Sustainability **2012**, *4*, 2838-2851; doi:10.3390/su4112838

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Environmental Profiles of Stirling-Cooled and Cascade-Cooled Ultra-Low Temperature Freezers

David M. Berchowitz * and Yongrak Kwon

Global Cooling Inc., 6000 Poston Rd. Athens 45701, OH, USA;
E-Mail: yongkwon@globalcooling.com

* Author to whom correspondence should be addressed; E-Mail: dberchowitz@globalcooling.com; Tel.: +1-740-274-7925; Fax: +1-740-274-7901.

Received: 20 September 2012; in revised form: 17 October 2012 / Accepted: 18 October 2012 / Published: 25 October 2012

Abstract: The environmental footprint of ultra-low temperature (ULT) freezers as used in bio-repositories, universities and other research organizations is investigated. These freezers, employing the cascade refrigeration system, use between 10 and 20 times the energy of an average household refrigerator/freezer. In addition, they often require high greenhouse gas potential (GWP) refrigerants. A new technology employing the Stirling cycle machine promises to reduce energy consumption of ULT freezers by 50% or more. The cascade and Stirling systems are compared for equivalent sized freezers in terms of embodied energy and equivalent CO_2 production from cradle to gate and use, including total equivalent warming impact (TEWI) estimations. End-of-life issues are discussed but not quantified. It is shown that Stirling technology is able to significantly reduce the environmental impact of ULT freezers.

Keywords: Stirling; ULT; cascade; refrigeration; bio-repository; TEWI; embodied energy

---

1. Introduction

In order to understand the environmental impact of any new technology, it is important to understand how the new technology utilizes materials and resources differently from the old. In this study, the environmental profiles of similar-sized Stirling-cooled and cascade-cooled ultra-low temperature (ULT) freezers are compared. The environmental profiles consist of estimating the energy uses and CO_2 generation of production and use-life of the equipment. Some discussion is included on end-of-life. Due to the much higher energy demand of ULT freezers, the embodied energy and CO_2 generation during manufacture of the product are much smaller than are generated during its use. As a consequence, the environmental impact of operating efficiency is dominant. This is different from household refrigerators where the environmental impact of producing the product is similar to the use of the product. To illustrate this last point, the current average use per day of household refrigerators is about 1.4 kWh [1] compared to cascade ULT freezers of about 24 kWh.

2. The Cooling Systems

2.1. Cascade System

Other than Stirling technology, all ULT freezers utilize cascade systems in order to provide the cooling effort. For −80 °C class freezers, two-stage systems are used. Figure 1 shows the basic components of a two-stage cascade system. Typically for systems around 650 liter to 800 liter internal volume, each compressor is a 1000 W class compressor. The evaporator is a copper tube that surrounds the internal volume while the condenser is a forced air finned tube construction. The inter-stage heat exchanger serves as the evaporator of the first stage and the condenser of the second stage. In addition, there are expansion devices, typically capillary tubes, oil separators and dryers in the circuit. The refrigerant for the two stages are different and have to operate effectively at the inter-stage temperature where the first stage is evaporating and the second stage is condensing. Both stages also require an oil distribution system for each circuit. Table 1 lists the significant materials and quantities in a typical two-stage cascade system.

Figure 1. Schematic showing the components of a two-stage cascade cooling system.

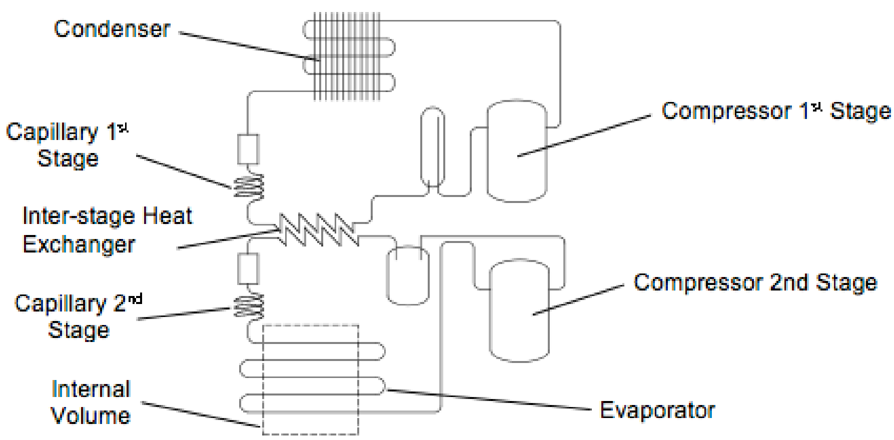


Table 1. Significant materials and associated masses used in a cascade refrigeration system.

Component	Subgroup	Material	Mass (kg)
Cascade System	Casings	Carbon Steel	11.1
	Laminations	Silicon Steel	10.1
	Structure	Cast Iron	6
	Coils, tubes, HX *etc.*	Copper	17.6
	Other parts	Aluminum	0.8
	Oil	Poly ester	1.72
	Refrigerant	R-407D	0.6
	Refrigerant	R-508B	0.3
Fan	Blades	ABS	0.3
	Coil	Copper	0.1
	Flux pieces	Silicon Steel	0.3
	Frame	Aluminum	0.2
	Magnets	Fe-Nd-B	0.05
Cabinet	Insulation	Polyurethane	13.5
	Vacuum Insulated Panels	Unknown	10
	Blowing agent	HFC-245fa	1
	Envelope, door, liner and structure	Steel	231
	Shelves 2X	Stainless steel	13.4
	Paint		14.5 sq. m.
	Thermal breakers, wheels *etc.*	ABS	8.2
	Gasket	Silicone	3.2
	Handle, trim *etc.*	Aluminum	1
	Wiring harness, *etc.*	Copper	0.5
Electronics	Controls	PC Board	2
	User interface	PC Board	0.12
	Transformer	Silicon Steel	2
		Copper	0.5
Shipping Carton	Carton	Cardboard	19
	Inner protection (0.05mm thick)	Plastic bag	0.5
	Pallet	Wood	33.7
Total			386.7

2.2. Stirling System

The Stirling refrigeration system is relatively new in this application and was first introduced in a 25 liter ULT portable unit during 2007. The basic components consist of the Stirling cooling engine and thermosiphon as shown in Figure 2. The Stirling engine employs helium gas as its working medium. There is no phase change of the working medium. The cycle expands and compresses the gas in segregated areas within the machine in order to provide a cold heat acceptor and a warm heat rejecter respectively. Thermal transport from the interior of the freezer to the cold acceptor of the Stirling is accomplished by a thermosiphon that contains a refrigerant, in this case ethane. The thermosiphon evaporator is a copper tube that is attached to the internal liner by aluminum tape in a similar manner to the evaporator of the cascade system. The condenser is integrated into the head of the Stirling. No oil is used; all running surfaces are suspended by gas bearings. Table 2 lists the significant materials and quantities of a recently developed 780 liter Stirling refrigeration system.

Figure 2. Major components of the Stirling system.

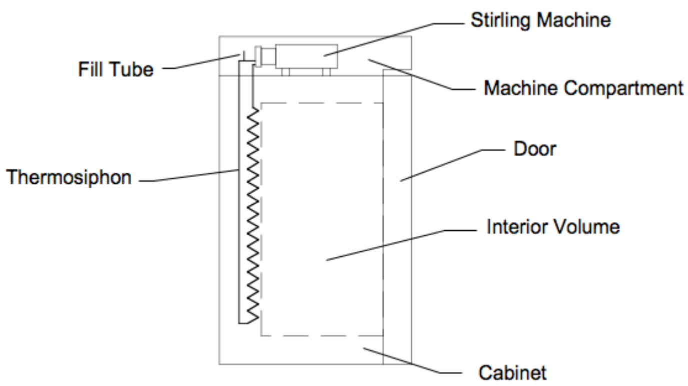


Table 2. Significant materials and associated masses used in a Stirling refrigeration system.

Component	Subgroup	Material	Mass (kg)
Stirling	Casing and other parts	Stainless Steel	7.455
	Flux pieces	Somaloy	3.568
	Structure	Aluminum	1.269
	Coils, tubes, HX *etc.*	Copper	3.912
	Other parts	Polycarbonate	0.34
	Magnets	Fe-Nd-B	0.4
	Springs, balance mass *etc.*	Steel	5.563
	Working gas	Helium	0.008
Thermosiphon	Evaporator	Copper	4.6
	Tape	Aluminum	0.5
	Refrigerant	Ethane	0.1
Fans	Blades	Polycarbonate	0.4
	Coil	Copper	0.3
	Flux pieces	Silicon Steel	0.4
	Frame	Aluminum	0.4
	Magnets	Fe-Nd-B	0.1
Cabinet	Insulation	Polyurethane	13.5
	Vacuum Insulated Panels	Unknown	10
	Blowing agent	HFC-245fa	1
	Envelope, door, and structure	Steel	121
	Inner liner, shelves *etc.*	Stainless steel	92
	Paint		10 sq. m.
	Thermal breakers, wheels *etc.*	Polycarbonate	8.2
	Gasket	Silicone	3.2
	Handle, trim *etc.*	Aluminum	1
	Wiring harness, *etc.*	Copper	0.5
Electronics	Power, inverter, LCD *etc.*	PC Boards	2.17
Shipping Carton	Carton	Cardboard	19
	Inner protection (0.05mm thick)	Plastic bag	0.5
	Pallet	Wood	33.7
Total			332.9

3. Mass Comparisons

From Tables 1 and 2 the overall mass for the Stirling is some 50 kg less than the hypothetical example cascade ULT freezer. Cascade units tend to be heavier than Stirling on a per unit volume basis as can be seen from Table 3. The Stirling ULT freezer uses more stainless steel but this is mainly in the inner liner of the cabinet though some of this material is used in the Stirling engine. The subject cascade unit does not use stainless steel for the inner liner. In some high-end units, stainless steel liners are used. Overall, copper use is less in the Stirling. The breakdown of the mass of each system is shown in Figure 3.

Figure 3. Mass breakdown.

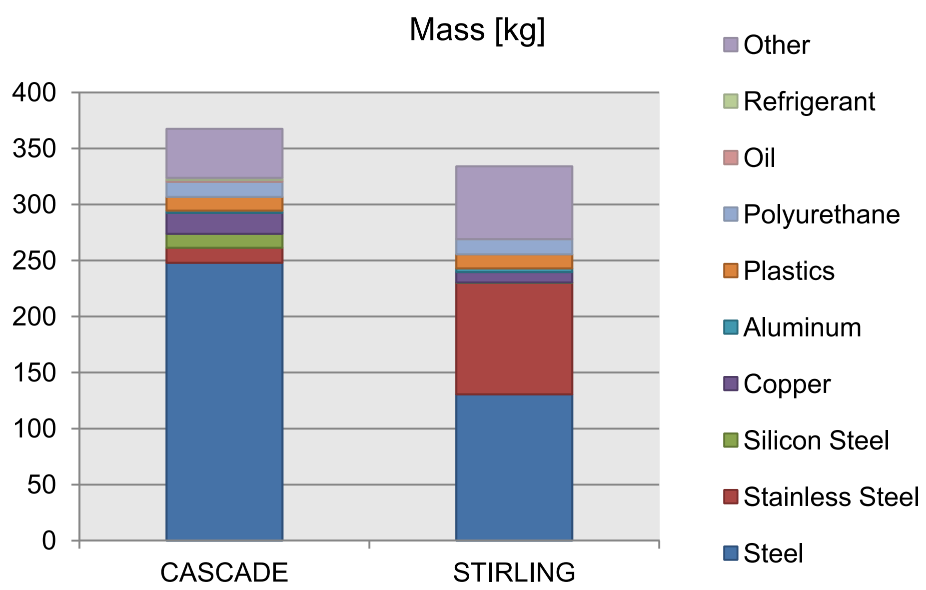


Table 3. Cascade energy consumption (raw data from [2]).

Brand	Volume (liters)	Shipping Mass (kg)	Energy (kWh/day)	Scaled Energy (kWh/day)
A	728	350	26.6	27.8
B	710	435	28.6	30.4
C	628	323	24.5	28.3
D.1	651	408	19.7	22.2
D.2	702	377	23.3	25.0
D.3	815	388	19.8	19.2
E	669	378	18.3	20.3
Average		379.9	23.0	24.7

The Scaled Energy is estimated for a 780l cabinet; D.3 data taken from manufacturers data sheet [3].

4. Energy Requirements and CO_2 Generation for Producing ULT Freezers

The energy required for production, or embodied energy, is a complex calculation because we need to determine the total primary energy required to produce each part. This includes process energy, transportation energy and transformation energy (effort to make the part). The energy, therefore, associated with the material of each component will include extraction, processing and transportation to the gate of the factory, namely, cradle-to-gate. Reasonably consistent data has been collected by Hammond and Jones [4] and will be used in this study. Hammond and Jones have also included the net CO_2 production associated with each material. Data not available in Hammond and Jones has been excerpted from [5]. Table 4 is a summary of the data as applicable to this study. Some items are best guesses since no data appears to be available or in some cases the material is proprietary as in the case of vacuum panels. Where a material cannot be reasonably matched with a similar material, the entry for that material is zero. The only example in this study is the vacuum insulation. The transformation energy is estimated on the basis of the total factory energy associated with the labor time to build one complete product ready for shipment at the gate of the factory. This depends on many items such as factory efficiency, building efficiency and type of electrical energy. In this study we are assuming similar factories operating at maximum efficiency and with identical transformation times. In a higher fidelity study, these items will be different though unlikely to be a major contributor to the total environmental impact. The CO_2 generation due to transformation is based on the average CO_2 generation per kWh for the U.S. [6]. In modern manufacturing methods, most cut-offs, tailings and other wastage is recycled. The ecological impact of recycled materials will be taken as small and is not included in this study. However, even with recycling, there is a wastage during transformation that we will estimate here as 3% overall. This number is unconfirmed and represents a space-holder to remind us that wastage should be controlled.

Cabinets of ULT freezers are generally constructed of a sheet steel envelope surrounding an internal volume also of sheet steel. The thermal insulation is a combination of vacuum insulation panels (VIP) and polyurethane insulation. A third generation blowing agent, HFC-245fa, is assumed for both systems, though at least one manufacturer uses a hydrocarbon-blowing agent. Hydrocarbon blowing agents such as isopentane have much lower direct GWP but have higher thermal conductivities of about 5% compared to HFC-245fa [7]. The polyurethane insulation contributes about 30% of the thermal insulation, the rest being VIP. All else being equal, a higher thermal conductivity will increase the power consumption according to the proportion of the two insulations, or about 2% for these numbers.

ULT freezers contain electronic controls and other items such as voltage stabilizers and LCD screens. The embodied energy and CO_2 for these parts have been estimated from data for computers and is a mass based average. Since the freezers are quite substantial, there is a significant amount of material in the shipping carton including a large polyethylene bag. This is included as an identical burden on both systems.

The total product embodied energy for both systems is shown in Figure 4. In this comparison, the Stirling cabinet has a higher energy burden due mainly to the higher content of stainless steel. The actual cooling device for the Stirling has a lower energy burden than the cascade system. This is due mainly to its lower copper content. Overall, the energy burdens for both systems are similar. The embodied CO_2, on the other hand, is significantly different and is shown in Figure 5 for two cascades and the Stirling. The cascade labeled 'cyclopentane' is calculated using this hydrocarbon as the blowing agent for the insulation. The other cascade and the Stirling are both assumed to have HFC-245fa as the blowing agent. By far the main contributors to embodied CO_2 are the refrigerants contained in the cascade systems. Bearing in mind that refrigerant leaks do happen, even one leak during the life of a cascade system has a substantial environmental impact. In theory, hydrocarbon refrigerants could be used in these systems, but practically it is not acceptable (in the US) due to flammability concerns. Flammable refrigerants are seen as a safety risk in cascade systems because a chain of consequences could lead to an explosive hazard. This might occur because the system operates sub-atmospheric and therefore if a leak should develop air could enter the system and potentially create an explosive mixture. A locked rotor condition or other energetic source, perhaps from a dry bearing due to oil starvation, may become an ignition source. The Stirling system uses helium in the engine but does require a refrigerant in the thermosiphon, in this case, a hydrocarbon. The quantity is small (100 g or less) and it is not exposed to any moving machinery or potential ignition sources, so the safety risk is negligible. Of course, in servicing, safety procedures would be well established as they are for any situation where flammable gases are involved. Even if this small risk were unacceptable, the Stirling could use a non-hydrocarbon refrigerant such as R-508B, the quantity would be about 200 g adding an equivalent 2.7 tons to the embodied CO_2, still considerably less than the burden on the cascade system.

Table 4. Embodied energy and carbon for materials [4].

Material	Embodied Energy (MJ/kg)	Embodied Carbon ($kgCO_2$/kg)
Aluminum (virgin)	218 [4] 221 [5]	11.46
Copper (virgin)	70 [4] 113 [5]	3.83
Steel (virgin)	35.3 [4] 39 [5]	2.75
Stainless Steel (304)	56.70 [4] 43.2 [5]	6.15
Cast iron	25 [4] 62.6 [5]	1.91
Polycarbonate	112.90	6.0
ABS	95.3	3.10
Lamination steel	50.4 [5]	2.51 (estimate)
Magnet	24.5 [5]	1.91 (estimate)
Helium	8 [5]	Negligible
R-407D	47 (estimated from [8]) [a]	1627 (GWP_{100})
R-508B	47 (estimated from [8]) [a]	13396 (GWP_{100})
Ethane (R-170)	Taken as zero [9]	5.5 [10]
HFC-245fa	47 (estimated from [8]) [a]	950 [8] to 1030 (GWP_{100}) [11]
Cyclopentane	0	25
Polyester (assume LDPE film)	89.3	1.90
Poly ester oil	117 [5]	3.5 (assumed similar to solvent paint)
Polyurethane	72.1	3.0
Silicone rubber	120.0	4.02
Epoxy	139.3	5.91
Cardboard	24.8	1.32
Timber	7.8	0.47
Plastic film (polyethylene)	83.1	1.94
Paint (single coat)	10.2 MJ/m^2	0.53 kg CO_2/m^2
Electronics	480 MJ/kg (estimated from [12]) [b]	23.6 (estimated from [12]) [c]

[a] Assuming 1 kg CO_2 is equivalent to 5.22 MJ of electricity, from average U.S. electrical energy mix [6]; [b] Data indicates 12 kg fuel per kg of computer [12]. Assume 40 MJ/kg for fuel as a reasonable guess for hydrocarbon based fuel; [c] Assuming 30% efficiency for central power plant with line losses (USA).

Figure 4. Product embodied energy.

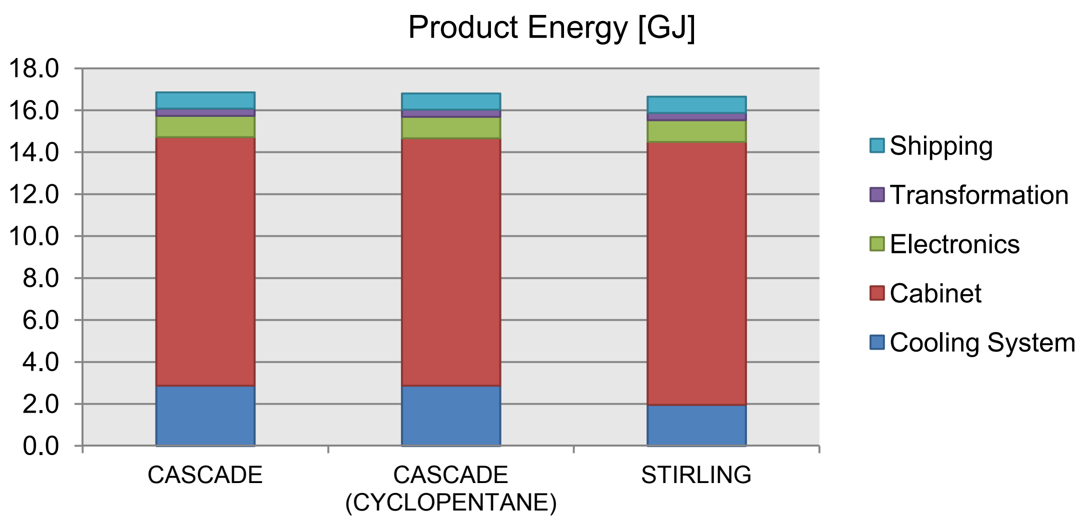
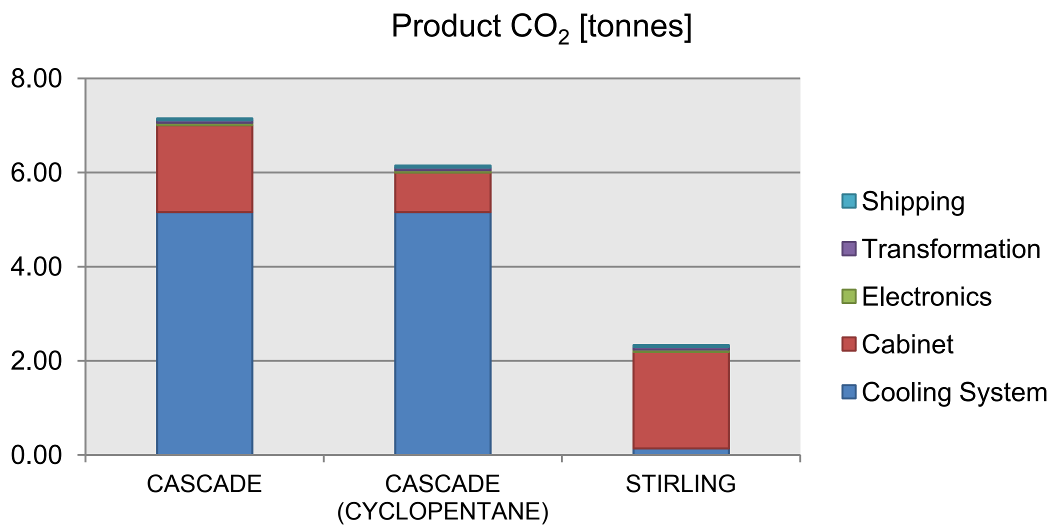


Figure 5. Product embodied CO_2.



5. Comparative Operating Efficiencies and Use Consequences

A measure of the efficiency of a cooling system is the coefficient of performance (COP). This is defined as the ratio of the heat removed from the system to the input energy, both in identical units. The cascade system will achieve a practical COP of about 0.25 and the Stirling about 0.39 at a cold side of −90 °C, roughly the temperature when the cabinet is at −80 °C. However, the cascade modulates its capacity by switching on and off which robs it of performance, perhaps reducing its effective COP by as much as 20%, to around 0.2. The Stirling, on the other hand, runs continuously and modulates by reducing its piston amplitude to reduce capacity. The Stirling COP will actually improve with reduced input thereby improving overall efficiency. There are other added parasitic requirements such as fan power, drive electronics and perhaps an electric door gasket heater. A significant factor in operating efficiency is the quality of the thermal insulation of the freezer. In the compared systems best-in-class vacuum insulation with polyurethane support structure has been assumed in both cases. With these factors, a typical modern 650 to 700 liter class cascade ULT freezer will consume about 24 kWh/day under steady-state conditions. Table 3 lists energy consumptions and associated internal volumes for cascade systems from different manufacturers (redacted from [2]). The scaled energy is estimated for an internal volume of 780 liter by scaling the energy consumed to the 2/3 power of the volume ratio. This is approximate and assumes that the cabinet heat leak is proportional to its surface area and that the input is proportional to the heat leak. It also assumes that the cabinet is a regular geometric shape. The scaled energy suggests an average consumption for cascade systems of about 26 kWh/day for 780 liter cabinets. The equivalent Stirling system consumes about 11 kWh/day.

Since use-energy is so dominant for ULT freezers, it is instructive to investigate the consequences of reduced insulation effectiveness due to hydrocarbon blowing agents. Therefore, for identical cabinets and as explained previously, assuming cyclopentane to have an increased heat leak of 2% above the baseline cabinet, results in a corresponding increase of 2% in the input.

The base load of ULT freezers to the building HVAC (Heating Ventilation and Air Conditioning) system is substantial. This load must be removed by the HVAC system in summer and in winter it may provide sufficient heating to offset the requirement to heat the building. For this study we will assume that the HVAC system cools with a COP of 3.2, the U.S. average cooling performance [13], during the summer months and that no heating is required during winter. This is not untypical; at least one bio-repository facility familiar to the authors provides no supplemental heating at all since the heat output from the freezers is in excess of what is needed to heat the building. We are assuming that this will be true whether Stirling or cascade ULT freezers are used. During summer, therefore, an added burden to the use energy of each system will be the energy that it uses divided by the COP of the HVAC system. This represents the effort required to remove the heat generated by the ULT freezer from the facility. Doyle [14] has reported an increase of 20 to 30% for the cooling load for a facility at the University of California, Davis campus. The approach used in this work produces a smaller HVAC burden than reported by Doyle and it is understood that this load is strongly dependent on the locality of the facility. Nevertheless, it is important to show that HVAC loads are a significant fraction of the total use energy and that they depend on the performance of the HVAC system and the amount of heat that needs to be removed. Using the energy consumption and HVAC COP figures and assuming CO_2 generation from the production of electrical energy at the U.S. rate of 0.69 kg/kWh (for 2007 [6]), a comparison of the two systems can be constructed assuming a 10-year life for both. This is shown in Figures 6 and 7 and includes the embodied energy and CO_2 for the product to demonstrate the relative contributions of use and manufacture.

Environmental impact is often analyzed on the basis of total equivalent warming impact (TEWI) calculations. TEWI considers only two contributions, the refrigerant released during the lifetime of the equipment, including unrecovered losses on final disposal and the impact of CO_2 emissions used to generate energy to operate the equipment throughout its life. The annual leak rate of refrigerant from a self-contained system is estimated at 2% and the recovery at end-of-life is between 90% and 95% [9]. Using these numbers on the example cascade systems, the loss of refrigerant over the life of the system would be 159 g for R-407D and 79 g for R-508B, about 1.3 tons CO_2 equivalent. Figure 8 shows the TEWI comparisons for this scenario. Included is the TEWI for a typical U.S. household 510 liter refrigerator consuming 1.6 kWh/day with a use-life of 15 years [15]. This is higher than the 1.4 kWh/day average use suggested by the IPCC report [10] probably because it is older data.

Figure 6. Embodied, use and Heating Ventilation and Air Conditioning (HVAC) energy over a 10-year life.

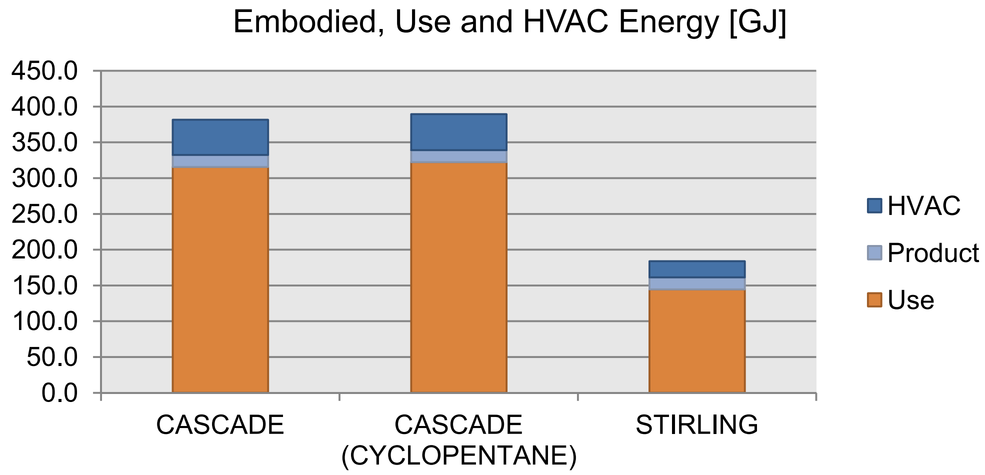


Figure 7. Embodied, use and HVAC CO_2 for a 10-year life.

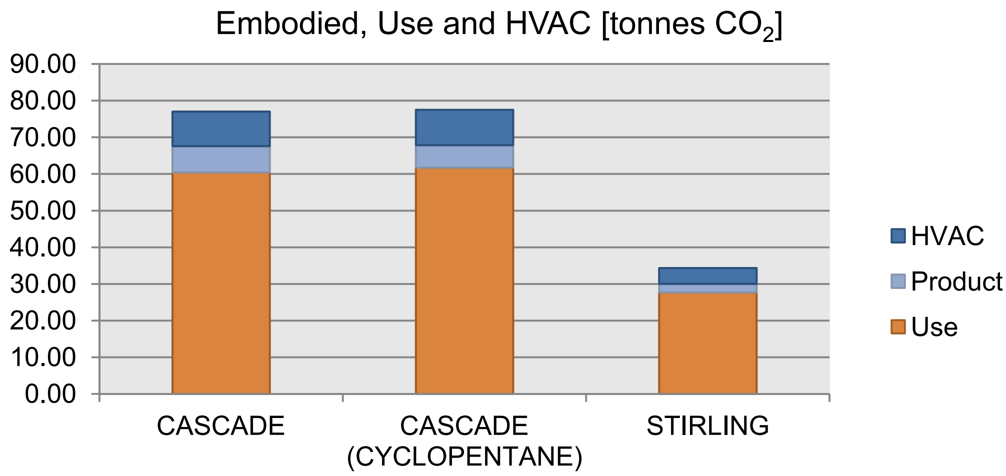
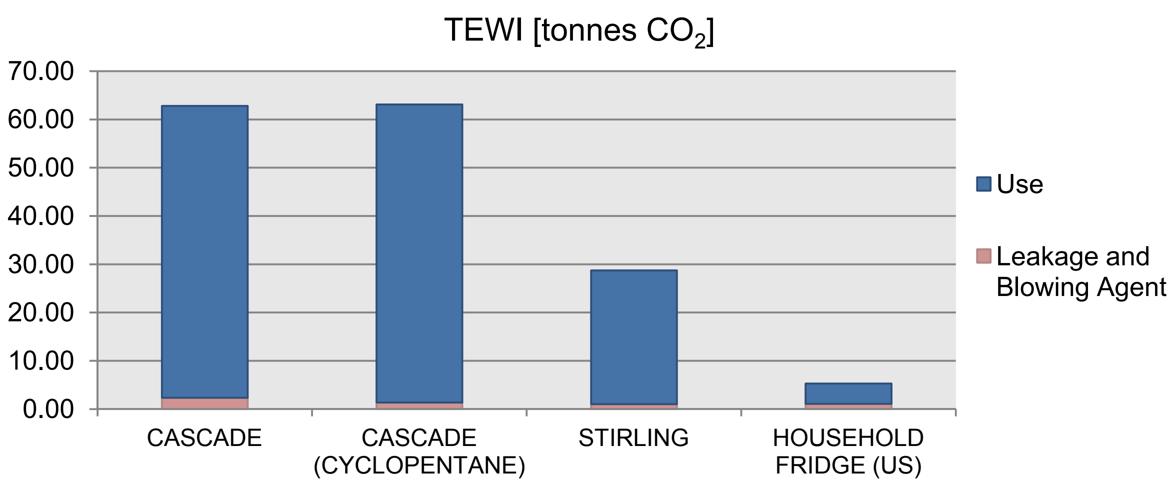


Figure 8. Total Equivalent Warming Impact (TEWI) over a 10-year Life (Household Refrigerator scaled from 15-year life data).



6. Other Items Contributing to the Ecological Footprint

During maintenance, refrigerants must be recovered. By U.S. law, this should be in excess of 90%. Since R-508B is such a strong GWP agent, even small amounts of unrecovered refrigerants present a huge environmental impact. For example, a loss of 30 g of R-508B as may be experienced in a single cascade system repair event, results in an equivalent environmental impact of 402 kg CO_2. That is more than is released by the manufacture of the Stirling cooling system unit.

How a machine is disposed of at its end-of-life is another increasingly important issue. In the case of HFC refrigerants, it is imperative that the refrigerants be recovered though recovery is not 100% effective and landfill issues such as oil contamination is an added difficulty with cascade systems. Hydrocarbon refrigerants are not environmentally toxic and may be released to the environment (or combusted) under controlled conditions. In this comparison no end-of-life recycling has been considered though it is worth noting that the Stirling runs on gas bearings and is not subject to wear-out. In this regard, Ross and Boyle [16] have investigated a number of Stirling devices and report no degradation in at least 5 years of continuous operation. Wood [17] reports 8 years of continuous operation without degradation. A practical recycling program could be envisioned whereby the Stirling engines are recovered and refurbished. This is unlikely with compressors. A true life cycle climate performance (LCCP) analysis would include end-of-life considerations as well as a more detailed analysis of statistical refrigerant loss for these systems.

7. Sustainability

The question arises as to what needs to be accomplished in order to develop a sustainable ULT freezer product? There are four specific areas where this can be addressed:

1. During manufacture. Avoid encouraging the production of high GWP refrigerants (e.g., R-508B) by safely using hydrocarbons or other low GWP refrigerants. Implement rigorous recycling and utilization of biodegradable materials.
2. During use. Plant trees to offset CO_2 generation. One acre of newly planted trees will sequester about 8 tons of CO_2 over a 10-year period [18]. That is about 8 acres for a cascade system and about 3.5 acres for each Stirling ULT freezer.
3. End-of-life. Implement a return policy for the ULT freezers, recycle or refurbish. Aside from wear and tear on the cabinet hardware and electronics, the cascade systems suffer much higher wear-out rates than the Stirling. The basic Stirling machinery will show no loss of performance over at least an 8-year period and because the machinery is more easily accessed, recovery and reuse of the Stirling unit is a practical proposition. The cabinets too can be designed for better recyclability. E.g., a concept by L. Schilf where the entire cabinet insulation is a vacuum supported by diatomaceous earth, which is a highly recyclable substance (Okokühlshrank project) [19,20].
4. Product improvements. While cascade technology is mature and therefore unlikely to show significant energy-use improvement with further development, the Stirling is new and is at the beginning of its development cycle. Deployment of this technology should see significant early improvements as the technology begins to mature.

ULT freezers currently use a huge amount of electrical energy and have an ecological impact that is between 10 and 20 times that of a domestic refrigerator. This is an application where energy efficiency can play a major role in mitigating climate change because reduced energy consumption does not necessarily mean higher deployment numbers [21].

8. Conclusions and Discussion

By comparing a typical ULT cascade freezer with its Stirling counterpart, it has been shown that the most dominant aspect to the ecological footprint is the use energy and consequent CO_2 generation. This is the key point where the ecological impact of these machines can be mitigated. Cascade cooling systems are optimized in roughly the same manner and universally use best-in-class cabinets. Therefore almost all ULT cascade freezers consume roughly the same energy for a given internal volume and temperature. The degree of thermodynamic improvement is likely to be minimal on the best units now available. What is really needed is a new technology that radically changes the expectation of the use energy. This is not only an issue of CO_2 generation but also impacts the cost of operation. There is only one obvious deployable technology that can reasonably address this and that is Stirling. In its first deployment, the Stirling has shown that it is able to obtain the same performance at less than half the use and embodied energy and CO_2 generation of a similar sized cascade system. In the future, this is likely to improve because this technology does not yet have the inevitable incremental improvements that will occur in performance and manufacturing efficiency. Other obvious improvements would be the use of a water- or hydrocarbon-based blowing agent that would reduce the entire embodied CO_2 of the Stirling freezer to about the same level now experienced by the refrigerant leakage from the cascade alone. Of course, the increased thermal conductivity of such insulation would have to be addressed by perhaps increasing the cabinet wall thickness to avoid offsetting this improvement by higher use energy.

Cost, of course, has not been dealt with in this study but clearly the reduction of energy use is a major cost savings since ULT freezers are long-lived and heavy users of electrical energy. Lowering the energy use profile reduces the requirements for HVAC, electrical power infrastructure and back-up equipment thereby reducing facility costs too. Any overall cost analysis would have to include these savings against the price differential of the cascade *versus* Stirling ULT freezer.

Acknowledgments

The authors wish to thank our colleagues for providing input and suggestions and particularly N. Lane for encouraging unbiased reporting of Stirling technology.

Conflict of Interest

Global Cooling Inc. manufactures Stirling ULT freezers. Independent testing and verification is a policy of the company.

References

1. Appliance Standards Awareness project. July 2011. Available online: http://www.appliance-standards.org/sites/default/files/Refrigerator%20Graph_July_2011.PDF (accessed on 18 September 2012).
2. Nash, R.V. ULT Freezer Performance Testing, Design Services Network, Project #111686, November 2011. Available online: http://escoglobal.com/products/download/1330394543.pdf (accessed on 18 September 2012).
3. Thermo Fischer Scientific. *Technical Data Sheet*; Model TSU600D, Revision 0; Thermo Fischer Scientific: Ashville, North Carolina, July 2011.
4. Hammond, G.; Jones, C. *Inventory of Carbon and Energy*, Version 1.6a; Department of Mechanical Engineering, University of Bath: Bath, UK, 2008; pp. 9–15.
5. Franklin Associates, Ltd. *Life Cycle Inventory of Production of Component Materials for Conventional Compressor and a Stirling Compressor*; Confidential report prepared for the Coca-Cola Company and Global Cooling Inc.; Franklin Associates, Ltd: Prairie Village, Kansas, USA, 2002.
6. U.S. EPA Calculations and References. 2007. Available online: http://www.epa.gov/cleanenergy/energy-resources/refs.html (accessed on 18 September 2012).
7. McMenamin, J.; Robin, M.L.; Loh, G.; Creazzo, J.A. *Development of Novel Blowing Agents for Polyurethane Foams*; UTECH Europe: Maastricht, The Netherlands, 2009. Available online: http://www2.dupont.com/Formacel/en_US/assets/downloads/UTECH_presentation_20090331.pdf (accessed on 18 September 2012).
8. Arthur D. Little, Inc. *Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant, and Fire Protection Applications*; Final Report; ARAP: Cambridge, MA, USA, 21 March 2002.
9. The Australian Institute of Refrigeration. Best Practice Guidelines. In *Proceedings of Air Conditioning and Heating, Methods of Calculating Total Equivalent Warming Impact (TEWI) 2012*, Melbourne, Australia, 2012.
10. Intergovernmental Panel on Climate Change, Working Group I. The Physical Science Basis, Non-Methane Volatile Organic Compounds. In *Fourth Assessment Report: Climate Change 2007*; Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L., Eds.; Cambridge University Press: Cambridge, UK and New York, NY, USA. Available online: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2–10–3-2.html (accessed on 18 September 2012).
11. U.S. Environmental Protection Agency. Transitioning to Low-GWP Alternatives in Domestic Refrigeration, EPA-430-F-10–042, October 2010. Available online: http://www.epa.gov/ozone/downloads/EPA_HFC_DomRef.pdf (accessed on 18 September 2012).
12. Low-tech Magazine 16 June 2009. Available online: http://www.lowtechmagazine.com/2009/06/embodied-energy-of-digital-technology.html (accessed on 18 September 2012).
13. Power Knot LLC. Reducing your carbon footprint. COPs, EERs, and SEERs. How efficient is your air conditioning system? 2011. Available online: http://www.powerknot.com/pdf/Power_Knot_about_COP_EER_SEER.pdf (accessed on 18 September 2012).

14. Doyle, A.; Ip, S.; Getty, A.; Stewart, L. Freezer Challenge: Are You Cool Enough? In *Proceedings of California Higher Education Sustainability Conference*, University of California, Davis, CA, USA, July 2011.
15. Sand, J.R.; Fischer, S.K.; Baxter, V.D. Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies. In *Alternative Fluorocarbons Environmental Acceptability Study*; U.S. DOE, Oak Ridge National Laboratory: Oak Ridge, TN, USA, 1997; pp. 30–31. Available online: http://www.afeas.org/tewi/tewi-iii.pdf (accessed on 18 September 2012).
16. Ross, R.G.; Boyle, R.F. An Overview of NASA Space Cryocooler Programs—2006. In *Proceedings of International Cryocooler Conference*, Annapolis, MA, USA, June 2006.
17. Wood, J.G. Status of Free-Piston Stirling Technology at Sunpower, Inc. In *Proceedings of 1st Int. Energy Conversion Engineering Conference*, Portsmouth, VA, USA, August 2003.
18. Upson EMC. Keeping Forests in Forests, 2009. Available online: http://www.upsonemc-carbonoffset.com/C02treestore.aspx (accessed on 18 September 2012).
19. Mennink, B.D.; Berchowitz, D.M. *Development of an Improved Stirling Cooler for Vacuum Super Insulated Fridges with Thermal Store and Photovoltaic Power for Industrialized and Developing Countries*; International Institute of Refrigeration: Hanover, Germany, May 1994.
20. Schilf, L. Thermal Insulation of Vessels and Method of Fabrication. U.S. Patent 4,349,051, September 1982.
21. Menzer, M.S. Use of Energy Efficient Products as a Measure for Responding to Climate Change, Air-Conditioning and Refrigeration Institute, Arlington, Virginia, USA. Available online: http://www.lcs.syr.edu/faculty/khalifa/MAE554/TEWI.htm (accessed on 18 September 2012).

© 2012 by the authors; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (http://creativecommons.org/licenses/by/3.0/).