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Procedia CIRP 135 (2025) 279–284

www.elsevier.com/locate/procedia

32nd CIRP Conference on Life Cycle Engineering (LCE 2025)

Hybrid Cooling Solutions for Sustainable Refrigeration: A Path to Net-Zero in the Food Industry

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Abstract

Refrigeration is essential for the food industry and global food security, yet it is associated with significant energy consumption, contributing for 1% of global carbon emissions and incurring substantial operating costs. As decarbonization and net-zero targets have become imperative in addressing climate change, the shift towards sustainable energy solutions in refrigeration has become crucial. While alternative cooling technologies and renewable energy integration have shown promises individually, their combined potential is largely untapped. This paper proposes the integration of evaporative cooling and solar cooling as a sustainable and cost-effective alternative to the conventional vapor compression cycle. By harnessing the strength of both technologies, we propose an affordable and scalable refrigeration solution for the food industry. A comprehensive techno-economic-environmental analysis is employed to evaluate the economic effectiveness and environmental competitiveness of this hybrid approach. Moreover, the combined refrigeration system performance is compared with the conventional vapor compression cycles, both fossil fuel-based and renewable energy-based, to highlight the potential for carbon emission reductions, as well as energy and cost savings. This research aims to facilitate the adoption of renewable energy into existing refrigeration facilities, promoting sustainable practices within the food industry, especially in developing nations.

Keywords: Vapour Compression; Evaporative Cooling; Cost Benefit Analysis; Techno-Economic Analysis; Sustainability

1. Introduction

With the natural resources and sinks of the biophysical environment reaching their ecological limits [1], the effects of global warming and climate change are becoming more prevalent. As a result, aggressive emission targets and net-zero roadmaps that align with the United Nations Sustainable Development Goals, are being proposed. This led to environmental sustainability (ES), which seeks to balance the use of natural resources and sinks while keeping them within their limits for human welfare, becoming a key consideration over the life cycle of products and services in all sectors. Moreover, since ES is a prerequisite for social sustainability [2], this study will focus on the ES of industrial refrigeration solutions in the food industry to analyse their environmental impact.

In addition to being the backbone for the food industry and global food security, refrigeration is an energy-intensive process that is responsible for around 1% of annual carbon dioxide (CO_2) and incurs substantial operating costs. Conventional refrigeration systems use the vapour compression (VC) cycle for temperature control [3]. It is used in domestic refrigeration, food processing and cold storage, industrial refrigeration systems, transport refrigeration, and electronic cooling, due to its high reliability, energy efficiency and practicality [4]. However, power consumption is a major concern for VC systems due to their relatively low 'coefficient of performance' (COP) [5]. Hydrofluorocarbon (HFC)

10.1016/j.procir.2024.12.035

refrigerants have a high global warming potential (GWP). They are used as the working fluid in conventional VC systems where they present an estimated annual leakage rate of 7% to 25% to the environment [6]. Therefore, refrigeration and cooling systems have both indirect (power consumption) and direct (refrigerant leakage) contributions towards their environmental impact. Consequently, in addition to being an economic burden, conventional refrigeration and cooling systems contribute to the excessive use of the natural sinks of the ecosystem.

The exponential rise in population growth corresponds to an increase in food demand [7]. Hence, the subsequent increase in the utilisation of refrigeration systems for food storage further accentuates their negative environmental impacts. A Climate Action Pathway for Net-Zero Cooling to decarbonise the cooling sector was introduced [8]. It comprised of three strategies. The 'Avoid' strategy aims at reducing the cooling demand while the 'Improve' and 'Shift' strategies aim at increasing the operating efficiency of cooling systems, and at integrating renewables respectively. With an increased and successful uptake of these AIS strategies, in the form of hybrid solutions, in HVAC (Heating Ventilation and Air-Conditioning) systems, their application to industrial refrigeration systems in the food industry seems to offer a certain potential towards reducing their direct and indirect contributions towards their environmental impact. Their implementation in refrigeration systems requires not only tapping into the potential of alternative practical cooling technologies and renewable energy integration, but also assessing their economic viability and environmental benefits.

This research therefore aims to present a hybrid cooling solution as a sustainable and cost-effective alternative to the conventional VC cycle. Section 2 reviews the applicability of alternative cooling strategies and the integration of renewables. Section 3 details the methodology adopted for this study. The economic and environmental analysis of the hybrid solution is presented in Section 4. In Section 5, the research contribution and the limitations of the proposed hybrid solution are discussed along with future work recommendations. Finally, key results and contributions are summarised in Section 6.

2. Related works

Refrigeration is characterised by a negative temperature gradient, indicating a high energy requirement. The associated cooling energy is achieved via a refrigeration cycle, which absorbs heat from one area and rejects it in another. VC systems use refrigerants as the heat absorption medium in the evaporator, and the condenser cools the refrigerant [3]. For industrial refrigeration applications, the VC cycle offers the best balance between efficiency and practicality with a COP (3 to 5) higher than other practical refrigeration cycles [4]. Due to its high energy efficiency and environmental-friendly operation, Evaporative Cooling (EC) is an attractive cooling system. Instead of refrigerants, EC systems use water vapour as the driving force for cooling. Their cooling range is therefore limited by the wet-bulb temperature of the ambient air.

Heuvelmans et al. [9] used a Life Cycle Assessment (LCA) to demonstrate a 24% lower climate impact for the EC cycle as compared to the VC cycle for HVAC systems. Moreover, using scenario analysis to account for the Danish government's energy transition targets of 50% renewables by 2030 and 100% renewables by 2050, the LCA showed that the operational phase of EC and VC systems displayed the highest climate impact by 78-92% and 56-80% respectively [9]. The economic efficiency and carbon footprint assessment guideline for hybrid cooling towers published by the 'Machinery and Equipment Manufacturers Association' (VDMA) showed that the carbon emissions from the manufacturing phase account for less than 1% than that of the operational phase [10]. This indicates that marginal improvements in operating energy requirements, and the adoption of renewable energy sources weigh heavily with regards to decreasing the climate impact of cooling systems.

This observation aligns with the research literature wherein, in addition to studies investigating novel cooling cycle like the Organic Rankine Cycle [11] or the use of refrigerants with lower GWP [12], consideration is also given to approaches to increase the energy performance of VC systems. This led to the development of indirect EC-VC cooling solutions in hot and humid regions where indirect EC (IEC) pre-cool the ambient air without adding moisture, and thus reduce the cooling load of the VC unit. This hybrid approach combines the benefits associated with EC systems (high energy efficiency) with that of VC systems (temperature and humidity control) [13]. IEC-VC cooling systems have only been applied to fresh-air-handling units and packed unit air-conditioner [13], [14]. The practical application of EC cycles for industrial refrigeration in the food industry is limited by its small cooling range.

With the fast reduction in photovoltaic (PV) panel costs over recent years and improvement in their operating efficiency [15], electricity generation from solar power positions itself as an attractive approach to the adoption of renewable energy for power generation. Solar energy can power refrigeration systems in two different forms: solar thermal, and solar electric. The economic and practical suitability of the latter was demonstrated for refrigeration systems while the former was deemed more suitable for waste heat recovery and domestic hot water systems [15]. Alkilani [16] demonstrated a proof of concept for pre-cooling in a fruit storage unit where PV panels were used to power the compressor. Its extension towards powering the complete refrigeration system was limited due to the high energy demand associated with the VC cycle. However, by reducing the cooling load of the VC unit in the hybrid approach, the potential of solar power for industrial refrigeration in the food industry can be explored.

The reviewed literature on alternative refrigeration cycles and the approaches towards cooling decarbonisation indicated the application of hybrid cooling solutions to reduce the energy requirement. Additionally, the dominance of the operating phase on the overall environmental impact of cooling systems was ascertained. Hence, this study proposes an IEC-VC hybrid configuration as a potential industrial refrigeration solution aiding the transition towards net-zero in the food industry.

3. Methodology

The proposed hybrid IEC-VC refrigeration system, for industrial refrigeration in the food industry, powered by solar power is illustrated in Fig. 1.

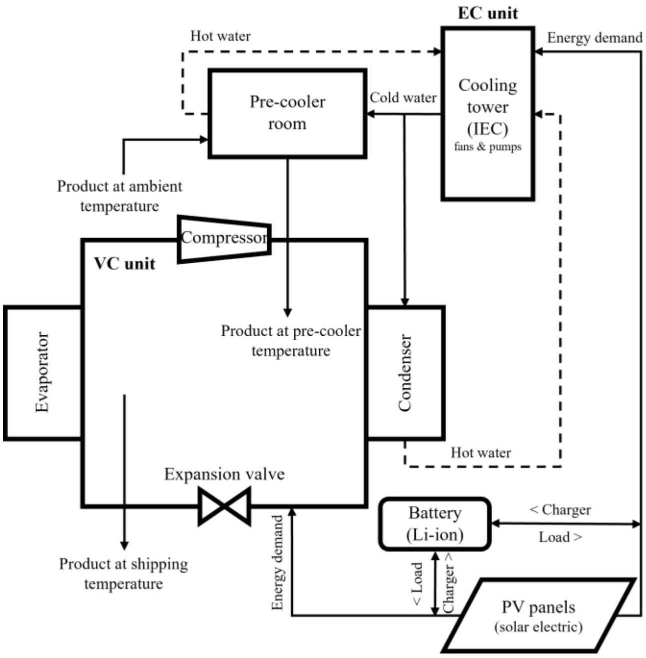


Fig. 1. Schematic of proposed hybrid refrigeration system with solar PV

The solar grid employs mono-crystalline PV panels due to high efficiency [17] and a battery unit for energy storage. The cooling tower can be effectively represented by its fan (for cooling) and pump (for water flow) [10]. Due to the latter's limited cooling range, a pre-cooler room is introduced to reduce the temperature of the product from ambient to wet-bulb temperature before feeding it to the VC unit (evaporator, compressor, condenser, expansion valve). Consequently, with a reduced cooling load requirement, the VC unit cools the product from the wet-bulb temperature to the lower shipping temperature. In addition to supplying the pre-cooler's cooling load, the EC unit also supplies the condenser.

Table 1 illustrates five refrigeration system configurations to evaluate the ES and economic benefits of the inclusion of an EC unit, a pre-cooler room, and solar power, as compared to 'Option 1', the business as usual (BaU) case where the cooling load is supplied by a VC unit powered by the grid. 'Option 4' represents the BaU case powered by solar PV. 'Option 2' and 'Option 5' represents the integration of the EC unit, and a pre-cooler room powered by solar PV and the grid respectively. 'Option 3' is a limiting case of IEC where the latter only supplies the condenser's cooling load with no pre-cooling.

Table 1. BaU scenario and potential hybrid cooling configurations

Option	EC application	Power source
1 (BaU)	n/a	Coal (grid)
2	Condenser & Pre-cooler loads	Solar PV
3	Condenser load only (no pre-cooling stage)	Solar PV
4	n/a	Solar PV
5	Condenser & Pre-cooler loads	Coal (grid)

For these five options, the 'Net Present Value' of annual savings ($NPV_{avoided\ cost}$) [18], and the 'total equivalent warming impact' (*TEWI*) index [19] and water footprint indicator are used to assess the economic effectiveness and environmental impact respectively. A cost benefit analysis (CBA) is used to evaluate the economic viability of the proposed configurations. The annual benefits considered are the avoided carbon costs (C_C) based on the carbon pricing mechanism and the energy saving cost (C_E) [18]. In addition to the capital investment (C_{CAPEX}) and operating (C_{OPEX}) expenditures, the cost model for annual expenses also accounts for the additional annual expense in the form of the cost of carbon (C_{ENV}), in line with the carbon pricing initiatives following the Paris Agreement. The net annual cost (ΔC) can thus be expressed as:

$$\Delta C = (C_C + C_E) + (-C_{CAPEX}) + (-C_{OPEX}) + (-C_{ENV}) \tag{1}$$

where either $C_{ENV} = (Emitted\ CO_2 \cdot CO2_{TAX})$ and $CO2_{TAX}$ is the carbon tax if taxation is used as the carbon pricing mechanism or $C_{ENV} = [CO2_{ETS} \cdot (CO_2\ permit\ shortage - CO_2\ permit\ excess)]$ and $CO2_{ETS}$ is the carbon market trading price if emission trading system issuing carbon permits is used as the carbon pricing mechanism.

$$NPV_{avoided\ cost} = \sum_{t=0}^{L_t} \frac{\Delta C}{(1+r)^t} \tag{2}$$

Considering the expected lifetime (L_t) of the refrigeration system, the $NPV_{avoided\ cost}$ is determined using the undiscounted ΔC from Eqn. (1) and a discount rate (r) adapted to green project [20] in Eqn. (2). In this study, due to the dominance of the operating phase on the environmental impact of cooling systems (refer to Section 2), the environmental analysis will focus on the environmental impact of the latter. The *TEWI* index of the refrigeration system considers both the direct emission due to refrigerant leakage (scope 1 emission) and the indirect emission associated with power generation (scope 2 emission) [19], [21]. Hence, the *TEWI* index is expressed as:

$$TEWI = (GWP_{100} \cdot m_r \cdot L_r \cdot L_t) + \left(Q \cdot E_f \cdot L_t\right) \tag{3}$$

where GWP_{100} is the global warming potential over 100 years of the refrigerant, m_r is the refrigerant charge which calculated based on the cooling load requirement of the VC unit, L_r is the annual leakage rate of the refrigerant, Q is the annual energy consumption of the refrigeration system, and E_f is the scope 2 emission factor for power generation.

The water usage in the EC unit comes from circulation and annual make-up water, which replaces circulation water lost due to leakage or evaporation, used for cooling [9], [10]. Schulze et al. [10], [22] accentuated the water-energy nexus for cooling systems and power generation but indicated that the environmental relevance of water footprint is highly dependent on the water scarcity in the region assessed. Therefore, the operating water footprint (W_{H2O}) of the refrigeration system includes both direct water use by the solar PV for cleaning $(W_{PV})$and by the EC unit (W_{EC}), and indirect water use for power generation (W_P) where $W_P = (Q \cdot WI_{PG})$ and WI_{PG} is the water use intensity of power generation in the grid. W_{H2O} is thus expressed as:

$$W_{H2O} = (W_{EC} + W_{PV}) + W_P \tag{4}$$

Moreover, with no carbon emission during operation, the E_f of solar PV is assumed to be zero in this study [23]. Mahmud & Farjana [24] used an LCA to show that the E_f of solar power is two orders of magnitude lower than fossil-fuel plants per kWh of power produced. Climatic temperature condition is a key parameter for both the economic and environmental assessment of cooling methods [25]. For this study, since the interest is in the economic and environmental performance of the five options operating within the same boundary conditions, the monthly average climate conditions are assumed to overcome the uncertainties due to the variations in climatic temperature conditions.

4. Case Study and Result

A case study from a South African fruit storage company is selected in this study to investigate the economic effectiveness and environmental competitivity of the proposed solar powered hybrid refrigeration system. The company has 24 cold rooms, with a capacity of 120 tons each, operating with grid-powered VC refrigeration systems. R134a is the refrigerant used by the VC unit, and it has a GWP_{100} of 1530 [26]. The cold rooms have a cooling range of ~12.5℃, i.e., from 16.5℃ (average ambient temperature) to 5℃ (shipping temperature). The annual average wet-bulb temperature is 11.9℃. The WI_{PG} for South Africa is $1.4\, m^3/MWh$ [27]. Based on IPCC good practice guideline, an industrial refrigeration system has typical L_t of 20 years and an average L_r of 15% [6]. With 86% of total electricity generation from coal [28], the E_f used is $0.985 kgCO_2e/kWh$ [29].

South Africa uses taxation as a carbon pricing mechanism for scopes 1 and 2 emissions [30]. Using 2024 as the base year, $CO2_{TAX}$ is $US\$10.41/tCO_2e$ [30]. Yearly revised rates are provided up to 2030 with an upper limit for 2050 which is the Net-Zero target year for South Africa [30]. Moreover, in the implementation phase of the carbon tax, tax-free allowances are planned up to 2025 [31]. By applying the latter to the five options in Table 1, the taxable carbon emissions are 30%, 15%, 15%, 15%, and 30%, respectively, until 2025. Beyond 2025, all the carbon emissions are taxable. The Stern review suggested r =1.4% in favour of strong actions to curtail greenhouse gas emissions [20]. However, due to the uncertainty about the interest rate value to discount costs and benefits of climate changes a century from now, r = 2-4% is proposed [20].

4.1. Techno-economic analysis

The highly efficient EC unit, when combined with the VC unit improves the COP of the refrigeration system from 3, for the BaU, to 5.7. Integrating a pre-cooling stage reduced the cooling load of the VC unit. This resulted in a total required PV panel size 64.3% smaller in 'Option 2' than in 'Option 4'.

Fig. 2 shows the cumulative $NPV_{avoided\ cost}$ for the five options. 'Option 2' was observed to offer the highest cost savings and is thus the most economically effective over L_t. This is attributed to the reduced dependency on the grid and the smallest PV panel sizing requirement. The latter is a consequence of the adoption of the EC unit, whose fan and pump have a relatively low power consumption, which reduces the total power consumption of the VC unit.

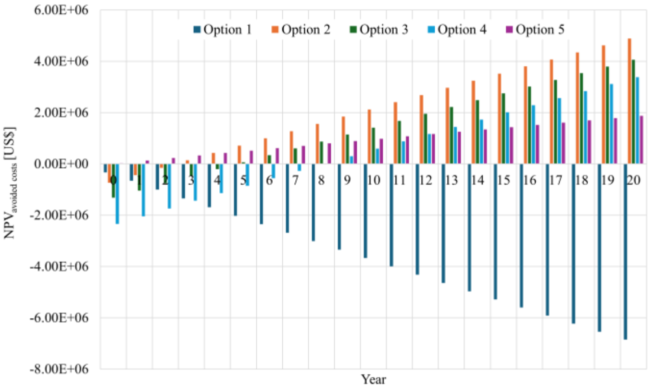


Fig. 2. Cumulated $NPV_{avoided\ cost}$ for proposed configurations

A comparison between 'Option 2' and its grid-powered alternative ('Option 4') demonstrated the economic benefits of shifting to renewables, in this case, solar, as of Year 6. This is due to the lower C_{OPEX} and C_{ENV} and higher C_C and C_E. Moreover, it also demonstrated the cost-saving potential of a system with higher COP. The $NPV_{avoided\ cost}$ for 'Option 5' shows that cost saving benefits of IEC can be observed even when grid power is used. The economic benefit of introducing a pre-cooling stage is illustrated by the higher $NPV_{avoided\ cost}$ of 'Option 2' relative to 'Option 3' in Fig. 2. Therefore, the CBA demonstrated the economic benefits of shifting to renewables (solar), reducing the cooling load of the VC unit (IEC and pre-cooling), and increasing the COP (IEC).

4.2. Environmental analysis.

The environmental analysis used Eqn. (3) and (4) to determine the GWP and the water footprint of the five options in Table 1. Fig. 3 showed that the shift to the solar grid ('Option 4') and the integration of the EC unit ('Option 5') corresponded to a 95.7% and a 63.4% reduction in the GWP when compared the BaU case. 'Option 2' had the lowest TEWI index. This is due to the E_f of zero for solar power, and the lower m_r that results from the reduced cooling load of the VC unit. The pre-cooling stage provided a 42.2% reduction in the TEWI index ('Option 2' against 'Option 3').

South Africa is ranked as the 30th driest country in the world, and its water demand predicted to exceed availability of economically usable freshwater resources by 2025 [32]. Therefore, W_{H2O} is an important consideration in determining the option with the lowest environmental impact. With the circulation and make-up water, EC systems have a higher water usage when compared to VC. In Fig. 3, 'Option 2', 'Option 3' and 'Option 5' were observed to consume 73.5%, 75.2%, and 75.8% more water than the BaU case. The difference between these values is due to the lower total evaporative cooling load for 'Option 2', which thus consumes less make-up water, the proportional link between panel size and W_{PV} for 'Option 2' and 'Option 3', and the use of power from the grid for 'Option 5' respectively. 'Option 4' had the lowest W_{H2O}, 98.9% with respect to the BaU case. This is because of its reduced dependency on the grid and thus lower W_P.

Since W_{H2O} and $TEWI$ index are both expressed in different currencies, $[m^3]$ and $[kgCO_2e]$ respectively, and the relative weighting associated with then is unknown, there is a need to establish a common currency that will allow the overall environmental impact (EI) to be defined. Tesfamichael et al. [33] proposed the use of the 'ecocost' method for the latter. This method is based on the marginal prevention costs needed to reduce the environmental stress of a product and is commonly applied in midpoint LCAs [34]. Therefore, it can account for the water scarcity in various geographical locations and provides a representative ecocost value $(US\$1.24/m^3)$ related to the extraction of water from nature [35]. The ecocost values associated to the HFC refrigerant $(US\$839.65/kgCO_2e)$ and the carbon emissions $(US\$0.145/kgCO_2e)$ are also available based on the global climate urgency [35]. The results for the five options showed that 'Option 2' displayed the lowest EI (42.4% lower than the BaU case – Fig. 4).

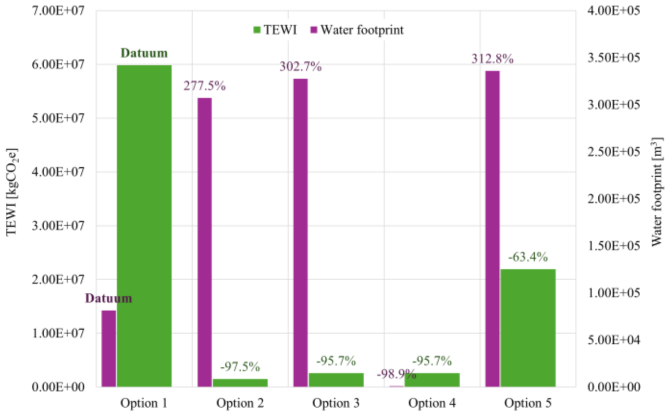
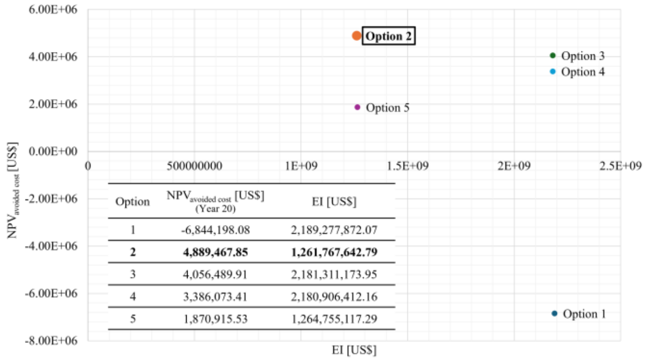


Fig. 3. TEWI indices and water footprints of the proposed configurations

5. Discussion

This study explored the cost-effectiveness of four proposed hybrid cooling solutions (see Tabel 1) within a case study from a South African food industry. Fig. 4 illustrates a trade-off graph summarising the economic and environmental analyses.



Option	$NPV_{avoided\ cost}$ [US$] (Year 20)	EI [US$]
1	-6,844,198.08	2,189,277,872.07
2	**4,889,467.85**	**1,261,767,642.79**
3	4,056,489.91	2,181,311,173.95
4	3,386,073.41	2,180,906,412.16
5	1,870,915.53	1,264,755,117.29

Fig. 4. Economic-Environmental trade-off graph

Based on the two objectives of minimum EI and maximum $NPV_{avoided\ cost}$, 'Option 2' was identified as the most economically effective and environmentally competitive. This validates the integration of IEC and solar power in the proposed hybrid cooling refrigeration system. It also illustrates the benefits of introducing a pre-cooling stage to maximise the potential of EC. As for the high W_{H2O} of 'Option 2', Chen et al. [13] proposed the recovery of the condensate from the VC unit and supplying it as make-up water to the EC unit to reduce the latter's water usage. With limited literature involving cost analysis for hybrid EC-VC cooling, Chen et al. [13] cautioned about its potential economic viability [13]. The CBA results from Section 4 demonstrates the economic viability of such systems for industrial refrigeration in the food industry.

In this study, the yearly revised rates for carbon tax based on its current implementation in South Africa is used to interpolate the rates between 2030 and 2050. However, this same approach was no taken for the E_f of and energy price from the grid. This was due to the unavailability of such data. With the coal still contributing to 86% of the electricity generation [28] and the renewable energy target of 2030 predicted to be missed [36], the results obtained are unlikely to provide a different conclusion. A sensitivity analysis, considering the two parameters, could be performed as a perturbation measure to confirm the observations. Moreover, the results were based on the use of R134a as refrigerant by the South African company. While the latter is being phased out and ban in most developed countries due to high GWP, its versatility and chemical properties make it still common in refrigeration systems in developing nations. This study did not fully investigate how the transition to a less polluting refrigerant, e.g., R717 (ammonia-based) and R744 (CO_2-based), affects the results. However, a preliminary investigation showed that 'Option 2' had the lowest and second lowest EI for R744 and R717 respectively. Furthermore, the ecocost method is based on the prevention cost and is thus not representative of the actual damage caused to the ecosystem. While shadow pricing approaches tend towards that, a shadow price for water in South Africa is not available.

In the transition to Net-Zero, the integration of the carbon pricing mechanism in the cost model allows for a more accurate representation of the environmental economics and links the improvements in the environmental performance of a system to its economic performance. This is relevant for the food industry which presents high export and import rates and thus affected by initiatives such as the European Union's 'Carbon Border Adjustment Mechanism'. The latter is predicted to shrink South Africa's exports by 10% by 2050 [37].

6. Conclusion

The consideration of carbon pricing initiatives in the cost model enabled an adequate representation of the climate urgency and accounted for the financial benefits of transitioning towards environmentally sustainable solutions. The use of IEC reduces the required size of PV panels in the solar grid and provides significant economic savings and reduced environmental impact even when powered by the grid. The introduction of a pre-cooling stage further enhances the economic and environmental benefits of integrating an EC unit in a refrigeration system. However, EC significantly increases the water footprint of refrigeration. Nonetheless, the actual environmental impact of the latter is highly dependent on the geographical location being considered and its associated water stress indicator. Moreover, the shift to solar power enhanced the cost saving potential of refrigeration systems over its lifetime. In addition to improving the TEWI index, the shift to solar power also reduced the water usage for power generation. Therefore, the proposed system shows significant potential towards an affordable transition to sustainable refrigeration solutions and the path to Net-Zero in the food industry.

Acknowledgements

This research was supported by the Centre of Digital Engineering and Manufacturing (CDEM) at Cranfield University.

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2025-07-17

Subhadu VV, Nafjan AA, Aria AI, Farsi M. (2025) Hybrid cooling solutions for sustainable refrigeration: a path to net-zero in the food industry. In: Procedia CIRP, Volume 135, July 2025, pp. 279-284. 32nd CIRP Conference on Life Cycle Engineering (LCE2025), 7-9 April 2025, Manchester UK

https://doi.org/10.1016/j.procir.2024.12.035