Engineers Without Borders USA: The "Chill Challenge"

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Introduction and Summary:

Refrigeration is a key to economic and social development, but affordable refrigeration will be a difficult challenge for hundreds of millions of people who will rely on off-grid electricity in the future. To address the problem, Engineers Without Borders USA launched its "Chill Challenge" in 2019, funded by a grant from the Open Philanthropy Project. In response to its solicitation, forty-three teams from ten countries submitted proposals for grants to test their refrigerator and icemaker concepts. A total of $305,000 was awarded to seven teams representing several innovative technologies, and a good mix of technical risk and reward.

Although the COVID pandemic delayed the work of all of the teams to some extent, all had completed their research by the summer of 2021, and final reports by the end of the year. Several of the teams have demonstrated technologies that appear to be commercially viable. As might be expected, others have reported "interesting failures" or inconclusive results that require additional evaluation. More broadly, the initiative has also highlighted the key design factors which innovators have to consider in providing more affordable refrigeration options. Based on the work to date, community sized icemakers appear to offer several technical and commercial advantages over refrigerators in meeting the initiative's affordability standards. Several additional technologies also appear to merit testing in future efforts.

Background

The Off-Grid Refrigeration Challenge

Refrigeration is a key to economic and social development; it is critical for health and nutrition, and can reduce food waste, provide economic opportunities for farmers and businesses, and reduce the burden on women. However, there may be as many 2 billion people worldwide without access to reliable refrigeration. Economic growth may bring refrigeration to a large portion of this population, but refrigeration will be a particularly difficult challenge for the hundreds of millions of people who will acquire electricity via "mini-grids" or "solar home systems." These distributed power systems increasingly have been used to provide power for lighting, cell-phone charging, and TV for households far from the electricity grid. However, refrigeration requires a quantum leap in power and investment, and with current technology may remain out of the reach of most off-grid households for the foreseeable future.

Several efforts have been made to address the problem. From a technology perspective, one pathway has been to promote small, highly efficient DC refrigerators for household use, powered by solar PV panels. Similar fridges have largely replaced older kerosene and propane powered units for vaccine storage. However, although most of these are more efficient than conventional AC-powered units, they are generally more expensive, well out of the reach of most off-grid households. While the goal is commendable, getting refrigerators into individual off-grid households faces several obstacles. One is a classic "chicken and egg" problem: The price of efficient DC fridges could fall significantly when they are produced at a larger scale, but there will only be a market for large-scale production when the prices fall. A second hurdle has to do with cost efficiency. Figure 1 is a plot of the estimated total monthly cost of ownership[1] of efficient DC refrigerators and refrigerator/freezers, compared to US "Energy Star" AC refrigerators. As can be seen, the smaller fridges, which have the lowest upfront cost and which would be most affordable to households, are considerably more expensive *per liter* of useable space than larger units. A 250-liter fridge, for example, would provide five times the volume of a 50-liter fridge, but might only cost 60% more. A third challenge with efficient DC fridges is that their advantage tends to disappear with the falling cost of solar PV electricity. Even at the high off-grid electricity cost assumed in Figure 1 ($0.80/kWh), the conventional AC fridges can be cheaper to own and operate than the DC units due to lower initial prices. As the cost of solar panels and batteries continue to decline, that advantage will become more pronounced.

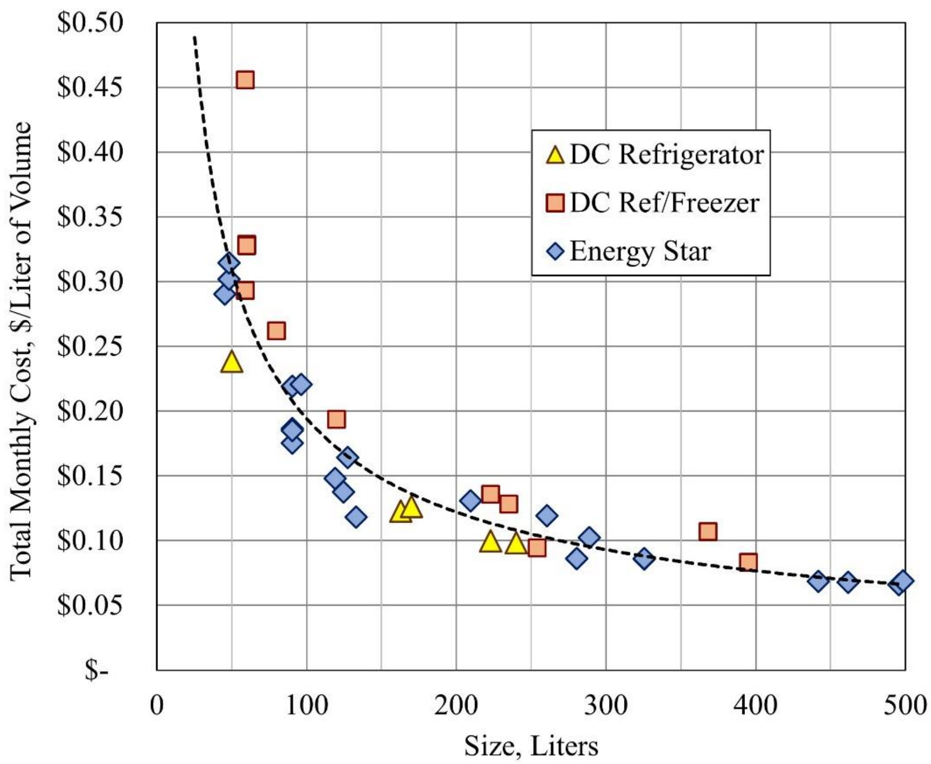


Figure 1: Cost of Off-Grid Refrigeration Options

EWB's "Chill Challenge"

To help address this problem, Engineers Without Borders – USA launched its "Chill Challenge" in September 2019. Funded by a generous grant from the Open Philanthropy Project, the initiative was designed to complement other programs in this space. Rather than existing refrigerators, however, the goal of the Chill Challenge was to examine innovative refrigeration technologies that might prove to be significantly cheaper. EWB solicited proposals from interested researchers for grants to build and test proof-of-concept prototypes meeting a number of parameters (Detailed in Appendix B). These centered on three key design elements:

[1] Price data was from 2019. Monthly cost includes amortization of the initial cost over 10 years at an interest rate of 10%/year, plus the cost of power assuming an electricity cost of $0.80/kWh. Costs for A/C fridges include $150 for an inverter which is assumed to operate at 95% efficiency.

1) *Two Design Tracks:* Rather than refrigerators sized for households, the initiative solicited designs for:
   a. A larger, 150–250-liter refrigerator appropriate for the small shops and bars that are typically the early adopters of refrigeration in communities.
   b. A community icemaker capable of producing 100-1000 kg. of ice per day that could address cooling needs for households, farmers, and small businesses.

   Either design needed to be powered by off-grid energy sources, be suitably reliable for a remote setting, and be transportable to the field in a small pickup truck.

2) *All Refrigeration Technologies:* The initiative was open to proposals using all refrigeration technologies, including those driven by thermal energy, as well as conventional vapor compression and other electrically powered technologies. The only technologies excluded were those that would be unsafe or that used high global warming potential (GWP) refrigerants.

3) *Focus on Affordability:* Proposed designs were judged primarily on affordability. The target for the refrigerator was a total cost to own and operate of no more than $12/month, and the icemaker target was a cost of no more than $0.03 per kg of ice produced. The parameters included details for calculating costs of the various energy options available and a formula for amortizing capital costs over ten years at an interest rate of 10%/year.

In response to the call for proposals, EWB received 43 submissions from 36 teams. Sixteen of the teams were linked to universities, including four EWB-USA university teams; ten represented companies or NGO's; and ten came from individuals. Sixteen of the teams were U.S.-based, and others were based in Cameroon, Ethiopia, France, Germany, Nigeria, South Korea, Switzerland, Uganda, and the UK.

	Energy Source							
Refrigeration Process	Solar PV	Solar Thermal	Minigrid	Biomass	None	Biogas	Other	Totals
Vapor Compression	20.5		3			1	1	25.5
Adsorption		3.5		2			0	5.5
Absorption		1				1	0	2.0
Stirling Cycle							2	2.0
Thermoelectric (Peltier)	0.5						1	1.5
Evaporative Cooling	1.5						0	1.5
Sky Radiant Cooling					1		0	1.0
Thermoacoustic							0	0.0
Caloric							0	0.0
Unknown/unclear							4	4.0
Totals	22.5	4.5	3	2	1	2	8	43.0

Table 1: Chill Challenge Proposals

Table 1 shows the distribution of refrigeration technologies, as well as their energy source, proposed in the submissions. (Several proposals combined two technologies, which are represented by fractions in the table.) As shown, almost half of the teams proposed vapor compression refrigeration driven by power from solar PV panels. Although many of these were solid proposals, most had difficulty in demonstrating how they would be substantially more affordable than refrigerators currently on the market. Thermal sorption (absorption and adsorption) refrigeration processes, driven by either solar or biomass, were the next most cited technologies, and a few teams proposed Stirling cycle, thermoelectric and evaporative cooling technologies. Somewhat surprisingly, there were no proposals to test thermoacoustic cooling or any of the various emerging caloric technologies (e.g., magnetocaloric, electrocaloric, elastocaloric, barocaloric).

Of the forty-three proposals submitted, fourteen were shortlisted for further consideration, and in April 2020 EWB awarded grants, totaling $305,000, to seven proposals that were ranked highest by the grantee review panel. The original target date for completing research was December 2020, but the emergence of the COVID-19 pandemic delayed all the teams, some more significantly than others. It also prevented site travel by some teams and limited plans for international collaboration by others. Nevertheless, all the teams had substantially completed their research by July 2021, and final reports had been submitted and approved for all the grantees by the end of the year.

Research Results

The proposals receiving grants represented several innovative technologies, and a good mix of technical risk and reward. Two grantees focused on vapor compression refrigeration powered by solar PV, two tested sorption systems using solar thermal energy as a source, two proposed sorption systems driven by biomass, and one examined the potential of using sky radiant cooling. Details of each of the teams' concepts and research results are included in Appendix A. A summary follows:

Vapor Compression Driven by Solar PV:

Conventional vapor compression refrigeration provides cheap and reliable cooling for billions of grid-connected households but can be unaffordable for many off-grid communities due to the high cost of electricity. The Chill Challenge targets, which called for a roughly 50% reduction in costs over conventional options, required innovative proposals for vapor compression processes. Two proposals, both for icemakers to be powered by solar PV, received grants,

Purdue University's Herrick Labs, West Lafayette, Indiana received a grant to explore the use of a vapor compression unit to provide both cooling for icemaking and heating for drying crops. Many of the target communities have a need for both, and the combined use could be a way to effectively lower the capital expense for refrigeration while providing improvements over conventional crop drying. The Purdue team assembled an icemaker using propane as the refrigerant and employed a metering valve to serve as a variable expansion valve. Preliminary tests showed that the metering valve could vary refrigerant flow rates and condenser temperatures, and the researchers demonstrated that the prototype could simultaneously produce ice and perform a drying function. However, the research also highlighted a basic challenge with the concept. Raising the condenser temperature as needed for crop drying significantly lowers the efficiency of the system for ice making and vice versa. Therefore, while it seems possible to build a unit that can perform either function, one would need to be prioritized at a time. There may be specific situations where such a capability would be commercially viable. Some areas, for example, might have a greater need for drying during rainy season, when the demand for ice is lower. Those potential applications may be limited, however.

Solar Cooling Engineering UG, Hohenheim Germany, received funds to build and test an icemaker using its SelfChill® cooling units. These are small, efficient, DC vapor compression units designed for solar PV power systems that use the low GWP refrigerant R600a (isobutane). The use of these standardized units allows for flexible, modular designs which promote local sourcing and assembly while minimizing transport costs and import fees. The team's prototype uses four compressor units to chill a brine heat transfer fluid contained in an innovative, low cost insulated box. Block ice is formed by immersing water-filled cans in the cold brine. The team tested the prototype in Stuttgart and found that the unit could freeze 50 kg of ice in 15½ hours. In its cost analysis, Solar Cooling concluded that two of these units could produce 100 kg of ice per day at a cost of 5.2 cents per kilogram, after including the cost of transporting and importing components and a 25% margin for labor and profit. While above the Chill Challenge target of 3 cents/kg, the unit appears to be commercially viable, particularly for a smaller icemaker that can be built by local craftsmen and entrepreneurs. Solar Cooling received an additional grant from Open Philanthropy to conduct field tests of the prototype design in East Africa.

Solar Thermal Sorption:
As an alternative to using solar PV panels to generate electricity to power vapor compression refrigeration, it is possible to use solar thermal energy directly to drive a sorption refrigeration process. Although solar sorption units have not been produced commercially at scale, a number of prototypes have been tested and demonstrated in the field. Two teams received grants to test their concepts.

Clean Energy Process (CEP) Laboratory, Imperial College London was awarded a grant to develop and test a solar-driven diffusion absorption refrigeration (DAR) icemaker. Diffusion absorption refrigeration, invented in 1922, is the basis for countless propane and kerosene refrigerators used in recreational vehicles and remote locations around the world. With no moving parts, they are quiet and reliable, but the cost of kerosene or propane makes them expensive for typical off-grid households. The CEP team adapted a conventional DAR unit design to specifically target solar-cooling applications in warmer climate conditions. With an ammonia-water working pair, the temperature needed to drive the unit is 150-200º C, which is provided by a high-performance external concentrating parabolic solar collector. The team was unable to test the unit in Egypt as planned but developed a dynamic model to predict the unit's cooling capacity and used tests in London to confirm the model. The prototype tested is small, capable of producing only 6.2 kg of ice/day, but CEP believes that multiple units could be combined to produce ice at 4-5 cents/kg. Further work will be needed to confirm the prototype performance in the field, to design larger units, and to explore potentially more efficient working pairs.

Xergy Corporation, Harrington, Delaware received funds to build and test a novel adsorption refrigerator driven by hot water from a solar collector and using a hydrogen/metal hydride working pair. Metal hydride heat exchangers (MHHX's) generate heat when absorbing hydrogen and absorb heat when desorbing hydrogen. While similar to other adsorption processes, a hydrogen/metal hydride working pair can, in theory, exhibit higher efficiencies (COP's of 0.7 or above) while being driven by relatively low temperatures ($<100^o$ C). That combination could permit the use of lower cost evacuated tube collectors for energy generation with hot water storage to cover days without sunshine. Xergy built its refrigerator using three MHHX's to act as a 2-stage hydrogen compressor. These were connected to hot water sourced from an evacuated tube solar collector, an ambient water loop and a cold-water loop to deliver refrigeration. The company ran a series of tests on the refrigerator and was gradually able to lower the temperature in the cold box from 25^o C to 7^o C. However, the cooling output was low, estimated at only 35 Watts by the company. In its evaluation, Xergy noted that there were potential inefficiencies in sensible heat losses in the prototype, but the placement of thermocouples made it difficult to accurately measure or minimize those losses. The use of this novel working pair may still have potential, but further research would be needed to demonstrate a proof of concept.

Biomass Powered Thermal Sorption:

Biomass, in the form of firewood and other cooking fuels, comprises an overwhelming percentage of the primary energy consumed by off-grid households. The widespread availability of biomass in rural communities and its low cost make it an attractive potential energy source for sorption refrigeration. Two teams researched options for the use of biomass-driven sorption for off-grid refrigeration.

Purdue University's Herrick Labs, West Lafayette, Indiana, received a grant to evaluate the use of heat from cook stoves to drive an intermittent sorption "cold storage battery." Similar to the Crosley "Icy-Ball" which was used in the early 1900's for off-grid refrigeration, the concept called for heat from a cook stove to generate a refrigerant which could be condensed and stored. The refrigerant could then be expanded in a discharging mode to create cooling on demand. Purdue researchers chose ammonia and activated carbon as the working pair for the process and, after delays due to the COVID pandemic, built an instrumented laboratory model to test the concept in early 2021. When testing the system, however, only very limited cooling was achieved due to poor heat and mass transfer. It was determined that considerable additional work and an extension of the research schedule would be required to properly test the concept and it was mutually agreed to terminate the project instead.

New Leaf Dynamic Technologies, New Delhi, India, was awarded funds to build and test a large ice maker using its "GreenCHILL™" technology, which uses an advanced biomass gasifier and an ammonia adsorption process for cooling. The company has successfully marketed its technology to refrigerate cold rooms in a number of locations in India, using several feedstocks, including agricultural waste. For the Chill Challenge, the company contracted for construction of a 1000 kg/day icemaker to pair with its adsorption unit. After assembling the prototype, New Leaf ran a series of tests of the icemaker and found it capable of producing 40-45 kg of ice per hour while consuming 8.8 kg of firewood per hour to drive the sorption process and 550 Watts of electrical power to power pumps, fans, and controls. As a result of its testing, the company identified several modifications that could improve efficiency and safety for a production prototype. Under the Chill Challenge parameters, New Leaf's prototype appears capable of producing ice at a cost slightly above the $0.03/kg target, but actual production costs should be lower, both through efficiency improvements and by the ability to use lower cost feedstock. Overall, the company's icemaker appears to be a commercially viable option for off-grid communities, and it has attracted interest from investors in this field.

Sky Radiant Cooling:
Sky radiant cooling is one of the more intriguing technologies explored under the Chill Challenge. "Night sky radiation" in arid climates is a well-known phenomenon, one used by the ancient Persians to produce ice and demonstrated for air conditioning in several prototype structures beginning in the 1960's. More recently, research has focused on selective radiators that emit infrared radiation with wavelengths of 8-13 µm, corresponding to the "atmospheric window." These can achieve greater cooling power and lower cooling temperatures, and, if designed to reflect light in the visible spectrum, can offer effective cooling during the day as well.

Arup Engineering, London, received a grant to explore the potential for using this phenomenon for refrigeration. The company proposed to use a sky-facing selective radiator combined with phase-change materials and a thermal "diode" to create a passive refrigerator without the need for electricity or other energy sources. The team examined three key questions to evaluate the feasibility of the concept. Researchers first investigated a radiative cooling material that demonstrated high cooling potential in the laboratory but were unable to produce a surface that was both durable and capable of achieving the low temperatures needed for refrigeration. Arup also evaluated a number of design configurations to minimize parasitic heat flows from the ambient to the radiant surface, but none met the company's design targets. Finally, the team found that an air gap could limit downward heat flows into the refrigerated space but that it would not be sufficiently effective in the proposed refrigerator. Since the initial research made it clear that a sky radiant refrigerator, as envisioned, would not work, a prototype was not built. Nevertheless, sky radiant cooling remains an intriguing possibility for a number of applications, and Arup's work provides several insights that may help guide future innovations.

Broader Observations and Lessons Learned

The primary objective of the Chill Challenge has been to identify, through the research conducted by the grantees, potentially viable refrigeration technologies. A secondary objective has been to use both successful and unsuccessful efforts to broaden our understanding of the underlying refrigeration challenge and the technologies that might address it. A few observations based on the work done to date:

The Refrigeration Value Chain
Engineers tend to focus on technology, but to understand the challenge it is useful to put technology in the broader framework of a refrigeration value chain, as shown in Figure 2. All of the technologies explored begin with a primary source of energy, which is converted to useable energy to drive a refrigeration device. The device can deliver net cooling output to the consumer

in various forms, ranging from household refrigerators to ice or community "cooling services." Whatever process is used, it is only viable if the value of the cooling delivered to the consumer is greater than the cost of delivering it. Refrigeration innovators have little or no control over the end points of the chain. They cannot change the price of diesel or the level of solar insolation, for example, or materially affect the value consumers ascribe to refrigeration. However, innovative designs need to examine four key factors within the value chain that have a significant bearing on affordability: 1) the cost of "useable" energy delivered to the refrigeration device, 2) its coefficient of performance, 3) how one addresses the "dark day" problem, and 4) how cooling is delivered to the consumer.

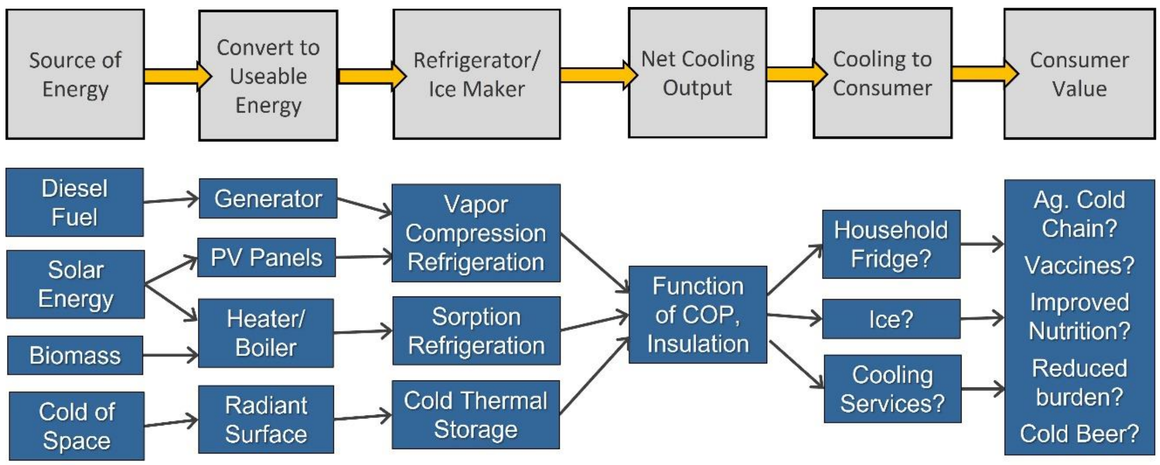


Figure 1: The Refrigeration Value Chain

Coefficient of Performance (COP)

It is useful to first look at coefficient of performance (COP), the ratio of cooling energy output to energy input. At refrigeration temperatures, vapor compression units typically exhibit COP's of 1.0-2.0, i.e., produce 1-2 kWh of cooling for every kWh of electrical input. The COP's of sorption technologies are much lower, typically ranging from less than 0.2 to 0.8 for smaller units. Vapor compression's higher COP is a fundamental reason why it dominates the market for households with access to cheap and reliable grid power. For off-grid communities, however, electricity is considerably more expensive, and thermal energy is generally abundant and relatively cheap, factors which can make sorption technology competitive.

The coefficient of performance for vapor compression refrigeration also varies with temperature and scale. Under the basic thermodynamics of refrigeration, it takes more work to achieve lower temperatures, i.e., everything else being equal, the COP for an icemaker will be lower than for a refrigerator. That disadvantage, however, is often less important than scale. Published COP's for refrigerators are often hard to find, but based on estimates of annual power consumption, larger fridges are typically more efficient than smaller ones, i.e., consume less power per liter of refrigerated space. For icemakers, COP's can be estimated from performance data. Figure 2 shows ice production per kWh, and imputed COP's,[2] for smaller efficient icemakers that qualify for the U.S. Energy Star program. As is shown, an efficient 1000 kg/day icemaker can be almost

[2] The calculation assumes that 130 Wh of cooling is needed to produce one kg of ice.

twice as efficient as one making 100 kg/day. At grid electricity prices of 10-12 cents/kWh, this variation has a negligible impact on the overall cost of ice, but it becomes a critical factor at off-grid electricity prices.

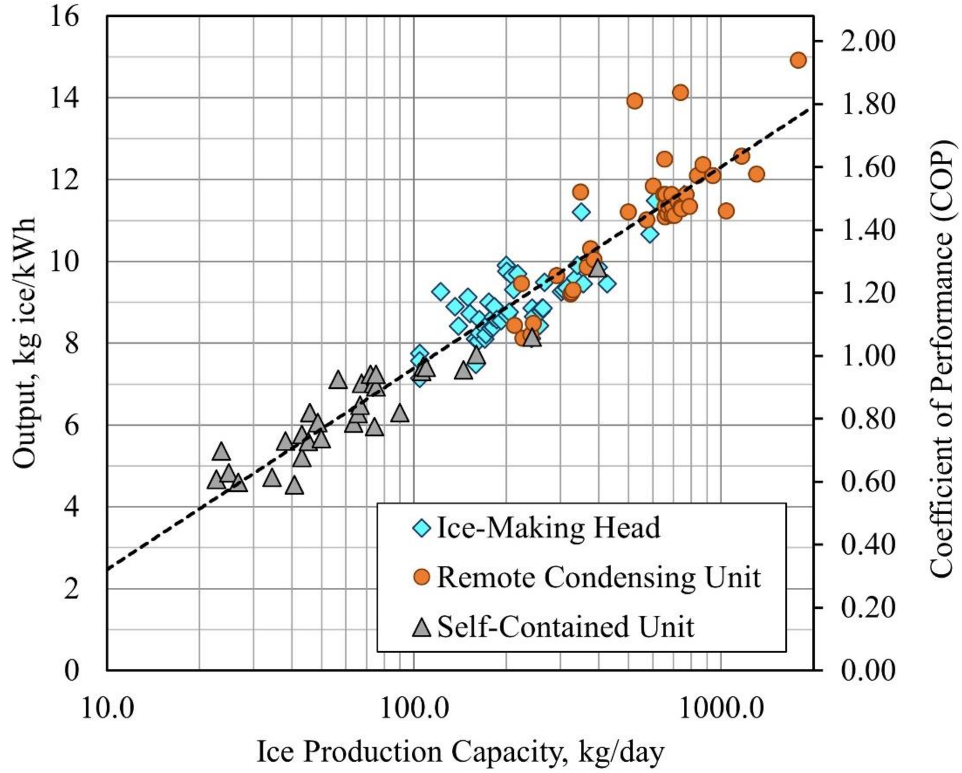


Figure 2: Performance of Energy Star Icemakers

Cost of Energy

Another key factor is the cost of energy driving the refrigeration process. Figure 3 illustrates the estimated levelized cost of electricity (LCOE) under the various options specified under the Chill Challenge parameters. Such estimates will vary with the assumptions used, but they illustrate key factors that need to be taken into account when designing a solution. One option specified under the Challenge was to purchase reliable electricity from a minigrid at a tariff of $0.80/kWh. A second option was to use a diesel generator. The estimated cost shown, $0.62/kWh, is for a small genset producing 20 kWh/day, appropriate for a mid-sized ice maker. A third option was to use power from solar PV panels. While the cost of solar PV panels has fallen dramatically in recent years, the cost of the panels, alone, contributes only about 5 cents/kWh to the total LCOE. Additional system components and installation result in an LCOE for generation of about $0.18/kWh. This does not include batteries, however, which have an enormous impact on final costs. For a system that only uses a battery to balance loads during 9 daytime hours, the estimated LCOE is $0.20/kWh; adding enough battery storage to run the system 24 hours/day bumps that up to $0.32/kWh. However, providing enough battery storage to cover two “dark days,” days without useable solar power, as specified under the Chill Challenge parameters, drives electricity costs to an estimated $0.82/kWh.

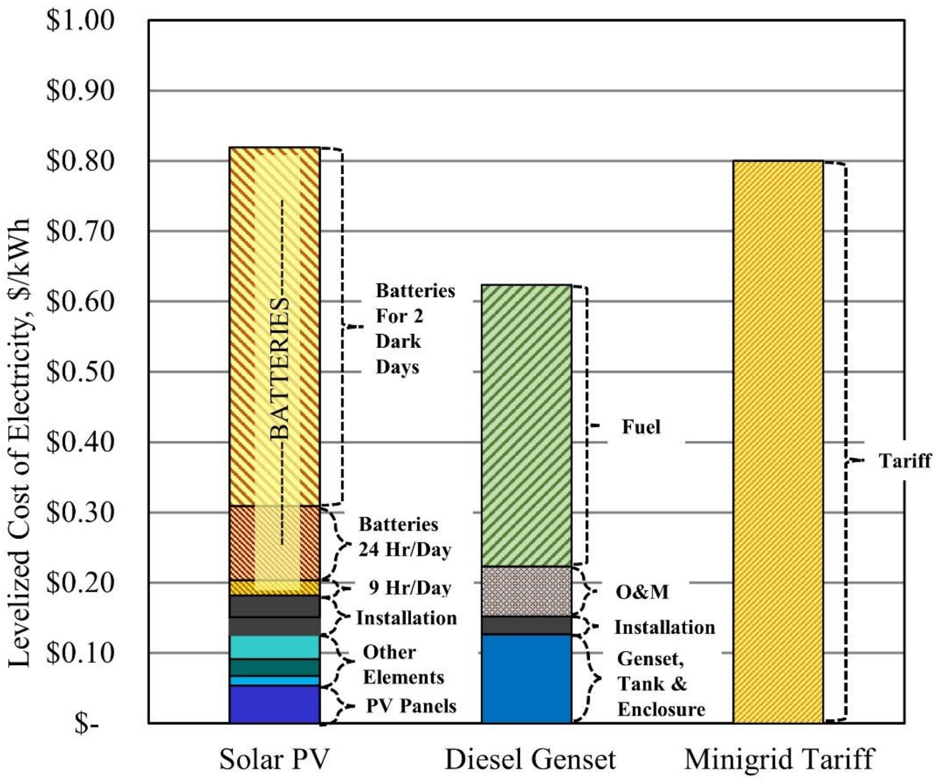


Figure 3: Estimated Cost of Electricity Under Chill Challenge Options

Similar to the electricity analysis, Figure 4 shows the estimated cost of thermal energy from several sources. The estimates for the solar collectors are calculated using a solar irradiance of 700 W/m^2, an ambient temperature of 32^o C, published prices and performance data, and Chill Challenge capital amortization parameters.[3] The cost of solar thermal energy depends on the cost and efficiency of the collector, but for all collectors varies with the available solar irradiance and the output temperature required. In general, flat-plate collectors can be the cheapest option at low output temperatures but become more expensive than evacuated tube collectors above about 100^o C. Estimated costs are also shown for an evacuated flat plate collector and an external concentrating parabolic reflector used by the Imperial College Team.[4] For comparison purposes, an estimate of the cost of thermal energy from firewood, using a cost of $0.10/kg specified in the Chill Challenge parameters, is also shown. The number shown, 5.2 cents/kWh, assumes an equipment amortization cost of 1.2 cents/kWh, and a constant boiler efficiency of 60% over the temperature range.

[3] The numbers do not include costs of related equipment or installation, as these would depend on the design of the refrigeration device being used.
[4] Artic Solar's XCPX Collector: https://articsolar.com/

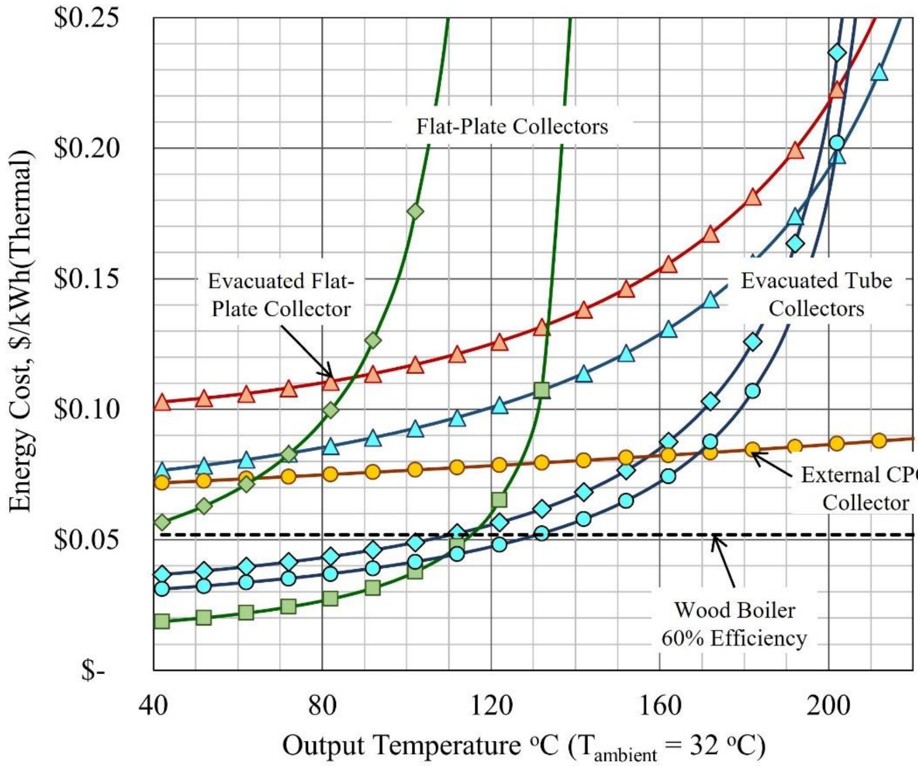


Figure 4: Estimated Cost of Thermal Energy from Solar Collectors and Firewood

The "Dark-Day" Problem

Solar energy, whether electricity from PV panels or thermal energy from solar collectors, is abundant in most of the target regions and an obvious energy source for many of the potential refrigeration technologies. A key design challenge for solar powered technologies, however, is to provide refrigeration for "dark days," days when there is no appreciable solar insolation. This is a minor problem for small solar home systems designed to power lights, cellphone charging, and television, as power usage can be reduced or curtailed altogether when faced with dark days. Systems that power refrigerators, however, are typically designed to accommodate several dark days to avoid the loss of food or other perishables.

The Chill Challenge parameters specified that refrigerators should *ideally* be able to fully function for two dark days, including meeting the load needed to chill 20 liters of water/day. Alternatively, *at a minimum*, it was decided that they should be able to maintain the contents of the fridge at the target temperature of 3° C for the two days. For vapor-compression fridges, dark day requirements are typically met via extra battery capacity or by freezing ice which can act as thermal storage. It appears difficult to meet the Chill Challenge cost targets using either. As shown in figure 3, the cost of battery storage for two dark days can almost triple the LCOE of solar power. With an efficient and inexpensive 150–250-liter fridge and a good design, it may be possible to meet the minimum Chill Challenge requirement using batteries, but to meet the ideal standard, the battery cost alone would likely exceed the cost target. A refrigerator with ice storage may be a more viable option, but it would presumably require a compressor with greater cooling capacity as well as additional insulated volume for ice storage. Refrigerators using solar thermal energy would face the same challenge but may be able to address the dark day problem by storing hot water. Solar thermal designs, however, would need to factor in the additional expense of a hot water tank as well as heat losses.

The dark day problem appears to be much easier to address for icemakers. The challenge parameters require icemakers be designed to either produce their rated output for two dark days, or to provide for ice storage equal to two days production. The latter option appears much cheaper. At the size of icemakers specified in the Challenge, ice storage would likely add less than $0.001/kilogram to total ice production costs.

Delivering Cooling to the Consumer

A final factor that determines affordability is how the cooling is ultimately delivered to the consumer. A refrigerator for every household is one option, and an appropriate aspirational goal, but community-level "refrigeration services" may prove to be a more attainable one for most off-grid households. Refrigeration services could include, for example, a local shop that sells cold drinks or frozen food, a community icemaker that sells ice to households, or an agricultural cold room that rents space to farmers. One advantage of community level refrigeration is that the cost of refrigeration tends to decline with scale: large fridges and icemakers are more efficient than smaller ones, and their cost of energy is generally cheaper per kWh.

A more important advantage, however, may be financing. Successful marketing of refrigerators to off-grid households would likely require a financing program, such as the "PayGo" systems currently being used for solar home systems. Even with automatic payment systems, however, many off-grid households will not be able to afford refrigerators, and those that do may pay effective interest rates of 3-4% per month, effectively driving up the cost of the refrigerator by 20-30%. Community level refrigeration, on the other hand, would involve many fewer transactions with relatively creditworthy local entrepreneurs, which should produce much lower financing costs. Other options, such as leasing, lease/purchase or franchise arrangements might also be viable for larger icemakers or cold rooms.

Outlook for Off-Grid Refrigeration

Refrigerators

An affordable household refrigerator will likely remain an elusive goal for most off-grid families for the foreseeable future. The market that is emerging, targeting small commercial users and wealthier households, is dominated by conventional vapor compression refrigeration, driven by solar PV power. Several new marketing initiatives in Africa have emerged since the Challenge was launched. These include a 100-liter refrigerator marketed by M-Kopa in Kenya,[5] and a 65-liter Surechill refrigerator marketed through the Angaza Paygo platform.[6] Also, in 2021, South Africa appliance manufacturer Defy launched two larger "solar hybrid" units designed to operate in regions with unreliable grids.[7] Although not designed for the off-grid market, these units have significant thermal storage, can operate on solar PV power, and are being marketed for

[5] https://m-kopa.com/products/
[6] https://www.surechill.com/
[7] https://defy.co.za/pages/solar-hybrid

approximately $420 US, much cheaper than similar sized off-grid units. As the market for off-grid and weak-grid appliances expands, the costs of conventional off-grid refrigerators will hopefully fall due to competition and scale economies.

Another potential technology for off-grid refrigerators is an intermittent sorption system driven by biomass, similar to Purdue's "cold storage battery" concept that unfortunately was not able to be fully evaluated. Intermittent sorption refrigeration was successfully used in the Crosley "Icy-Ball" of the 1930's and 1940's and has been demonstrated in various devices since. These range from the Intermittent Solar Ammonia Absorption Cooling (ISAAC) off-grid icemaker[8] to portable refrigeration containers and self-chilling beer kegs.[9] Off-grid households consume significant amounts of energy for cooking, on a daily, intermittent basis. Using some of that energy to drive a household refrigerator seems entirely plausible, would avoid the dark day problem of solar fridges, and is too good an idea not to revisit.

Solid state refrigeration technologies, without moving parts, could also have future potential for off-grid refrigerators. Thermoelectric (Peltier) refrigeration is already being used in portable coolers and is relatively cheap and reliable. However, it is less efficient than vapor compression and most units cannot lower temperatures by more than 20-22^{o} C below ambient. Nevertheless, thermoelectric units tied to solar panels may serve some off-grid cooling needs, particularly those that don't require lower temperatures, such as chilling drinks or fresh produce. In addition, there is continuing research into potentially more efficient thermoelectric materials which could make these units more competitive.

Icemakers

There appears to be wider array of viable technology options for larger units, such as icemakers or cold rooms. Conventional vapor compression is certainly one. By relying on ice storage, rather than batteries to provide dark day coverage, the cost of solar power for icemakers could be as low as $0.20-0.32/kWh (Figure 3). Similarly, some of the larger and more efficient Energy Star icemakers (Figure 2) produce more than 10 kg of ice/kWh. Therefore, for an existing efficient icemaker, the embedded cost of electricity might be only 2-3 cents per kilogram, and the total cost, including the amortization of capital, could approach 4 cents/kg under the Challenge's methodology. It should be possible to lower those costs to below the 3 cents/kg target with only minor efficiency improvements. There could be a significant market for efficient vapor compression icemakers that are also robust, simple to operate and easy to transport and service. In addition to the off-grid market, many island fishing communities have a large demand for ice and expensive (diesel-generated) grid power. They could also be a target market for an efficient icemaker.

Thermal sorption technologies also appear quite viable for larger applications. One of the Chill Challenge grantees, New Leaf Dynamic Technologies, is currently deploying its sorption units for cold rooms in India and has demonstrated that its GreenCHILL™ technology can also be used to drive an icemaker. This technology appears particularly viable where low-cost feedstock, such as agricultural waste, is available. The use of solar thermal energy is also an

[8] https://www.energy-concepts.com/_pages/app_isaac_solar_ice_maker.htm
[9] https://www.zeo-tech.de/home-41.html

option for driving sorption refrigeration, but its cost depends quite a bit on the temperature the sorption process needs and the available solar insolation. At lower temperatures, such as that needed for the New Leaf (or potentially for the Xergy) sorption processes, conventional evacuated tube collectors may be able to provide the hot water needed. The cost of these has fallen significantly in recent years with high volume production in China. The diffusion absorption refrigeration process tested by Imperial College is a simpler device but needs a solar collector that is more efficient at higher temperatures. Other sources of thermal energy could also be used. A minigrid operator, for example, might be able to use waste heat from a diesel generator to power a community icemaker or cold room and provide an additional source of revenue.

It should also be possible to combine cooling technologies to achieve higher performance for larger refrigeration applications. Simple evaporative cooling, for example, can be quite effective in drier climates, but cannot lower temperatures below the dew point. However, evaporative pre-cooling systems are already in use to lower the temperature of air-cooled condensers, which improves the COP of conventional vapor compression units. For off-grid refrigeration, those efficiency gains could more than justify the additional cost and complexity. Similarly, although it appears that sky radiant cooling will not provide the temperature drop needed for refrigeration, it may also be used to effectively lower the condenser temperatures of refrigeration units. In a recent case study in California, sky radiant panels were able to reduce the energy consumption of an icemaker by 25%.[10] Various other combinations of evaporative and radiant cooling might also be employed to improve the efficiency of off-grid units.

Conclusion & Acknowledgments

EWB's Chill Challenge has provided an opportunity to explore innovative technologies to address the need for affordable off-grid refrigeration, and several of the teams have demonstrated viable technologies. Hopefully one or more of these will ultimately be successfully deployed at scale. Whatever positive outcomes this initiative may produce, however, it has examined only one facet of this multidimensional challenge. Significant work remains for engineers, innovators and supporting institutions to make refrigeration affordable for the millions of people who will rely on off-grid power. While the challenge is difficult, however, it also offers tremendous commercial opportunities to the innovators and entrepreneurs who succeed in addressing it.

The Chill Challenge would not have been possible without the contributions of our colleagues at EWB USA and the generosity and support of our donor, Open Philanthropy. We also want to express our appreciation for the work of our colleagues on the Grantee Review Panel and, of course, all of the work done by the grantee teams. The opinions expressed in this report are those of the authors, and do not necessarily represent those of EWB USA.

[10] https://www.skycoolsystems.com/convenience-store-case-study-3/

Appendix A: Team Summaries

Arup, London, UK:
Passive Cooling Box:

Concept:
Arup's Advanced Digital Engineering team received a grant to research refrigeration using passive cooling materials that emit heat as infrared radiation into space. "Night sky radiation" is a well-known phenomenon and was used by the ancient Persians to produce ice. Beginning in the 1960's, it also has been demonstrated to be effective for air conditioning in a number of prototype structures. More recently, research has focused on selective radiators that emit infrared radiation within the wavelengths of 8-13 μm, corresponding to the "atmospheric window." These can achieve greater cooling power and lower cooling temperatures, and, if also designed to reflect light in the visible spectrum, can offer effective cooling during the day as well.

Arup's proposed design envisioned using one of these selective radiators on the top (sky-facing) surface of a refrigerated cabinet where it would generate maximum cooling power. Phase-change materials (PCM's) inside the cabinet would be used to stabilize temperatures and an air gap would act as a "thermal diode" to minimize potential heat flows from the top surface into the cabinet.

Research and Development Activities:
Arup's research investigated three key questions:

1. *Could the radiative cooling materials be made at scale with adequate cooling performance and sufficient durability?*

Arup studied a radiative cooling material made from a polymer with micro- and nanopores, which achieved some of the highest cooling powers reported in literature and is readily manufactured from common precursors. The company prepared dozens of material samples using different primers and application methods, to test adhesion, durability, and ease of application. However, only samples overcoated with an enamel spray finish, which compromised their thermal performance, were resistant to scratches and fouling. Thermal imaging showed the radiative cooling samples to be capable of achieving temperatures lower than unpainted surfaces and those painted with white paint. However, mock-up installations on containers did not demonstrate sufficient reductions in surface temperature to achieve refrigeration.

2. *Could parasitic heat flows be reduced to the required levels with practicable, low-cost interventions?*

To achieve the temperatures needed for refrigeration, substantially below even low nighttime temperatures, it is necessary to minimize conductive or convective heat flows from the ambient to the radiative cooler. Academic researchers have shown that radiative coolers can achieve temperatures well below 0^{o} C when parasitic losses are kept nearly to zero, but those results required high tech materials typically unavailable for use in off-grid contexts. Arup used computational fluid dynamics (CFD) to study 15 different configurations of wind screens and other practicable interventions to reduce parasitic losses. They also used a raytracing sky view calculator to measure the amount of obstruction introduced for each intervention. Unfortunately, even under calm or light wind conditions, the net parasitic losses predicted by CFD exceeded Arup's design target of no more than 5 W/m^2.

3. *Would the thermal diode successfully prevent bidirectional heat flows between a cold source and a payload?*

Arup hypothesized that an air gap might serve as a thermal diode to limit heat flows from an upper radiative surface into the refrigerated space below. Researchers tested the concept using ice packs and thermocouples to measure heat flows in both an upward and downward direction across an air gap created between two polished aluminum plates. The company found that the air gap did allow 32% greater heat flow in an upward direction than a downward direction. However, they concluded that the radiative surface would have to achieve a temperature of -4^{o} C to achieve refrigeration temperatures at the bottom surface, which was not considered feasible using radiative cooling materials alone.

Given the results of the preliminary research, Arup and EWB agreed to terminate the project without building a prototype refrigerator.

Comment:
Arup's concept was always considered a high risk/high reward proposal, but the review panel felt that the potential of a totally passive refrigeration process certainly justified a research grant. Although the results are not promising, the company has done a commendable job in exploring the idea. Other radiant surfaces might arguably be more effective than the one tested, but it seems clear that parasitic losses will pose a difficult challenge for any practical system trying to achieve refrigeration temperatures. Nevertheless, sky radiant cooling remains an intriguing technology to augment cooling for other applications, such as for cold rooms, or for improving the COP of vapor compression refrigeration. Further research in this area seems justified.

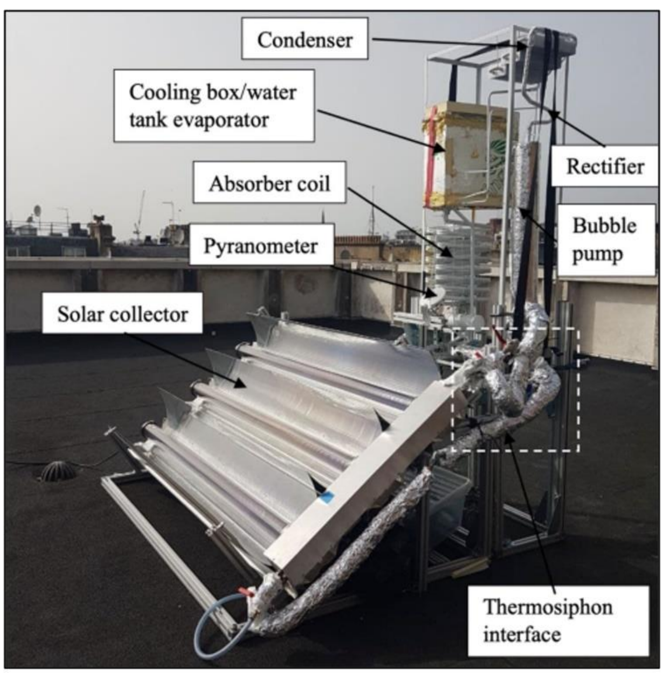
Imperial College London: Clean Energy Processes (CEP) Laboratory
Affordable Decentralized Off-Grid Icemaking:

Concept:

The Clean Energy Process (CEP) Laboratory at Imperial College London, with support from Solar Polar Ltd. (UK), received a grant to develop and test a solar-driven diffusion absorption refrigeration (DAR) icemaker. Diffusion absorption refrigeration was invented by Baltzar von Platen and Carl Munters in 1922. It uses a source of heat to drive a process involving three fluids (typically water, ammonia, and hydrogen gas) and is the basis for countless propane and kerosene refrigerators used in caravans and remote locations around the world. The CEP team proposed building a DAR icemaker, featuring a heat pipe design driven by solar thermal energy. The researchers also proposed to improve the technology's COP with a more efficient design and potentially the use of novel fluid combinations.

Research and Development Activities:

The CEP team built and tested an instrumented DAR unit as shown below. The design of the prototype was adapted from conventional systems to specifically target solar-cooling applications in warmer climate conditions. All heat exchanger areas were increased to improve heat rejection at relatively high ambient temperatures, and the generator heat exchanger was adapted to receive heat from solar collectors. A conductive copper powder-epoxy resin mixture was also used to connect the evaporator with the water filled tank (ice compartment). The unit was connected via a thermosiphon to an ArcticSolar external concentrating parabolic (XCPX) solar collector with three rows of evacuated tube, each equipped with reflectors to concentrate solar radiation. The effective area of the collector was 1.5 m^2.



Solar DAR Icemaker Prototype

Due to COVID-19 travel restrictions, the CEP team was unable to test the unit in Egypt as originally planned. Instead, they developed a dynamic model to predict the cooling capacity of the unit under various conditions and tested a prototype unit in London between February and June 2021, using the measured performance to confirm that the model could accurately predict the ice formation process. Using the model, and assuming a 6-hour flat insolation profile with a total insolation of 4 kWh/m^2-day, the team calculated that the prototype would produce 6.2 kg of ice/day. In doing so, it would achieve an overall solar-heat-to-cooling conversion efficiency of 0.26. This is the result of a mean COP of the DAR unit of 0.42, and a calculated solar collector efficiency of 62% at an output temperature of 200 ^{o}C.

In its economic analysis of the icemaker, the team examined several alternative solar collector options, including four evacuated tube collectors and an evacuated flat-plate collector. Based on collector costs and performance characteristics, the levelized cost of ice production for the four evacuated tube collectors was calculated to range from $0.10-0.32 per kilogram of ice produced when using conventional working fluids in the DAR unit, which is significantly higher than the Chill Challenge target of $0.03/kg. However, the evacuated flat-plate collector exhibited a lower cost, of about $0.05/kg, and the ArcticSolar collector had the lowest calculated cost. The CEP team calculated the costs for 100, 500 and 1000 kg of ice production per day as shown in the table below.

	Ice production		
	100 kg/day	**500 kg/day**	**1000 kg/day**
Exact ice production rate (kg/day)	99.1	501.4	1001.4
Number of DAR units	16	82	161
Solar collector area (m^2)	12	61	122
DAR modules cost ($)	1,570	7,530	13,510
Solar collectors cost ($)	6,250	28,360	49,050
Total investment cost, C_{inv} ($)	7,820	35,890	62,560
O&M costs, $C_{O\&M}$ ($/year)	480	2,420	4,860
Total monthly cost, C_{TM} (c$/kg)	4.6	4.3	3.9

As can be seen, the ice production for each unit is small – 16 units would be required to produce the Chill Challenge minimum ice production target of 100 kg/day. The CEP team points out that the system offers a modular design that can easily be scaled up or down to meet specific requirements. Based on their analysis, the calculated costs, which include O&M costs, are near the challenge target of $0.03/kg.

Comment:
Despite being hampered by COVID travel restrictions, the CEP Laboratory at Imperial College London has succeeded in building and testing its concept DAR prototype. An ice maker using this design has several commendable characteristics. Diffusion absorption refrigerators have proved to be extremely reliable and combining one with a passive solar collector design should produce a robust solution for remote off-grid communities. The big challenge with solar thermal refrigeration has been the difficulty in generating the temperatures needed for sorption processes. The team at Imperial, however, has identified a solar collector that is efficient at 150-200^{o} C and has developed a highly efficient DAR design to produce ice at a reasonable cost. It remains to be seen what market these small icemakers might serve. It may be possible to assemble scores of these units to produce hundreds of kilograms of ice per day, but it seems more likely that they would be used for smaller applications such as individual shops or health units. Hopefully, additional research can be carried out in the field to further develop the concept, for example, by designing larger units for applications where larger quantities of ice are required or selecting alterative working fluids more suitable for use with lower cost evacuated tube collectors.

New Leaf Dynamic Technologies, New Delhi, India
Ice Maker Powered by Farm Waste:

Concept:
New Leaf received a grant to build a large 1000 kg/day ice maker using its "GreenCHILL™" adsorption technology. The company developed this technology to refrigerate cold rooms for storage of agricultural produce and has successfully deployed a number of units in India. The GreenCHILL™ process uses an advanced biomass gasifier, fired by loose or pelletized agricultural waste, to heat water and drive an adsorption refrigeration process using ammonia refrigerant. The unit can also be driven using biogas, steam or even waste heat.

Research and Development Activities:
New Leaf contracted with an ice machine manufacturer to build a 1000 kg/day ice machine using ammonia as the refrigerant and it adapted one of its GreenCHILL™ units to operate at the lower temperatures needed for ice making. The unit built for New Leaf is a typical tube ice machine, employing a flooded evaporator surrounding the ice tubes, and charged with 25 kg of ammonia. The ice making process is initiated by pumping water into the tubes and then allowing evaporation of the ammonia surrounding the tubes to lower temperatures sufficiently to freeze the water. Once the ice is frozen, hot gas is circulated from the desorber to allow the ice to be released. A rotating cutter is used to cut the ice into cubes as it falls from the machine.

Figure 1: GreenCHILL™ Unit with Ice Maker (in Blue), and Producing Ice

After assembling the prototype, New Leaf experimented with the design, trained operators to run the system, and ran a series of production tests. The icemaker was run for a total of 144 hours over 13 days of testing and produced 40-45 kg of ice per hour. Fuel consumption averaged 8.8

kg of firewood per hour, equivalent to a fuel cost of $0.02/kg of ice produced. The machine also used approximately 550 W of electrical power. While the prototype met its target production of 1000 kg ice per day, New Leaf identified several modifications that could be made to improve efficiency and safety of the machine. If automation is added to the prototype design, the company believes production could be substantially increased to 60 kg ice per hour. The company also suggested that alternatives to the flooded evaporator design should be explored to reduce the amount of ammonia needed, which should improve both the safety and efficiency of the machine.

Since completing its research under the Chill Challenge, New Leaf has continued to deploy its technology for cold rooms in India, including in a partnership with bigbasket.com, India's largest online food and grocery store. The company has also received considerable interest in an ice maker using its technology, including from fishing villages in coastal regions, shrimp farm operators, village level entrepreneurs, and food retailers. GreenCHILL™ installations have already surpassed all previous year numbers and now we're on path to 2x growth trajectory.

Going ahead, New Leaf plans to launch more environmentally friendly cooling solutions for both commercial and domestic segments to fight climate change and empower people who are traditionally underrepresented in the climate movement.

Comment:
New Leaf Technologies' research demonstrates that its sorption technology, driven by heat from biomass, can be a cost-effective icemaking process, particularly suited for larger ice makers. Using the Chill Challenge cost parameters, the prototype appears capable of producing ice at a cost of less than $0.04/kg, a bit higher than the Challenge target of $0.03/kg. However, we expect actual production costs to be lower, both through efficiency improvements incorporated into a production design, and by the ability to use lower cost biomass feedstock, such as agricultural waste. New Leaf's technology also demonstrates a relatively high COP at hot water temperatures of 105-115^o C, which may offer the potential for solar thermal applications. Overall, the company's ice maker appears to be a very viable option for off-grid communities.

Purdue University: Ray W. Herrick Laboratories, West Lafayette, Indiana
Cold Storage Battery for Domestic Refrigeration:

Concept:

Purdue's Herrick Laboratories received a grant to evaluate the use of heat from cook stoves to drive an intermittent sorption "cold storage battery." The proposed system was inspired by the Crosley "Ice-Ball" which was used in the early 1900's for small scale refrigeration needs employing ammonia and water as the working pair. Like the Icy-Ball, the proposed system would have two modes of operation. In a charging mode, heat from a cook stove would generate a refrigerant which is stored for use during discharging. In the discharging mode, the refrigerant is expanded to create cooling. Purdue researchers referred to the system as a "cold storage battery" because the generated refrigerant does not need to be immediately discharged but can be stored and expanded later to provide cooling on demand. Purdue intended to work in collaboration with Moi University in Kenya to identify the working pair and to design the unit to work with existing cookstoves being used in Kenya.

Research and Development Activities:

The COVID pandemic delayed academic activities at Purdue for most of 2020 and thwarted the team's planned collaboration with Moi University. In early 2021, Purdue researchers were able to resume activities and they chose ammonia and activated carbon as the working pair for the intermittent refrigeration system. A laboratory tabletop model of the system with instrumentation was built and was charged with activated carbon and ammonia. When testing the system, however, only very limited cooling was achieved due to poor heat and mass transfer.

Figure 1: Laboratory Setup of Cold Storage Battery Test

It was determined that considerable additional work would be required to properly test the concept, which would have required an extension of the research schedule to the end of 2021. After consultations between Purdue and EWB, it was agreed to terminate the project instead.

Comment:

Although Purdue's proposed research could not be completed, we believe this concept still has considerable merit. Biomass, typically firewood used for cooking, is the largest primary energy source for off-grid households and is a low-cost source of thermal energy. Moreover, various intermittent sorption systems, including the Icy-Ball, have been demonstrated and/or deployed in the past. A practical device, with a working pair and design that is compatible with the cooking practices of off-grid households, seems an attainable goal.

Purdue University: Ray W. Herrick Laboratories, West Lafayette, Indiana
Combined Heating and Cooling:

Concept:
Purdue's Herrick Labs received a grant to explore a combined heating and cooling vapor compression system, which would use evaporator capacity to create ice and the condenser heat to dry crops. Conventional vapor-compression refrigeration is often unaffordable for off-grid communities due to the capital cost and high cost of electricity. However, many off-grid communities also need to dry agricultural produce before it can be transported and sold. Traditional crop drying methods, such as spreading crops on the ground to dry in the open sun, can result in reduced yield and impaired crop quality. Development of an ice maker that can also be used for crop drying is one potential way to achieve more affordable refrigeration. It could also provide better control of the drying process, enhancing crop quality and yield.

Research and Development Activities:
Purdue intended to collaborate with Moi University in Kenya on this project to determine which products offered the best economic gain from drying and to evaluate the drying temperatures needed. However, the COVID pandemic thwarted the team's planned collaboration with Moi University and delayed research activities at Purdue for most of 2020. The Purdue team therefore used online resources to study the prices of fresh and dehydrated agricultural products in several countries in Africa and to determine the potential economic gains that could be achieved with a drying operation. The team also concluded that the optimum temperature for drying most fruits, vegetables and herbs was 60^{o} C.

The team modeled the vapor compression cycle to select the system components. This included a SECOP 2 kW compressor employing R290 (propane) and a fin and tube heat exchanger for the evaporator. To minimize the propane charge, a microchannel heat exchanger was used for the condenser, and a metering valve was chosen as a variable expansion valve. A cold box and hot box were constructed to test the efficiency of the system for both heating and cooling, and a series of tests were run at various settings of the metering valve.

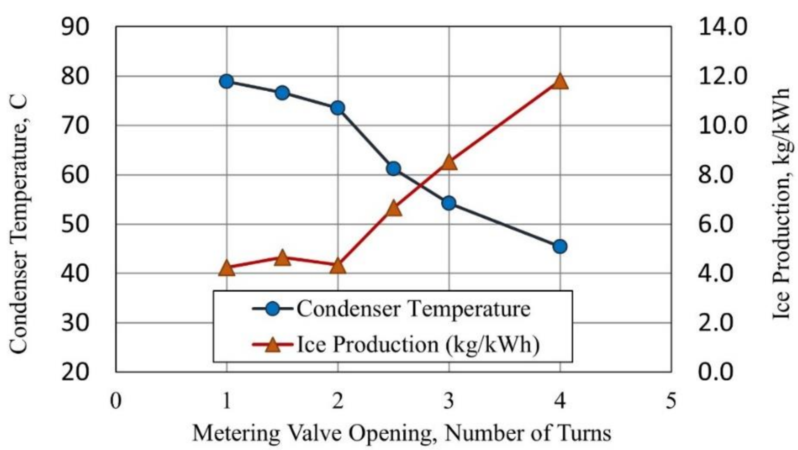
Valve Opening (turns)	T_{cond} (°C)	P_{cond} (kPa)	T_{evap} (°C)	P_{evap} (kPa)	W_{comp} (W)	$Q_{cooling}$ (W)	Ice (kg /hr)
4	45.42	1549	-12.1	321.9	819.8	1372	11.3
3	54.24	1877	-15.06	291	837.1	1013	8.3
2.5	61.2	2170	-16.9	273	808.5	769.4	6.3
2	73.56	2772	-19.58	248.2	647.4	412.8	3.4
1.5	76.62	2939	-15.48	286.8	764.7	507.8	4.2
1	78.93	3070	-16.7	274.9	688.3	422.0	3.5

Various Operating Conditions Achieved
Table from Purdue Team Report

As shown in the table, the team found that they could effectively control working conditions for the system by changing the opening on the metering valve. (The evaporating and condenser pressures shown were measured while the other parameters are calculated based on the system model.) The researchers chose to test performance of the system while keeping the valve opening between 1.5-2.5 turns. At that setting, they were able to freeze water in various containers placed in the cold box. However, actual ice production rates were only 2 kg/hour, significantly lower than predicted by the model, due to poor heat transfer through the ice as it began to form on the surface of the containers. The team simultaneously tested the drying capacity of the system by drying wet paper towels and apple slices in the hot box. Although the condenser temperatures ranged between 60-77^{o} C at those settings, the air temperature in the hot box was only about 30^{o} C due to the relatively high air volume delivered by the condenser fan.

The cost of the prototype, as built, was $952, but the team believes those costs would be lower for volume manufacturing. However, they estimated the cost of electricity from solar PV would be $0.40/kWh. Even at the most efficient ice production setting, and assuming 100% efficiency in the ice production process, the embedded electricity cost, alone, would be 3.4 cents/kg of ice produced, above the Chill Challenge target.

Comment:
The Purdue team has built a reasonably efficient refrigeration unit using a near Zero GWP refrigerant, but the research findings highlighted basic challenges with the concept. The figure below illustrates the expected condenser temperature and specific ice production from the prototype at various metering valve settings. As shown, there is a trade-off between the ice production rate and the condensing temperature. Raising the condenser temperature to levels needed for crop drying significantly lowers the efficiency of the system for ice making and vice versa. Therefore, while it seems possible to build a system that can serve either function, an economic decision needs to be made prioritizing one function over the other. Further improvements can be made to optimize the system performance based on the operating scenarios and users' preferences. There may be specific situations where such a system would make commercial sense. As an example, there may be locations where there is a need for crop drying during rainy season, when the demand for ice is fairly low and sun-drying is problematic. However, these potential applications may be quite limited.



Prototype Performance at Various Metering Valve Settings

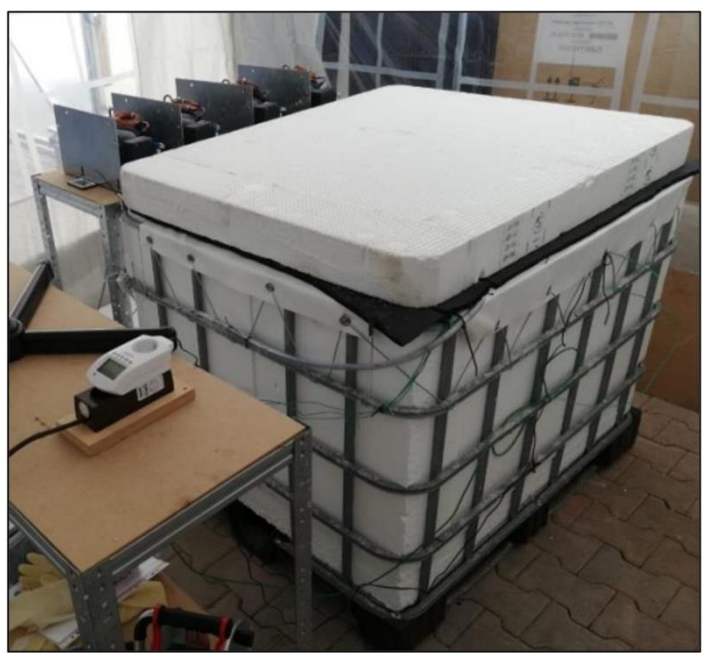
Solar Cooling Engineering UG, Hohenheim, Germany
Community Solar Ice Maker Using Key Components and Engineering:

Concept:

Solar Cooling Engineering received a grant to build an ice maker using its SelfChill® cooling units. These are small, efficient, DC vapor compression units designed for solar PV power systems that use the low GWP refrigerant R600a (isobutane). In addition to efficiency, the use of these units provides for flexible, modular designs for refrigerators and icemakers, and allows for local sourcing and assembly which lowers manufacturing costs. The strategy also minimizes transport costs, taxes, duties, and other fees which can comprise a significant share of system value. For its design, Solar Cooling Engineering proposed to immerse the evaporators of multiple cooling units in a brine heat transfer fluid to produce block ice. In addition to efficient heat transfer, this configuration would allow significant thermal storage through freezing a portion of the brine.

Research and Development Activities:

Solar Cooling performed an extensive evaluation of options for construction of the prototype icemaker and chose a modular design using IBC (intermediate bulk container) grid boxes, which are cheap and widely available. These containers were modified, insulated with foam panels, and lined with a PVC foil to create the refrigeration compartments. The compartments were filled with a 9% salt brine to serve as a heat transfer fluid, and four SelfChill units, with their evaporators submerged in the brine, were used to chill the fluid. Five-kilogram ice blocks are produced by immersing water-filled stainless steel ice block cans in the heat transfer fluid. Each unit is capable of producing 50 kg of ice/day. Solar Cooling's design calls for four 335-Watt solar panels and two 150 Amp-hour batteries to provide power for operation of each unit in the field. Two units, which are transportable in a small pickup truck, would satisfy the Chill Challenge requirements for a minimum of 100 kg/day ice production.

Left: Solar Cooling Icemaker with ice cans. Right: In operation with lid in place

Solar Cooling ran performance tests on the unit in December 2020 and January 2021 in its labs in Stuttgart, using a temperature-controlled tent at 32° C and a DC power source. After chilling the brine, ice cans filled with fresh water were lowered into the fluid and 50 kg of ice was frozen to -6° C in 15 ½ hours. The frozen cans were manually removed from the brine and the ice was released after a small amount of warming. In addition, the tests also created a thick layer of frozen brine on the evaporators of the four cooling units. This frozen brine can effectively increase the thermal storage capacity of the unit, although it may also decrease the heat transfer efficiency between the evaporator and brine.

The Solar Cooling team performed an extensive cost analysis of the icemaker. The total cost of materials for the prototype (2 units) was $6,958, which under the Chill Challenge parameters, would be equal to about 3.3 cents/kg of ice produced. Solar Cooling estimated, however, that after including the cost of transporting, duties, and taxes for imported components, plus a 25% margin for labor and profit, the system would cost $11,674 in a typical developing country. This would equate to a cost of 5.3 cents per kilogram of ice produced. While this is above the Chill Challenge target of 3 cents/kg., the team found, though contacts in coastal Kenya, that ice demand there was robust, with premium prices reaching as much as $0.82-1.36/kg. to bridge frequent power outages. These economic assumptions will be evaluated with partners in several African countries during an upcoming field trial.

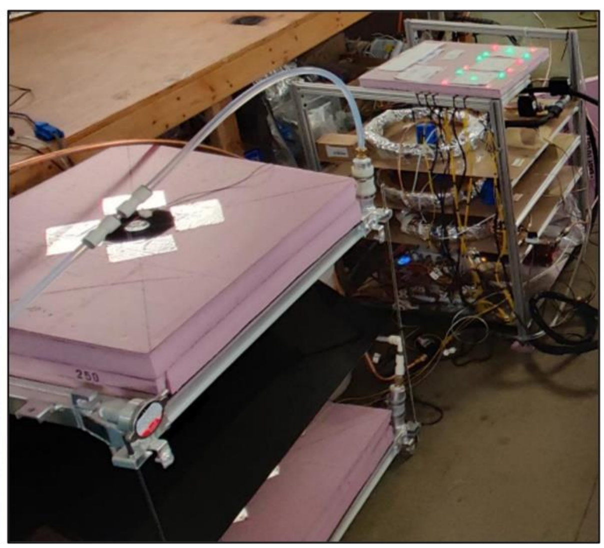
Comment:
The Solar Cooling team did an excellent job of designing, building, and testing their prototype. The unit illustrates several innovative ways to lower capital costs while maximizing flexibility and local construction. The work by Solar Cooling also demonstrates just how difficult it is to dramatically lower the cost of vapor compression refrigeration. The prototype they built, however, appears to be commercially viable, particularly for smaller ice makers built by local craftsmen and entrepreneurs. The basic design, featuring efficient DC refrigeration units driven by solar PV, a brine heat transfer fluid, and a simple manual block-ice production process, might also be suitable for manufacturing at scale. In recognition of its work, Solar Cooling Engineering's ice maker was one of the winners of the ASME (American Society of Mechanical Engineers) ISHOW USA 2021. In addition, the team was awarded an additional grant from Open Philanthropy to conduct field tests of the prototypes in Africa.

Xergy, Inc., Harrington Delaware
Off-the-Grid Refrigerator Utilizing Solid-State Refrigerants:

Concept:
Xergy received a grant to research an intermittent adsorption refrigerator using hydrogen and metal hydride as the working pair and hot water from solar collectors as the energy source. Metal hydride heat pumps use metal hydride heat exchangers and hydrogen gas to produce cooling. When subjected to hydrogen gas pressure, the heat exchangers adsorb the gas and reject the heat of formation to a heat transfer fluid. When the hydrogen gas pressure is reduced, the gas desorbs from the surface and extracts heat from a heat transfer fluid. While this is similar to other adsorption refrigeration processes, Xergy believes the hydrogen/metal hydride is significantly more efficient than other working pairs (COP of >0.7) and can work at relatively low temperatures (<100^{o} C). This would allow the process to be driven by hot water from solar collectors and use hot water storage to cover days without sunshine.

Research and Development Activities:
To test the concept, Xergy employed three metal hydride heat exchangers (MHHX's) to act as a 2-stage hydrogen compressor. Different alloys, with different hydrogen adsorption characteristics were used for each of the MHHX's. The system also included three water loops: a hot water loop heated by solar collectors, an ambient water loop for heat rejection, and a cold-water loop for refrigeration. The refrigeration process takes place in 3 stages:

1. The first heat exchanger, MHHX I, is heated by hot water, raising its pressure, and pushing hydrogen gas to MHHX II, which is being cooled by the ambient water loop.
2. MHHX II is heated by the hot water loop, boosting the hydrogen pressure even higher, pushing hydrogen to MHHX III, which is being cooled by the ambient water loop.
3. After cooling, the hydrogen in MHHX III, at a considerably higher pressure, is allowed to flow back to MHHX I, which is cooled by the ambient water loop, and the desorption from MHHX III cools water for the cold-water loop.

Left: Solar Collector. Right: Heat Rejection and MHHX Systems in Operation

To provide the heat to drive the system, Xergy used a solar collector with 30 evacuated tubes (4.5 m^2 gross area) and a 100-gallon hot water storage tank. In addition to the metal hydride heat exchangers, the prototype incorporated two radiators with fans for heat rejection, three water circulation pumps, 16 motorized ball valves, and a programmable logic controller (PLC) to control operations. An insulated refrigeration box was also built, containing 20 liters of water to serve as the heat load. For testing, Xergy installed thermocouples on the inlets and outlets of the MHHX's and a pressure transducer to measure hydrogen pressures.

Xergy ran a series of tests over three days to evaluate the cooling capacity of the refrigerator. The system repeatedly cycled through the three stages, gradually lowering the temperature of the water in the refrigeration box from 25.2^o C to 7.2^o C. However, cooling was very slow, averaging less than 1^o C per hour. The company estimated that the refrigerator averaged 35 Watts of cooling over the test period. The placement of the thermocouples in the prototype created problems in fully evaluating the system, but Xergy estimated that the prototype achieved a COP of 0.20.

In evaluating the performance, Xergy noted potential inefficiencies in sensible heat losses. As designed, at each stage of the cooling cycle, a fluid from one loop is pumped into the jacket surrounding the MHHX and displaces the fluid previously occupying the space. MHHX I & II cycle between hot water and ambient water; MHHX III cycles between ambient water and cold water. The design introduces some inherent parasitic heat losses in heating and cooling elements of the heat exchangers other than the hydride. Potential losses also occur with mixing of the fluids. Xergy programmed the PLC to minimize mixing losses but noted that the placement of the thermocouples made it difficult to accurately do so.

Comment:
Xergy's concept is innovative, and any adsorption process that can exhibit a COP greater than 0.5 using temperatures below 100^o C merits investigation. As noted by the company, those attributes would open the door to relatively low-cost solar thermal energy collection and storage. Unfortunately, while the team assembled a sophisticated prototype to test the concept, those tests failed to demonstrate a successful proof of concept. The hydrogen/metal hydride working pair may still have potential for efficient refrigeration. However, further research is needed to understand whether the prototype performance was due to a flaw in the concept or inefficiencies in the design.

Appendix B:
EWB-USA Chill Challenge: Affordable Off-Grid Refrigeration Initiative Parameter and Targets

Teams are invited to submit proposals to build and test a prototype of either a small commercial refrigerator or an icemaker that would be an affordable option for communities in developing countries that rely on off-grid power. Target parameters are as follows:

Targets for a Small Commercial Refrigerator

- Between 150 and 250 liters of usable space
- Powered by energy sources commonly available for off-grid systems (see below)
- On a daily basis, able to cool 20 liters of water from 35ºC to 3ºC in 3 hours and maintain it at that temperature
- If using solar energy, the refrigerator would ideally be able to repeat this performance for two "dark" days – i.e., two days with no solar input. At a minimum, the unit should be able to maintain existing chilled contents for two dark days.
- Assumed average daily temperature of 32ºC, and an average dew point of 20ºC
- Uses refrigerants with low global warming potential (e.g., no HFC's). The use of hydrocarbon refrigerants, pursuant to standards accepted by the US or EU, is acceptable.
- Levelized cost of ownership of $12/month or less, with capital costs amortized over 10 years at an annual interest rate of 10% (further details below).
- If water is used for evaporative cooling, operating expenses will include a charge of $0.003/liter ($3/cubic meter) of water consumed.
- The unit will be safe and suitable for indoor use by normal household members.
- Robust and simple to install, operate and maintain by non-technical users
- Weigh less than 150 kg, transportable to the field in a Toyota Hilux pickup truck

Targets for a Community Icemaker

- Can produce between 100 and 1000 kg of ice/day.
- Powered by energy sources commonly available for off-grid systems (see below).
- Levelized cost of production of $0.03/kg, or less, with capital costs amortized over 10 years at an annual interest rate of 10% (further details below).
- If water is used for evaporative cooling, costs will include a charge of $0.003/liter ($3/cubic meter) of water consumed.
- Assumed average daily temperature of 32ºC, and an average dew point of 20ºC
- If using solar energy, the icemaker should be able to produce ice for two "dark" days – i.e., two days with no solar input, or hold two days' worth of production in storage
- Uses refrigerants with low global warming potential (e.g., no HFC's). The use of hydrocarbon refrigerants, pursuant to standards accepted by the US or EU, is acceptable.
- The unit will be safe, robust and simple to operate by non-technical users with only minimal training.
- The unit or its components should be transportable to the field in a Toyota Hilux pickup truck. ***Note:*** A Hilux (single cab) truck has a maximum bed length of 231 cm,

maximum width of 152 cm, width between wheel wells of 110 cm, and can transport a maximum weight of 820 kg. Icemakers may require multiple loads to transport, but components should be small enough to unload and set up by hand, .i.e. without requiring additional equipment.

Off-grid energy options:
The following energy options, under the assumptions shown, will be assumed to be available to power either the commercial refrigerator or the community icemaker, and used to calculate costs:

- Power from a mini-grid: It will be assumed that a reliable supply of electricity (220 V/50 Hz AC) is available from a local mini-grid for a price of $0.80/kWh.
- Solar PV: Alternatively, designers may want to incorporate a stand-alone solar PV system into their design, using current published prices for equipment and assuming solar insolation will average 4 kWh/m2-day.
- Batteries: For units relying on battery storage of power, battery performance will assume an ambient temperature of 32ºC., and unless performance is otherwise certified, design assumptions for lead acid batteries will assume a round-trip charge/discharge efficiency of 85%, and a service life of 5 years at a depth of discharge of 50%. Lithium chemistry batteries will be assumed to have a service life of 10 years at a depth of discharge of 90%, with a round-trip efficiency of 92%.
- Solar Thermal: Applications will assume an average solar insolation of 4 kWh/m2-day.
- Diesel Generator: Systems using diesel generators will use published prices for equipment and (if not otherwise certified) assume a generator life of 10,000 hours, annual O&M expenses of 2% of initial cost, and a diesel price of $1.00 per liter.
- Biomass: For systems using biomass, fuel wood will be assumed to cost $0.10/kg, and have a
- heating value of 15 MJ/kg. Charcoal will be assumed to cost $0.30/kg and have a heating value of 29 MJ/kg.
- Kerosene will be assumed to be available at a cost of $1.00/liter and have a heating value of 36
- MJ/liter.
- Waste Heat: For icemakers using waste heat from a diesel generator, designers should assume a generator sized between 10 and 50 kW in output, operating for no more than 10 hours/day at 75% of maximum output. Exhaust temperature and available heat varies widely, depending on operating conditions and system design. For cost purposes, waste heat will be assumed to be free, but capital costs will include the cost of heat exchangers or other modifications required to extract the heat.

Notes on Levelized Cost:
"Levelized cost" is a method used to assess the overall cost of owning and operating an asset. It incorporates both capital and operating expenses and can be used to compare the costs of different technologies with unequal life spans and cost components. The "levelized cost of electricity" (LCOE), for example, can be used to compare the cost of diesel power generation, with a relatively low capital cost but high fuel expense, with the cost of electricity from solar panels, which has a high capital cost, but minimal operating expense. Levelized cost can also be used to compare the cost of owning vehicles or other capital equipment. Key assumptions for any levelized cost calculation include the discount rate and the life over which capital expenditures are amortized.
While levelized cost calculations can be complex, for purposes of this challenge, we will use a simplified calculation:

Total Monthly Cost = Capital recovery cost + Fuel expenses + O&M expenses

Where:
- Capital recovery cost = 1.3% of the estimated initial capital cost of the equipment[11]
- Fuel expenses = monthly cost of electricity or fuel purchased to operate the equipment
- O&M expenses = any additional monthly direct operating and maintenance costs (not to include labor or administrative costs)

For the refrigerator, the total monthly cost target is $12, or less.

For the icemaker, the total monthly cost would be divided by kg of ice produced per month to calculate a cost per kilogram, with a target of $0.03/kg, or less.

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[11] The monthly capital recovery cost (1.3% of initial capital cost) is based on the use of a capital recovery factor (CRF):

$$CRF = D\ (1+D)^N / (1+D)^N - 1$$

Where:
D = the monthly discount rate (0.797% at 10%/year annual rate)
N = the number of months over which capital costs are amortized (120 months)

Source: https://openei.org/apps/TCDB/levelized_cost_calculations.html