (€) | Ratio (%) |
| R134a | 11936.68 | 43.80 | 8760.49 | 31.23 | 8656.01 | 30.92 |
| R1234yf | 14154.65 | 50.43 | 9452.46 | 33.36 | 9389.45 | 33.17 |
| R1234ze(E) | 12440.95 | 42.29 | 8810.65 | 29.04 | 8737.67 | 28.85 |
| R513a | 13254.98 | 48.35 | 9207.13 | 33.05 | 9087.36 | 32.66 |
| R513b | 13338.90 | 48.62 | 9229.51 | 33.12 | 9122.05 | 32.79 |
| R450a | 12259.01 | 45.27 | 8796.98 | 31.48 | 8700.63 | 31.17 |

Source: Authors' own research results.

*Absorption refrigeration*

The obtained LCOC for the investigated absorption refrigeration variants is presented in Table 11. As observed, the simple variants exhibit the highest costs. Integrating a condensate precooler reduces the LCOC by 9.2 to 10.2%, depending on the capacity. Meanwhile, the combination of a condensate precooler and rectifier heat integration leads to an 11.1 to 12.8% reduction.

Regarding the variation of the LCOC with capacity, the 3.2 kW variants benefit from lower specific energy consumption due to the higher cooling setpoint temperature. However, this advantage is offset by their higher specific capital expenditure. Conversely, the 10.8 kW variants experience the opposite effect. The variants designed to meet the combined case demand benefit from the economies of scale associated with higher capacity, leading to a lower specific capital expenditure while maintaining a specific energy consumption similar to that of the 10.8 kW variants.

**Table 11. LCOC (in €/kWh) of the absorption refrigeration variants**

| Cooling capacity | Simple | Condensate precooler | Condensate precooler and rectifier HI |
|---|---|---|---|
| 3.2 kW | 0.1660 | 0.1508 | 0.1476 |
| 10.8 kW | 0.1665 | 0.1495 | 0.1459 |
| Combined | 0.1661 | 0.1492 | 0.1449 |

Source: Authors' own research results.

Table 12 presents the control system cost threshold for the absorption refrigeration variants. Similar to the VCC variants, the economic viability of adopting a control system improves as capacity increases. Additionally, the use of a control system remains more economically viable for the simple variants compared to the two more advanced configurations.

**Table 12. Control system cost threshold value and its ratio to CAPEX for the absorption refrigeration variants**

| Cooling capacity | Simple | | Condensate precooler | | Condensate precooler and rectifier HI | |
|---|---|---|---|---|---|---|
| | Threshold (€) | Ratio (%) | Threshold (€) | Ratio (%) | Threshold (€) | Ratio (%) |
| 3.2 kW | 3144.45 | 46.13 | 2559.48 | 38.41 | 2289.06 | 33.59 |
| 10.8 kW | 11586.20 | 83.74 | 9339.39 | 69.34 | 8524.87 | 61.58 |
| Combined | 15291.80 | 90.38 | 12068.06 | 71.76 | 11113.44 | 66.73 |

Source: Authors' own research results.

*LCOC comparison*

Figure 9 compares the costs obtained in this study (blue rectangles) with those reported by Mortadi & El Fadar (2022). It is clear that the costs for the different VCC and absorption refrigeration variants achieved in this work fall within the lower range of values reported by the aforementioned authors.

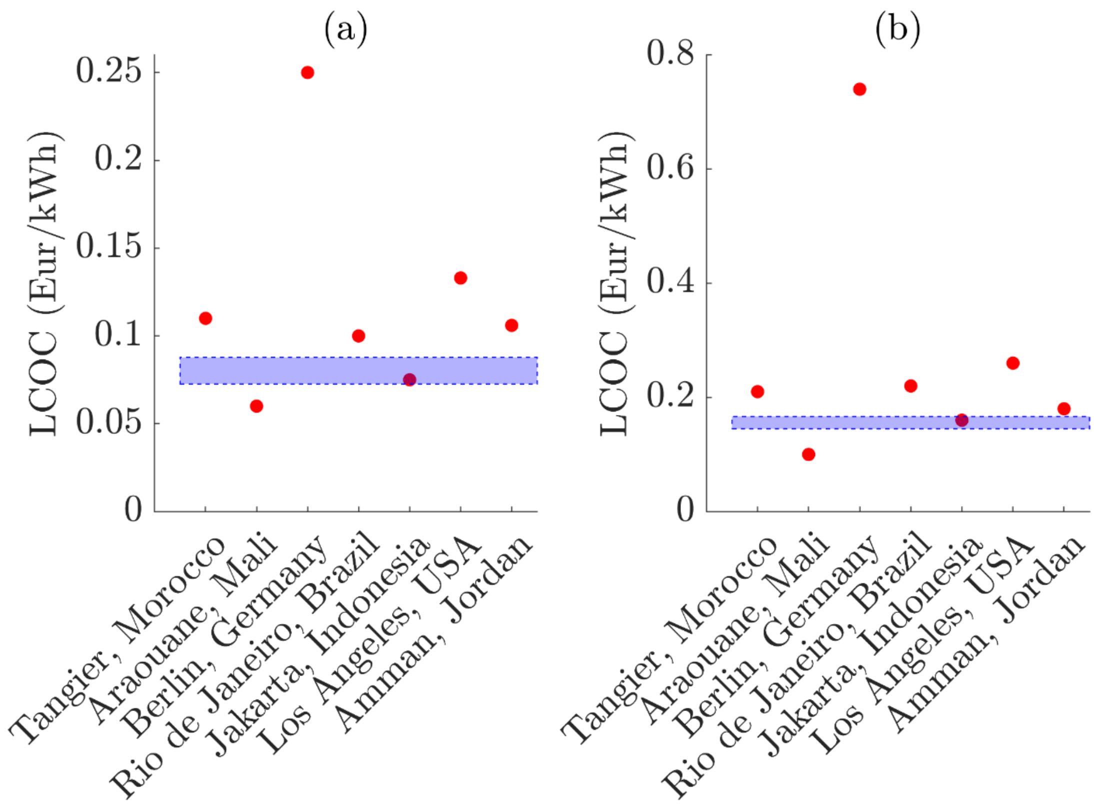


**Figure 9. Comparaison between the obtained LCOC in this study and the values reported by (Mortadi & El Fadar, 2022) (a): VCC, (b): absorption refrigeration**

Source: Authors' own research results and (Mortadi & El Fadar, 2022).

***Parametric studies***

For the sake of simplification, the parametric studies discussed in this subsection focus solely on the 10.8 kW cooling capacity case study. Similarly, only the results related to R134a variants are presented.

*Vapor compression cycle*

Figure 10 illustrates the variation in LCOC as a function of electricity cost. As electricity cost increases from 0.09 to 0.16 €/kWh, the LCOC for the simple configuration rises by 47.22%, whereas for the two-stage variants, the increase is 44.9%.



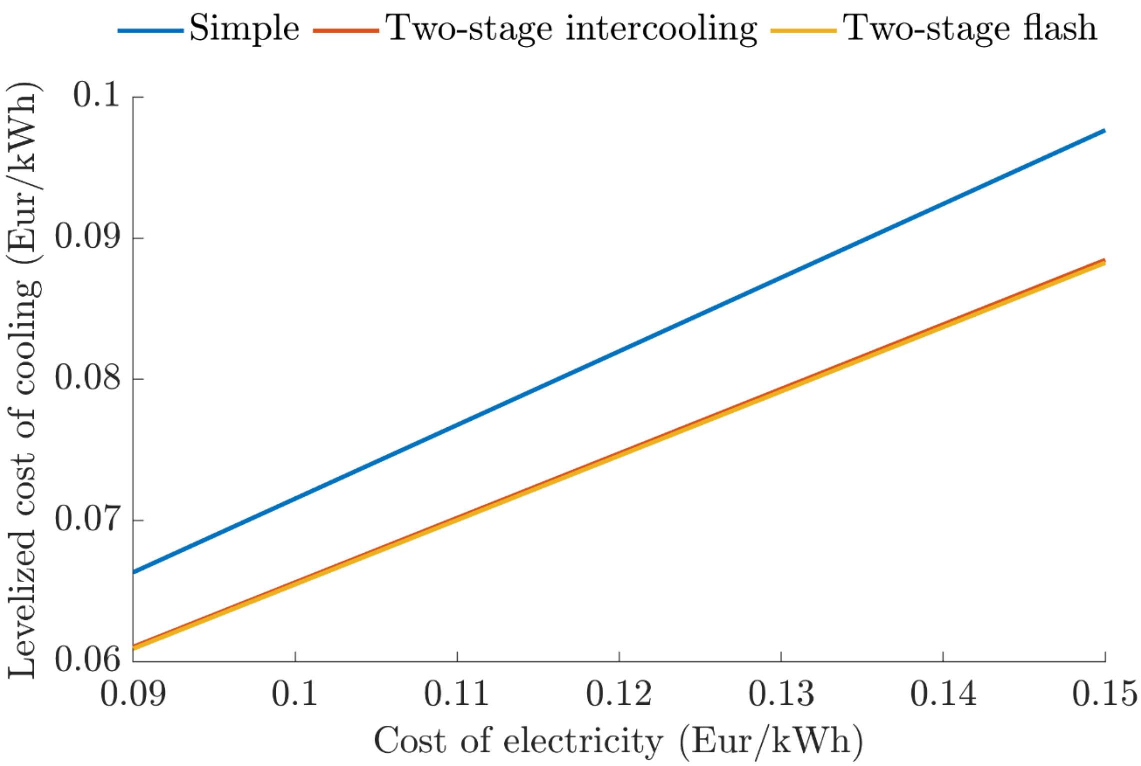


**Figure 10. Variation of the VCC variants LCOC with the cost of electricity**

Source: Authors' own research results.

Figure 11 illustrates the variation in the control system cost threshold as a function of electricity cost. As electricity cost increases from 0.09 to 0.15 €/kWh, the threshold value for the investigated configurations rises by 66.67%. This indicates that the economic viability of applying variable operating conditions to the VCC improves as electricity costs increase. This can be explained by the electricity consumption savings achieved through variable operation.

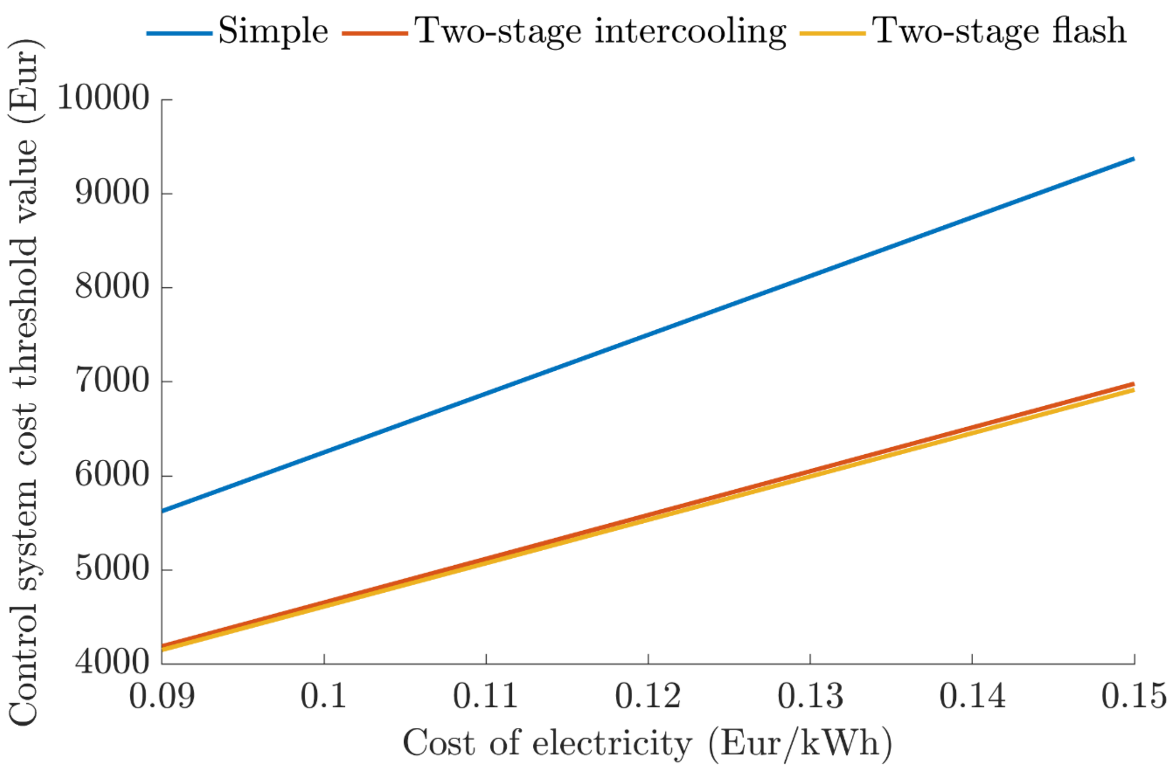


**Figure 11. Variation of the VCC variants control system cost threshold value with the cost of electricity**

Source: Authors' own research results.

*Absorption refrigeration technology*

Figure 12 illustrates the variation in LCOC for the investigated absorption refrigeration variants as a function of heat cost. As the heat cost increases from 0.02 to 0.08 €/kWh, the LCOC rises sharply from 0.089 to 0.244 €/kWh for the simple configuration, and from 0.08 to 0.218 €/kWh and 0.213 €/kWh for the condensate precooler and condensate precooler with rectifier heat integration, respectively. This highlights the strong dependence of LCOC on the cost of the heat source.

Figure 12 also highlights the LCOC range for the VCC variants under reference conditions, represented by a blue rectangle. Notably, for absorption technologies to be competitive with VCC, the heat cost must be below 0.018 €/kWh for the simple configuration and below 0.022 €/kWh for the other configurations.

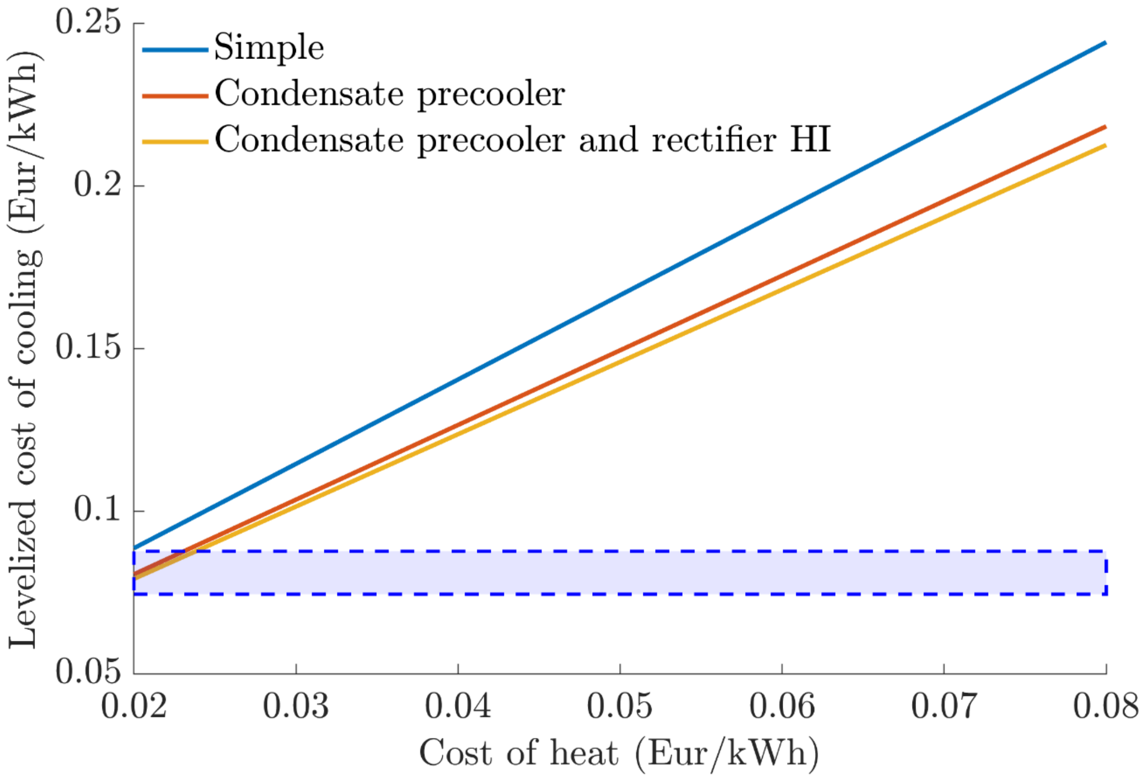


**Figure 12. Variation of the absorption refrigeration variants LCOC with the cost of heat**

Source: Authors' own research results.

Finally, Figure 13 illustrates the variation in the control system cost threshold as a function of heat cost for the three investigated configurations. As the heat cost increases from 0.02 to 0.08 €/kWh, the threshold value rises by 300% across all configurations.

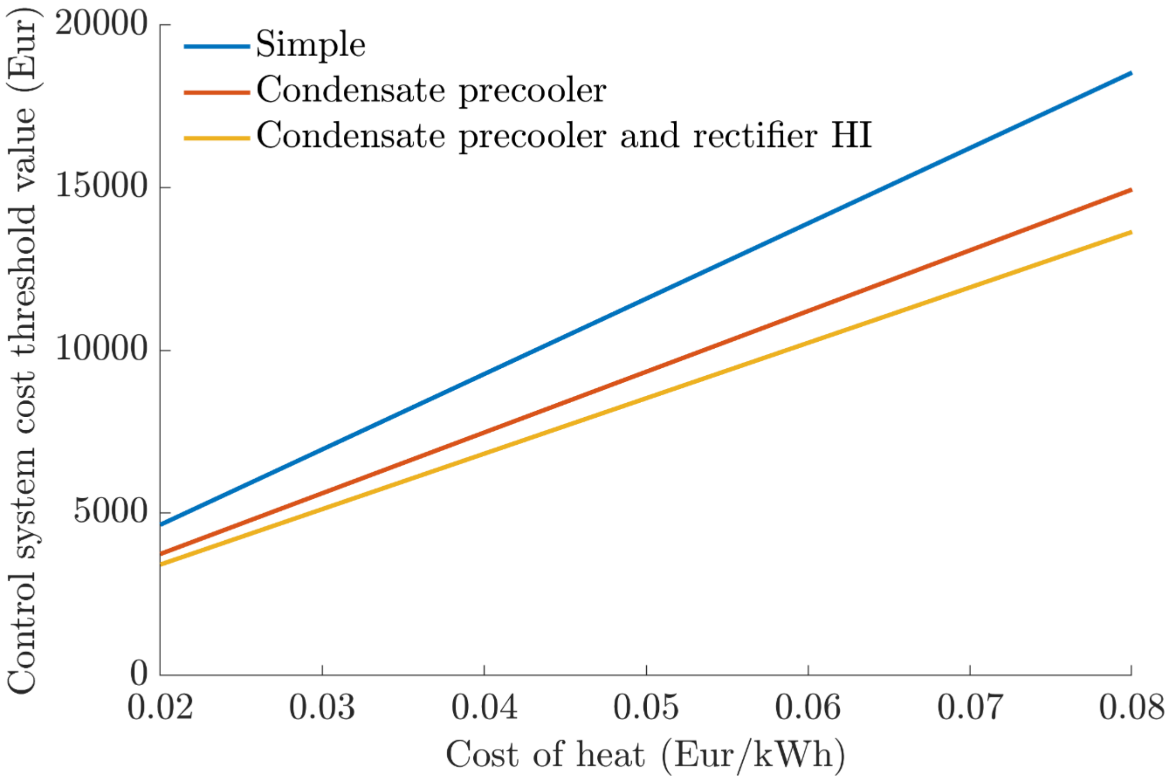


**Figure 13. Variation of the absorption refrigeration variants control system cost threshold value with the cost of electricity**

Source: Authors' own research results.

## Conclusion

This paper focused on the technical and economic performance evaluation of refrigeration system variants designed to meet the cooling requirements for food preservation of a farm in Nigeria. The variants investigated were based on VCC and absorption refrigeration technologies.

The results indicate that two-stage vapor compression configurations achieved a 13–20% improvement in the COP across the investigated refrigerants compared to the single-stage VCC. Regarding refrigerant performance, R134a, the reference refrigerant, exhibited the best performance for both the single-stage and two-stage intercooling configurations, while R1234ze(E) slightly outperformed in the two-stage flash configuration. Additionally, operating the vapor compression cycle under variable conditions resulted in significant energy consumption reductions compared to operating under fixed conditions. For absorption refrigeration, adopting the condensate precooler and rectifier heat integration configurations instead of the simple cycle led to a 20% improvement in the COP.

In terms of economic performance, under reference conditions, the levelized cost of cooling for VCC variants ranged between 0.0726 and 0.0878 €/kWh, while for absorption refrigeration variants, the cost varied between 0.1449 and 0.1665 €/kWh. Furthermore, parametric studies demonstrated that for absorption refrigeration technologies to achieve economic competitiveness with VCC, assuming an electricity cost of 0.12 €/kWh, a discount rate of 0.03, and an annuity period of 20 years, the heat cost must be below 0.018 €/kWh for the simple configuration and below 0.022 €/kWh for the other configurations.

While this study relied on detailed models to estimate the technical performance of the investigated variants, experimental validation remains essential to confirm the accuracy and reliability of the obtained results.

## Acknowledgements

The author would like to thank MESRSI for its support of the REPTES project under the LEAP-RE program. Additionally, the author expresses gratitude to the project partners for their collaboration.



## References

Altun, A. F. (2022). A Conceptual Design and Analysis of a Novel Trigeneration System Consisting of a Gas Turbine Power Cycle with Intercooling, Ammonia–Water Absorption Refrigeration, and Hot Water Production. Sustainability (Switzerland), 14(19).

Amjad, W., Munir, A., Akram, F., Parmar, A., Precoppe, M., Asghar, F., & Mahmood, F. (2023). Decentralized solar-powered cooling systems for fresh fruit and vegetables to reduce post-harvest losses in developing regions: a review. Clean Energy, 7(3), 635–653.

Aste, N., Del Pero, C., & Leonforte, F. (2017). Active refrigeration technologies for food preservation in humanitarian context – A review. Sustainable Energy Technologies and Assessments, 22, 150–160.

Cengel, Y., Boles, M., & Kanoglu, M. (2020). Thermodynamics: An Engineering Approach (Ninth). McGraw-Hill Education.

Cepoi, C.-O., Bran, M., & Dinu, M. (2020). INVESTIGATING THE NEXUS BETWEEN FUEL ETHANOL AND CO2 EMISSIONS. A PANEL SMOOTH TRANSITION REGRESSION APPROACH. Journal of Business Economics and Management, 21(6), 1774–1792.

Dinu, M., Pătărlăgeanu, S. R., Petrariu, R., Constantin, M., & Potcovaru, A.-M. (2020). Empowering Sustainable Consumer Behavior in the EU by Consolidating the Roles of Waste Recycling and Energy Productivity. Sustainability, 12(23), 9794.

Gardner, J. (2022). Thermodynamic Analysis for Industrial Refrigeration Systems. Springer.

Herold, K. E., Radermacher, R., & Klein, S. A. (2016). Absorption chillers and heat pumps. CRC press.

Jenny Gustavsson, Christel Cederberg, & Ulf Sonesson. (2011). Global Food Losses and Food Waste.

Leiva-Illanes, R., Escobar, R., Cardemil, J. M., & Alarcón-Padilla, D.-C. (2018). Comparison of the levelized cost and thermoeconomic methodologies – Cost allocation in a solar polygeneration plant to produce power, desalted water, cooling and process heat. Energy Conversion and Management, 168, 215–229.

McLinden, M. O., Seeton, C. J., & Pearson, A. (2020). New refrigerants and system configurations for vapor-compression refrigeration. Science, 370(6518), 791–796.

Mortadi, M., & El Fadar, A. (2022). Performance, economic and environmental assessment of solar cooling systems under various climates. Energy Conversion and Management, 252, 114993.

Olympios, A. V., Song, J., Ziolkowski, A., Shanmugam, V. S., & Markides, C. N. (2024). Data-driven compressor performance maps and cost correlations for small-scale heat-pumping applications. Energy, 291.

Pătărlăgeanu, S. R., Constantin, M., Dinu, M., Petrescu, I. E., & Deaconu, E. M. (2024). Farm Carbon Footprint Measurement Frameworks Based on the Digitization and Environmental Sustainability Paradigm. Proceedings of the International Conference on Business Excellence, 18(1), 1602–1612

Sun, D.-W. (2011). An Overview of Refrigeration Cycles. In Handbook of Frozen Food Processing and Packaging. CRC Press.

Tsogt, N., Gbadago, D. Q., & Hwang, S. (2024). Exploring the potential of liquid organic hydrogen carrier (LOHC) system for efficient hydrogen storage and Transport: A Techno-Economic and energy analysis perspective. *Energy Conversion and Management*, *299*, 117856.