Sustainable Refrigeration in the Peruvian Amazon: Addressing Energy, Environmental & Economic Challenges

by Olaseni Osho

Supervised by Dr. Edwin Nowicki[1], Ken Robertson[2] and Alex Diaz Sotil[2]

[1]Schulich School of Engineering; [2]Star Energy and the Grupo de Innovación y Desarrollo Social ante la Crisis Climática

INTRODUCTION

- Remote communities in the Peruvian Amazon cannot depend on continuous electricity to power even basic refrigeration.
- Approx. 86 % of the Peruvian rural population has access to electricity, many settlements in the Amazon depend on isolated micro-grids or diesel generators. [3]
- Outages, limited-service hours and high fuel costs prevent households, clinics and micro-enterprises from operating with cold-chain technology.

Map of Peru[6]

~ 50% Annual national food supply lost and wasted, mostly in off-grid supply chains. [4]

> 50% Indigenous children under five suffer from chronic malnutrition and anaemia. [5]

RESEARCH QUESTION & SCOPE

Can refrigeration be used in the Peruvian Amazon to improve health and local economies in a technically reliable, environmentally sustainable and economically viable way?

Interdisciplinary Aspects
- Energy consumption
- Environmental impact
- Economic viability

UN Sustainable Development Goals [7]

METHODOLOGY

- **Comparative design:** Three technologies across three use-cases. All units are scaled to a 100 L cabinet to ensure comparability. [8]

	Solar	Propane	Grid
Fridge	Vaccine/Medicine refrigeration (2–8 °C)		
Freezing	Fish freezing (−18 °C storage)		
Flash Freezing	Fish flash-freezing (rapid cooling to −18 °C)		

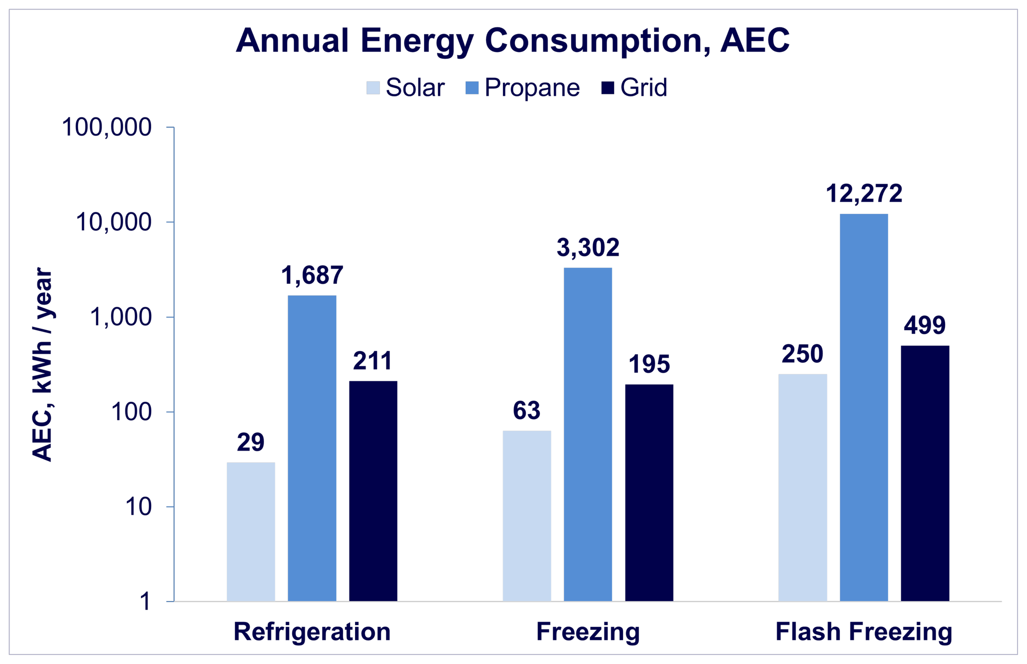
- **Data sources:** Local data, manufacturer and independent test data, peer-reviewed literature, grey reports, SAM & NASA POWER (climate data), national electricity board, retail outlets, LPG suppliers. [9, 10]
- **Key data:** Daily energy input (kWh or kWh_{th}), capital cost ($ US), local fuel and electricity prices ($ US), and emission factors for manufacturing (refrigerator cabinets, PV modules, $LiFePO_4$ batteries) and operation (grid and LPG), lifespan

Assumptions	Refrigeration	Freezing	Flash Freezing
Volume	100 liters		
Internal Temp	-4°C	-18°C	-18°C (rapid)
Ambient Temp	26°C		32°C
Utilization	100%		70%
Power Rating Source	Manufacturer Data		+12.5%
Door Opening Corr	+25%	+25%	+12.5%
Lifespan	15 years	15 years	7.5 years
Lifecycle Boundary	Cradle-to-use (manufacturing + operation)		
Horizon & Disc. Rate	15 years & 8%		

Metrics (15 years)	Refrigeration	Freezing	Flash Freezing
Energy Analysis	Energy consumption, kWh or kWh_{th}		
Economic Analysis	Net present cost, $ US		
	Levelized cost of energy, $ US / kWh or kWh_{th}		
Carbon Footprint	Total emissions (cradle to use), kg CO_2e		
	Emissions intensity, kg CO_2e / (kWh or kWh_{th})		

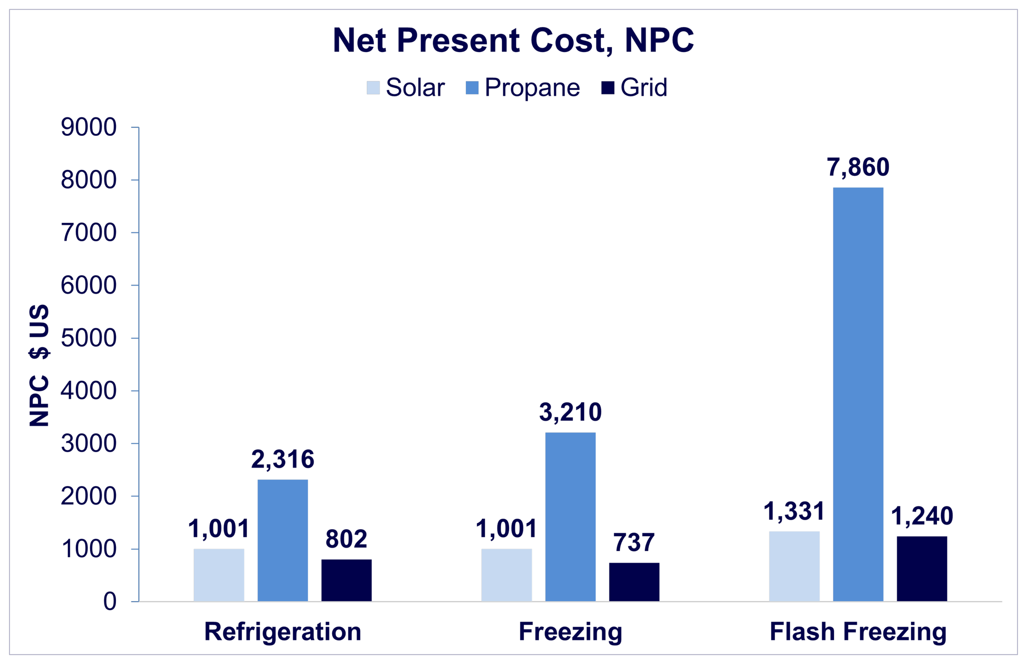
RESULTS

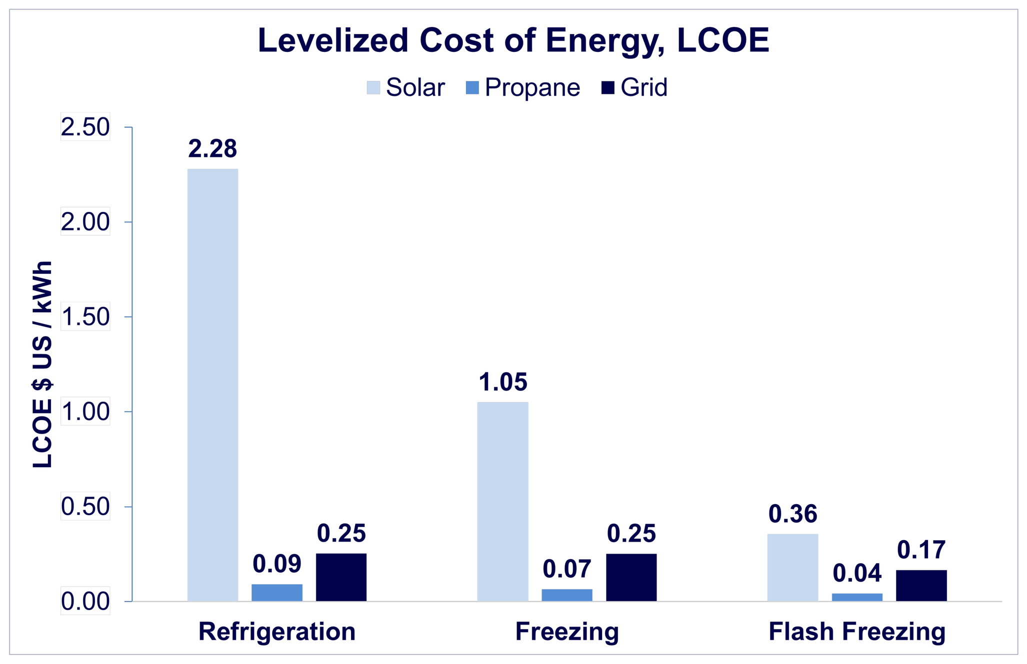
Energy Analysis



- The solar system demonstrated consistently low energy demand across all use cases. These values reflect the unit's compact design, high-efficiency DC compressor, superior insulation, and partial thermal storage via PCM.
- In contrast, the propane-powered systems required significantly higher thermal input. These figures underscore the inefficiencies of combustion-based cooling and the high cost of thermal energy from LPG in remote areas.
- The grid-powered units occupied a middle ground. While more efficient than propane, their annual energy use remained significantly higher than solar in all three use cases.

Economic Analysis





- The grid-powered systems consistently offered the lowest NPC, owing to its low capital cost and minimal maintenance needs. Their main constraint, however, remains infrastructure availability and reliability.
- The propane systems showed the lowest LCOEs due to the relatively high energy throughput. However, their NPCs were the highest across all use cases, reflecting heavy reliance on purchased fuel.
- The solar system offered a middle ground in NPC, owing to its zero-fuel design and minimal maintenance needs. However, its high capital cost and high energy efficiency, led to the highest LCOE values across all use cases. The economic competitiveness, though not enough, improved as energy demands increased.

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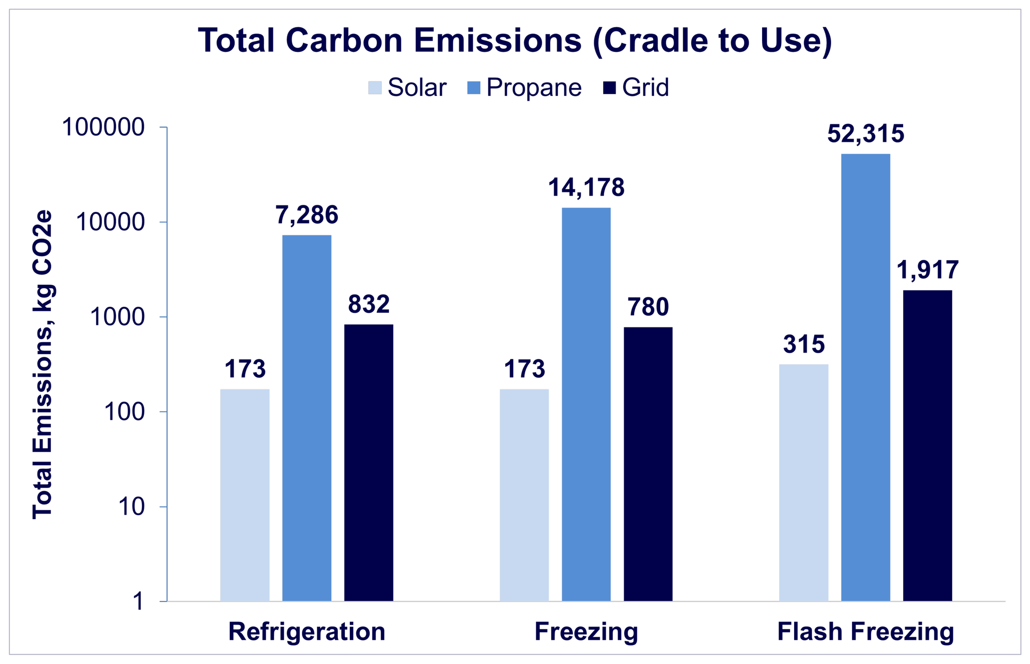
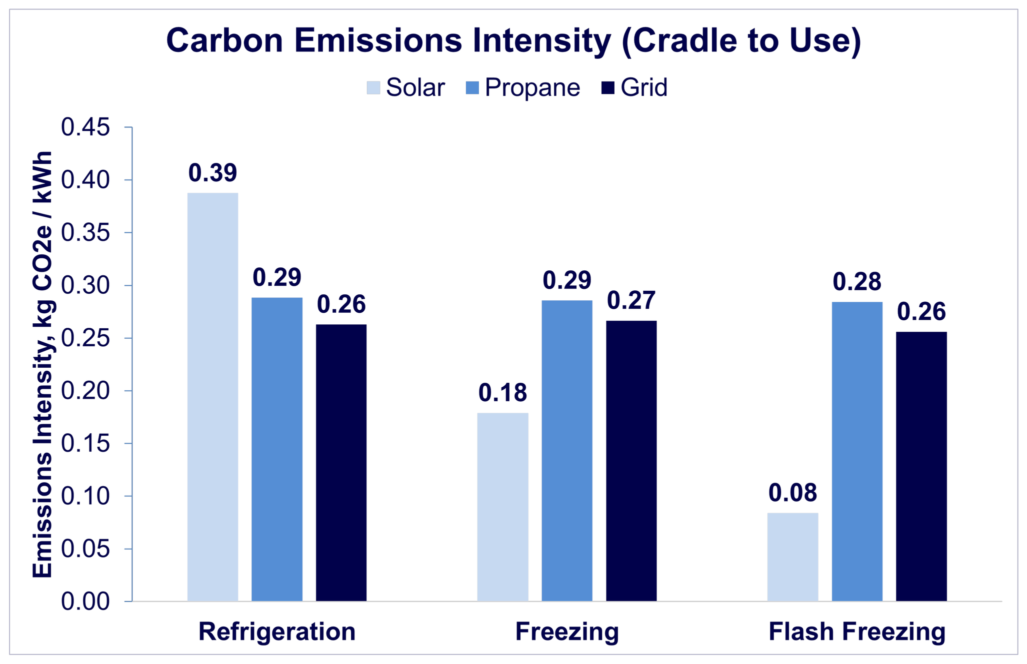
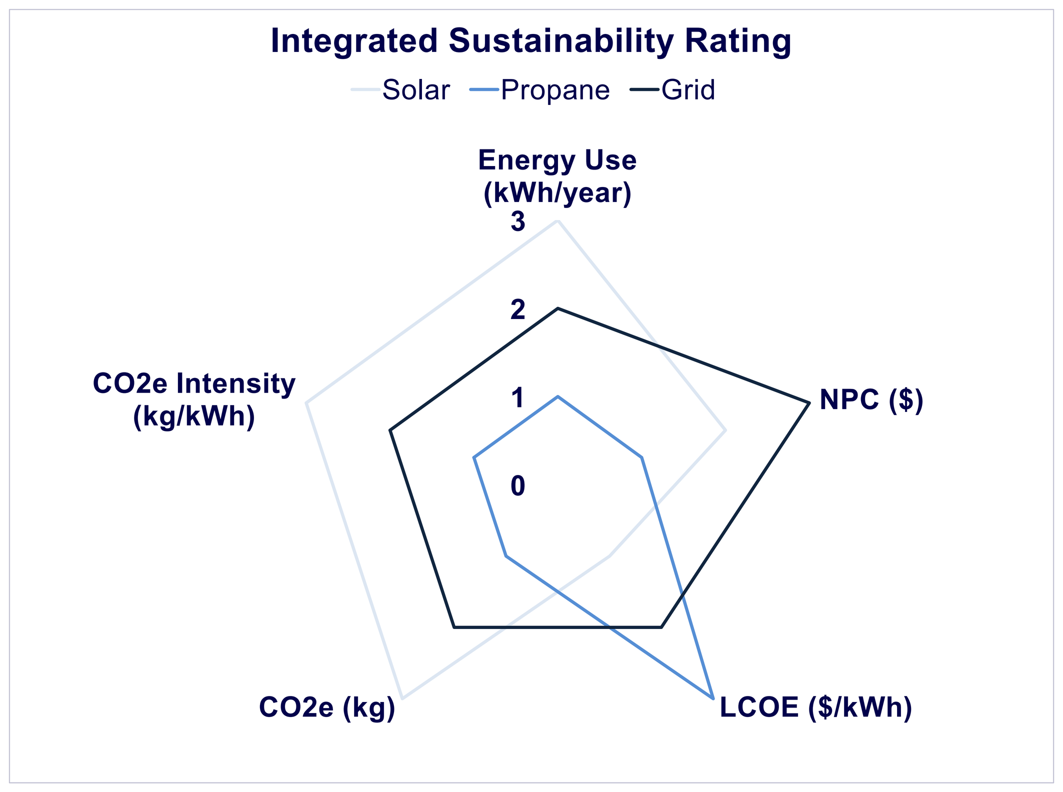
Environment Analysis





- The solar system consistently demonstrated the lowest total carbon footprint, with zero operational emissions assumed and relatively modest embodied emissions. The emissions intensity improved across the three use cases due to increased utilization, as cooling output spread over the same system emissions.
- In contrast, the propane system incurred the highest total and normalized emissions in all cases, due primarily to combustion-based operational emissions. While propane systems offer flexibility in off-grid contexts, the emissions trade-off is significant.
- The grid-powered system exhibited intermediate carbon performance, with normalized emissions steady across use cases. While it avoids direct fuel combustion and is cleaner than propane due to Peru's hydro-rich grid, its carbon intensity remains markedly higher than solar, particularly in off-grid or unreliable electricity contexts.

DISCUSSION



- Solar systems offer reliability and low emissions but require higher upfront investment and battery replacement; grid units are efficient and inexpensive to operate where electricity is stable; propane is only suitable for emergencies or where no electrical power exists.
- Recommend solar DC-powered compression fridges for clinics and vaccines; solar DC freezers for fish storage in villages; hybrid (solar+grid) systems for flash-freezing hubs.
- Challenges include financing (consider Pay-As-You-Go or cooperative models), training for users, technical support & maintenance, logistics for replacement parts and infrastructure for telecommunication.
- Future work required include field trials to validate assumptions, inclusion of end-of-life impacts, exploration of hybrid solar-grid options.

CONCLUSION

- Study confirms that refrigeration can be used sustainably in the Peruvian Amazon, but only when technologies are matched to the demands of each use case and anchored in local realities.
- Solar powered compression systems emerge as the primary pathway for off grid clinics and small-scale fishers, offering zero emissions and favourable long-term economics.
- Grid tied systems serve high duty applications (flash freezing) where reliable electricity exists and can be decarbonized.
- Propane absorption units remain useful as short-term bridges or emergency backups but are unsustainable as a primary solution due to high fuel use and emissions.
- By combining right sized technology, innovative financing, local capacity building, and rigorous monitoring, refrigeration can strengthen health services (SDG 3), expand clean energy access (SDG 7), and support climate action (SDG 13) in the Amazon

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