LIFECYCLE GREENHOUSE GAS EMISSIONS ASSESSMENT OF OFF-AND WEAK-GRID REFRIGERATION TECHNOLOGIES

Note for policymakers

APRIL 2023

EFFICIENCY FOR ACCESS COALITION

About Efficiency For Access

Efficiency for Access is a global coalition working to promote high-performing appliances that enable access to clean energy for the world's poorest people. It is a catalyst for change, accelerating the growth of off-grid appliance markets to boost incomes, reduce carbon emissions, improve quality of life, and support sustainable development.

Efficiency for Access consists of 20 Donor Roundtable Members, 19 Programme Partners, and more than 30 Investor Network members. Current Efficiency for Access Coalition members have programmes and initiatives spanning 62 countries and 34 key technologies.

The Efficiency for Access Coalition is coordinated jointly by CLASP, an international appliance energy efficiency and market development specialist not for-profit organisation, and UK's Energy Saving Trust, which specialises in energy efficiency product verification, data and insight, advice and research.

The Low Energy Inclusive Appliances programme is Efficiency for Access' flagship initiative.

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This policy note summarises the key insights from the report published by Efficiency for Access entitled, 'Lifecycle greenhouse gas (GHG) emissions assessment of off- and weak-grid refrigeration technologies' in an accessible manner. The work carried out a detailed cradle-to-grave lifecycle assessment of three off-grid cooling technologies: one refrigerator and two cold rooms. This allowed emission hotspots to be identified and appropriate mitigation actions to be recommended.

While the main report describes the methodology and insights in detail, this document provides an abridged version, tailored to assist policymakers in implementing a low carbon cold storage infrastructure. The key insights that can help minimise the carbon footprint of cold storage technologies are as follows:

1. **Appropriately size the system and optimise loading**

- Design your cooling systems to the optimal size in line with the needs of the customer – oversizing can result in additional emissions and cost more to build and run
- Once the cold room is built, maximise the utilisation rate to minimise emissions per unit of cooling energy
- If the utilisation rate is not an issue, a bigger cold room will result in much lower levels of carbon emissions per unit of cooling energy than a smaller cold room

2. **Optimise system lifetime**

- Maximise the lifetime of your system by using reliable, easy to maintain components. This avoids the need to replace the entire system too early

3. **Use high efficiency solar panels**

- Choose solar panels with high efficiencies to reduce the number of panels required

4. **Prioritise thermal (ice) storage over chemical batteries**

- Use thermal (ice) storage wherever possible to reduce the impact from chemical batteries. Where this is not possible, consider using hybrid battery banks to reduce cost and climate impacts. Develop re-use, refurbishment and recycling capacity for lithium-ion batteries in developing countries

5. **Maximise re-use and recycling**

- Always recycle the components of the system where possible and focus on developing higher quality recycling facilities in developing countries
- Making the manufacturer at least partly responsible for end-of-life recycling can be a more efficient mechanism than expecting the sector to evolve as a pro-recycling ecosystem. Manufacturers are also best placed to re-use and repurpose used components and systems and especially in service-based business models, could be best placed to bear the burden of recycling

6. **Account for the carbon impact of materials at design stage**

- Choice of materials especially virgin versus secondary materials can have a significant impact on the carbon footprint of refrigeration technologies. To achieve net zero targets, it is important to consider climate impact from mining, other raw material extraction processes and production

7. **Select refrigerants and blowing agents with a low global warming potential**

- Choose low global warming potential refrigerants and blowing agents wherever feasible

8. **Cooling technologies are particularly effective at mitigating food waste emissions in developing countries**

- Food waste emissions are significantly higher than the emissions for constructing a cold room or a refrigerator. The development of the cold chain to mitigate post-harvest losses in developing countries is key to reducing emissions in these countries. The use of lower carbon refrigeration technologies will maximise this benefit

Introduction

This document has been developed to assist policymakers in incentivising the development of least carbon off- and weak-grid refrigeration technologies suitable for developing countries. The primary aim of this document is to deliver the key insights from the main technical report, 'Lifecycle greenhouse gas (GHG) emissions assessment of off- and weak-grid refrigeration technologies' developed by the LEIA programme, in an accessible manner.

Among other things, a lack of reliable energy in large rural pockets of many developing countries, especially in Africa, South Asia and South-East Asia makes it challenging to provide suitable access to cold storage for vaccines and food or provide sufficient levels of refrigeration access for small businesses and household needs. To highlight the scale of the problem, around half of the food produced in developing countries goes to waste partly because it cannot be stored or transported at a low temperature.[1] This results in significant release of greenhouse gases from the decomposition of the produce. According to Driven to Waste: Global Food Loss on Farms, a report from WWF and Tesco, 1.2 billion tonnes of food is lost on farms, during, around, and after harvest. This is equivalent to approximately 15% of all food produced. In the case of African and South Asian countries, a key reason for food waste is due to lack of sufficient cold storage.[2] Therefore, it is clear that enabling access to cold storage can be a powerful tool in mitigating climate change.

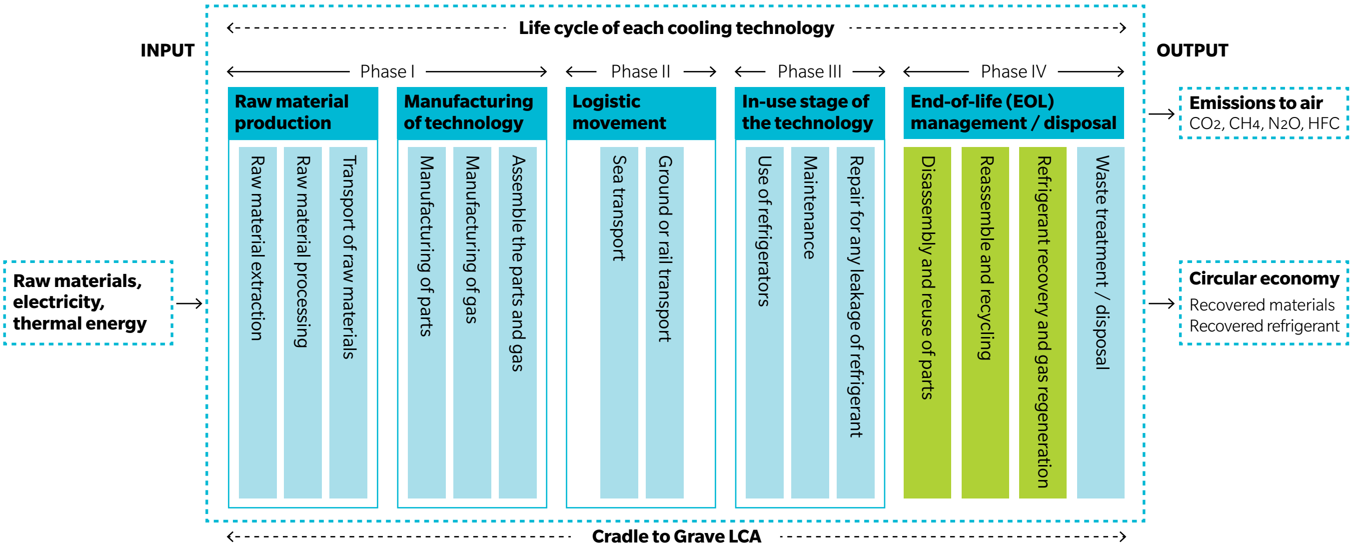
While cooling technologies can help with mitigating emissions related to food losses, cooling technologies themselves have been responsible for some significant climate impacts in the past. This was particularly from the use of ozone-depleting substances (ODS) that caused significant damage to the ozone layer in the 1970s and 1980s. While ODS have been phased out, the use of fluorinated gases as refrigerants and blowing agents continues, which can have a high global warming impact. In addition, other system design and material choices can have a significant carbon footprint.

It was therefore important to understand the climate impact of cooling systems in the off-grid market and highlight areas where steps can be taken to minimise this. With this in mind, a comprehensive 'cradle-to-grave' lifecycle greenhouse gas emission assessment was carried out on three cooling technologies used in low- and middle-income off- and weak-grid markets. This accounts for all the emissions throughout the life of the product (see Figure 1); from extracting the raw materials (eg mining the minerals), manufacturing the system, transporting it, using it and then disposing of and recycling it.

In the sections below, we detail and synthesise the combined findings across these three technologies with implications for the climate impacts of off-grid cooling technologies generally. Eight sub-sections under the chapter 'Key Learning Points' bring together these findings including:

1. Appropriately size the system and optimise loading
2. Optimise system lifetime
3. Use high efficiency solar panels
4. Prioritise thermal (ice) storage over chemical batteries
5. Maximise re-use and recycling
6. Account for carbon impact of materials at design stage
7. Choose refrigerants and blowing agents with a low global warming potential
8. Cooling technologies are particularly effective at mitigating food waste emissions in developing countries

Figure 1: Cradle to grave lifecycle emissions covering all the stages of a products lifetime within the context of this work



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[1] Covestro, 2018. Pure Facts, Polyurethane and sustainability. Available in www.solutions.covestro.com. Accessed 14 Nov 2020.

[2] https://ourworldindata.org/food-waste-emissions , https://wwf.panda.org/discover/our_focus/food_practice/food_loss_and_waste/driven_to_waste_global_food_loss_on_farms/

Technology summaries

Three technologies were examined in this project which are all grantees of funding from the LEIA programme. We are extremely grateful to all three companies for providing full details of all the components of their systems which enabled a thorough analysis of each product.

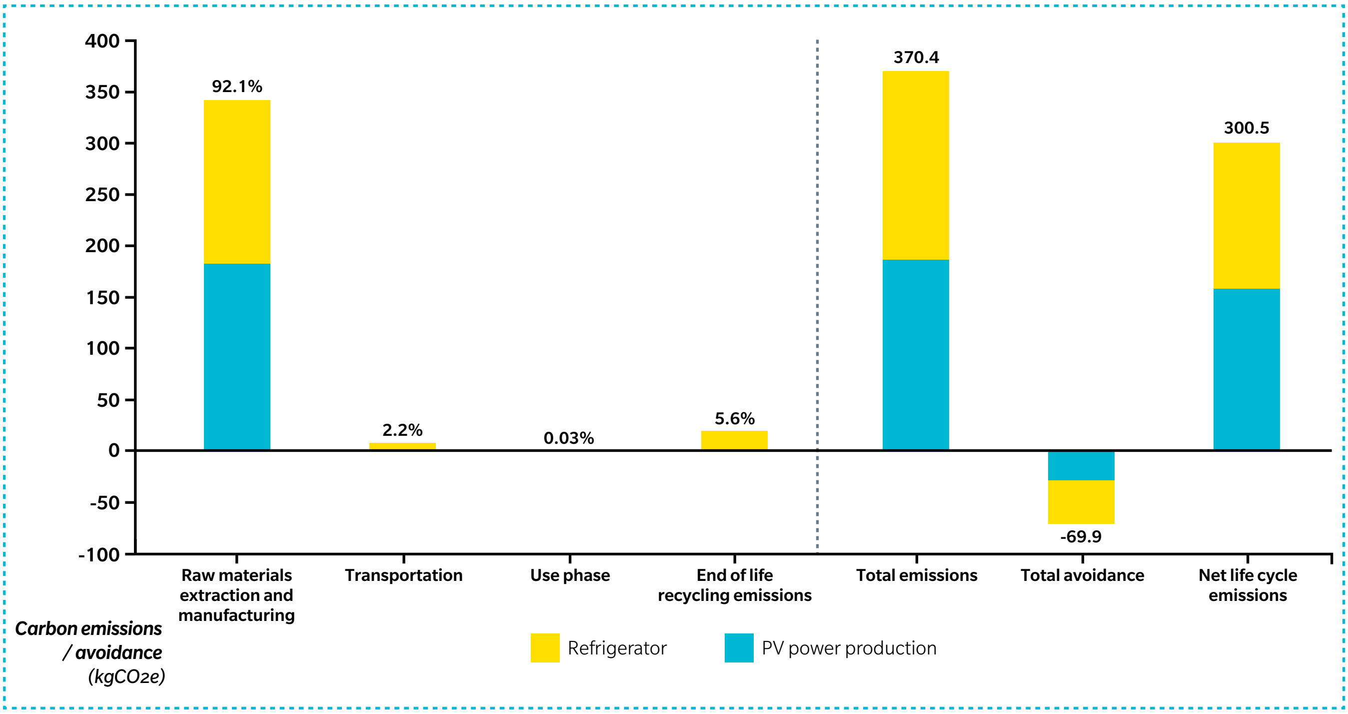
1. SureChill refrigerator

SureChill a refrigerator manufacturer which originally specialised in vaccine refrigerators. The refrigerator examined in this report is their 65 Litres (L) refrigerator designed specifically for the off-grid domestic market. It is a solar direct drive (SDD) system, meaning it has no chemical battery storage. Instead, energy storage is supplied by water/ice which surrounds the storage compartment. The water is cooled and frozen when there is sun to run the compressor via the solar panels and melts to provide cooling energy when it is cloudy or dark. By using direct current (DC) components system is extremely efficient, enabling it to use very little energy to run. This is an important advantage of an SDD system compared to an off-grid system that uses chemical batteries or which operates in hybrid mode by using a mix of chemical batteries and diesel generator or on-grid back-up services. In the latter case there will always be emissions associated with either the production and disposal of chemical batteries and/or the burning of fossil fuels. An SDD refrigerator is superior to a) those that rely on diesel generators where fuel shortages or price hikes can pose a risk to energy security or b) those that rely on weak-grid mains where poor power quality can often take down refrigeration. Organisations such as the World Health Organization (WHO) and the United Nations International Children's Emergency Fund (UNICEF) almost entirely use SDD refrigerators for vaccines.

Figure 2 shows the greenhouse gas emissions from the SureChill refrigerator, with the majority of emissions coming in the extraction of resources and manufacturing stages. One of the key features of battery-free off-grid systems is low emissions during the in-use phase. Once the solar power system is made, it has no subsequent emissions until the recycling stage.[3] The solar power system and the main body of the refrigerator itself account for the majority of those emissions in approximately equal amounts. There are negative emissions at the recycling stage, which means that materials are recycled back into the supply chain and will result in avoided emissions elsewhere. It should be noted that only ocean and land transport was used, with no materials transported by air throughout all technologies. This has resulted in particularly low transport emissions for these systems.

By comparing the SureChill refrigerator to a baseline version (i.e. a typical, low-cost alternative powered by alternating current (AC) adapted for use in the off-grid market), it was possible to identify key emission savings points. For example, the use of thermal (ice) storage instead of chemical batteries reduced the overall impact of the solar photovoltaic (PV) power production system by around 65%. This meant that the entire solar PV power system for an equivalent baseline system generated around 50% more emissions (440 kgCO$_2$e) than the entire SureChill refrigerator (300 kgCO$_2$e). Similarly, by using low carbon impact refrigerants and blowing agents, the SureChill refrigerator can reduce the climate impact from these by around 30 times (600 kgCO$_2$e for the baseline blowing agent and refrigerant compared to 20 kgCO$_2$e for SureChill). Overall, this produces a refrigerator with emissions around 25% of those of the baseline system examined (with high impact refrigerant and blowing agent, together with chemical battery storage).[4]

Figure 2: Emission summary for SureChill 65 L refrigerator



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[3] Assumed to be informal recycling – see page 17 for definition.

[4] Based on an assumed lifespan of 10 years for the refrigerators and 7 years for the batteries.

2. SelfChill cold room

SelfChill has developed an off-grid modular cold room design approach. The solar power system and efficient DC cooling units are sized to the precise cooling requirements of the user. Locally sourced materials can then be used to construct the rest of the system, reducing the cost for the end-user. This cold room uses ice thermal storage to provide cooling when the sun is not shining, with a small number of lead acid batteries required to operate electronics and fans to keep the cold room at the required temperature. The precise model considered in this analysis had a volume of 20 m^3 and stores 500 kg of food per day.

Figure 3 shows the overall emissions for the SelfChill cold room, with the majority of emissions coming in the raw material extraction and manufacturing stages.

As with SureChill, the SelfChill system greatly benefits from thermal storage and low carbon impact refrigerants and blowing agents, with emissions for their refrigerant and blowing agent reduced by over 99% compared to other currently used gases.[5] SelfChill is considering utilising an innovative hybrid battery system, which uses Li-ion and lead acid batteries together, to power the fans and electronics within their system and which can reduce emissions by around 50% compared to using Li-ion or lead acid batteries individually.

Using both battery types together would reduce emissions as well as cost, providing greater economic benefits for customers. Finally, SelfChill is currently investigating the possibility of a net-negative carbon cold room, using carbon offsetting materials (such as mud bricks) to build the structure.

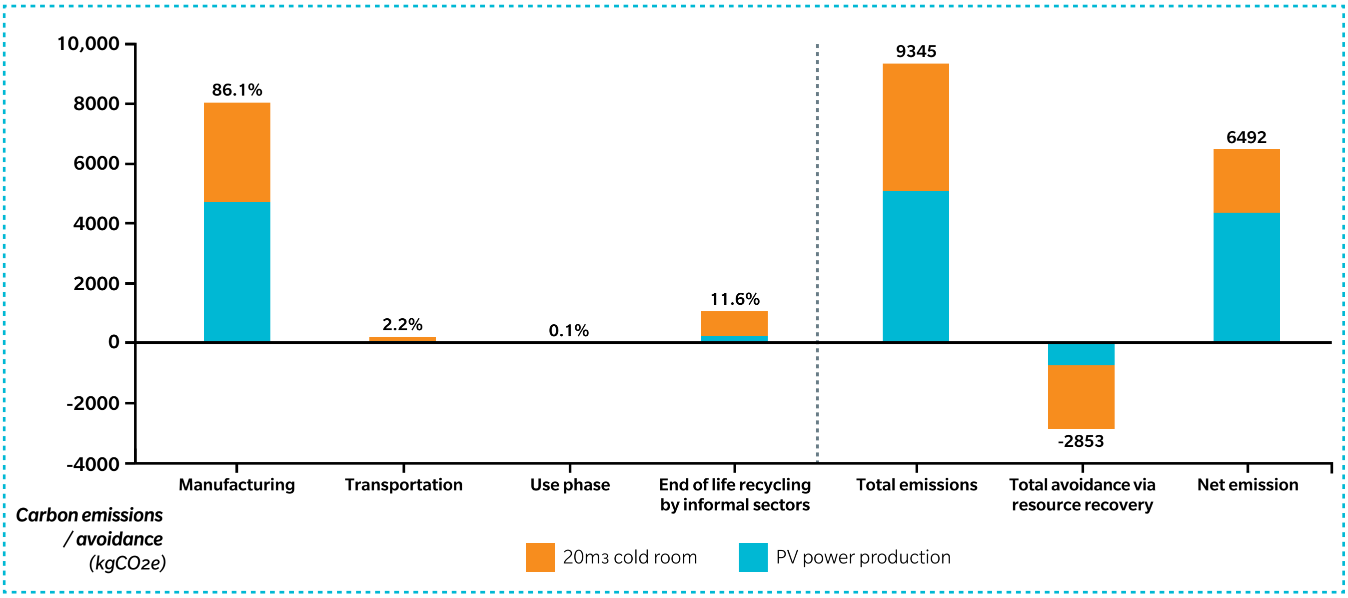
3. ColdHubs cold room

The model developed by ColdHubs considered in this report has an internal volume of 20 m^3, however it uses off the shelf components within its cooling system. The cooling unit deployed is one that is typically used in on-grid refrigeration applications with an inverter added to the solar power production system to make it compatible. Energy storage is exclusively provided for by lead acid batteries. This system has various operating scenarios, with some users filling it with around 3 tonnes of food per week, while others have higher utilisation, filling it with around 2 tonnes per day. This allowed an interesting comparison of emissions at varying capacity utilisation levels which is covered further on in this report.

Figure 4 shows the emissions for the ColdHubs cold room. As with the other two systems, the emissions from manufacturing of power system components (PV panels, mounting system and cables, charge controller and batteries), are accounted for in the extraction and manufacturing stages, leading to zero emissions during use phase owing to electricity generation. In this case, the solar power system has proportionally higher emissions than the other two technologies due to the much larger battery bank required in the absence of thermal storage.[6]

This ColdHubs system analysis highlighted some key emission hotspots which could be reduced in such systems. The use of lead acid batteries contributed 8400 kgCO2e to the system, around 45% of the entire PV power production system. The company is now designing an SDD system in which they hope to ultimately remove batteries altogether, replacing it with thermal storage.

Figure 3: Emission summary for SelfChill cold room



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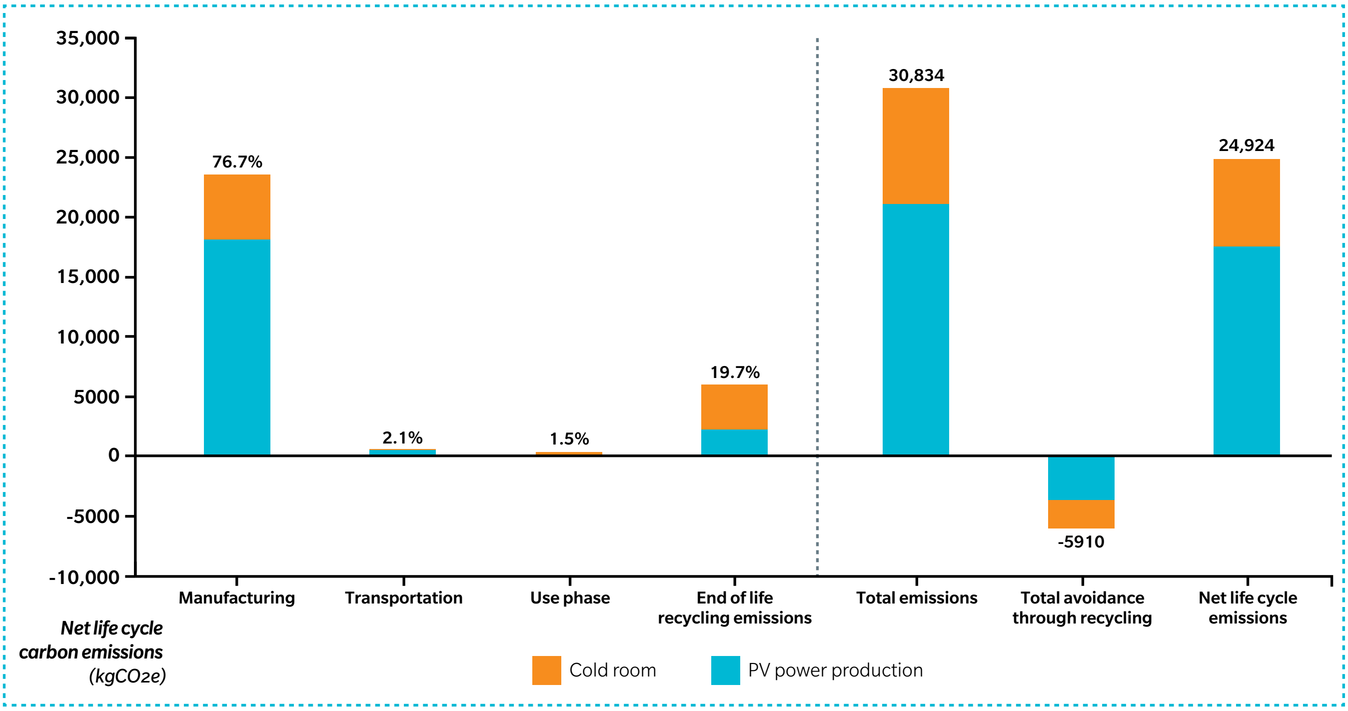
[5] Refrigerants: HC600a produces 2 kgCO2e compared to 1900 kgCO2e for HFC134a and 5900 kgCO2e for HFC404A. Blowing agent: HC-601 produces 60 kgCO2e compared to 16,100 kgCO2e for HFC-245fa

[6] In ColdHubs' latest designs, they are incorporating ice storage into the system

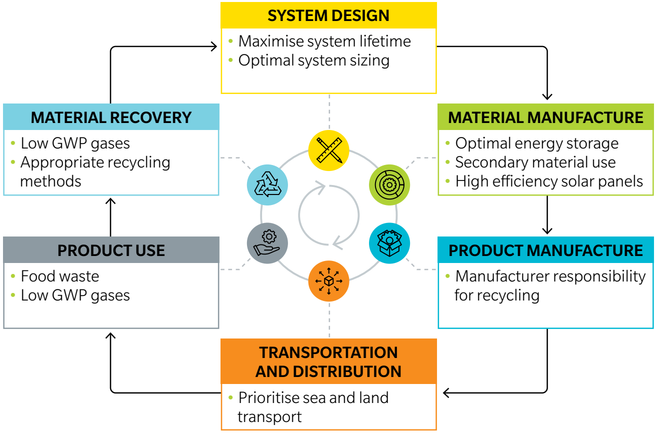
Figure 4: Emission summary for ColdHubs cold room



Key learning points

The next few pages will present the key learnings and takeaways from this body of work covering a range of topics which can be related to the principles of a circular economy lifetime as shown in Figure 5.

Figure 5: Key learning points related to their position within the circular economy



1. Appropriately size the system and optimise loading

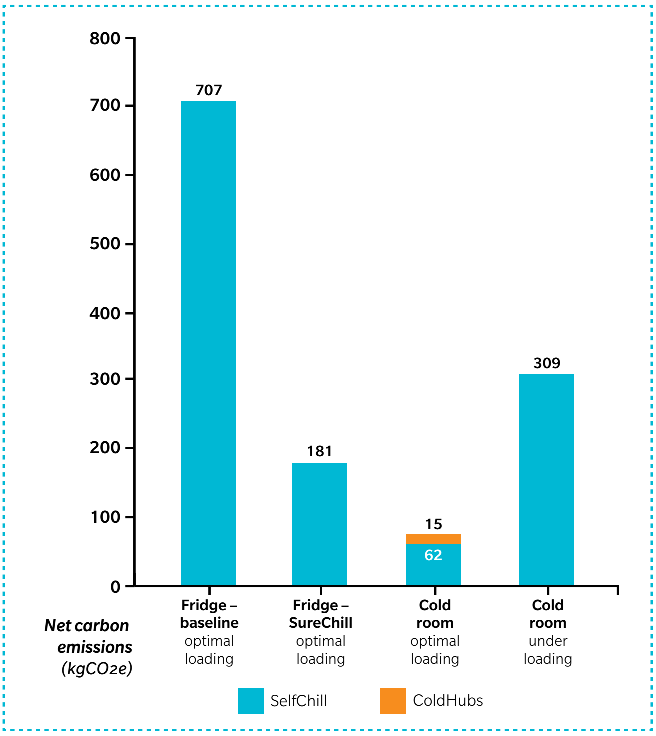
> **"Design your cooling systems to the optimal size in line with needs of the customer – oversizing can result in additional emissions and cost more to build and run.**
>
> **Once the cold room is built, maximise utilisation rate to minimise emissions per unit of cooling energy.**
>
> **If utilisation rate is not an issue, a bigger cold room will result in much lower levels of carbon emissions per unit of cooling energy than a smaller cold room."**

1.1 Economies of scale

Figure 6 shows the emissions per unit of food cooled or per unit of cooling energy for the three technologies considered in the report. This Figure helps highlight the benefits of the low carbon design refrigerator (in this case SureChill) when compared to the baseline alternative, but also shows that cold rooms generally have a lower impact than refrigerators (if insulated to similar levels).[7] This is because of the economies of scale offered by the larger systems – essentially, because of the square-cube law, there is a larger volume to cool for a smaller surface area (and therefore less material in the cold room structure and better thermal performance). A lower material requirement implies fewer emissions in extraction and production per unit of cooling energy. One could also proportionally reduce the size of the cooling units for additional emission reduction benefits.[8]

This shows the efficiency savings that can be made from using larger systems with greater volumes. However, each use case should be carefully considered as it is important to choose a solution which is right for the situation. For example, there is no point building a cold room if a refrigerator will serve the purpose. However, if there is space in a cold room to rent which would work as an alternative to a refrigerator, this could be the more climate friendly option.

Figure 6: Comparison of emissions per unit of food cooled between refrigeration and cold room technologies



Note 1: Optimal loading is defined as the scenario which produces the least emissions per unit of food, whilst also ensuring the food can achieve the correct temperature.
Note 2: The optimal load for cold rooms in the optimal cold room loading scenario includes emissions for **SelfChill** (dark blue) and **ColdHubs** (orange).

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[7] For example, it is possible that a well-insulated refrigerator is more carbon efficient than a poorly insulated cold room. This is because a poorly insulated system will require additional cooling energy and therefore would need a larger power system resulting in higher emissions.

[8] Cooling unit refers to the part of the cold room which cools the food. The main components are typically thermostat/control, condenser, compressor and evaporator together with various pumps and fans to distribute the cooled air.

1.2 Maximising use

Comparing different loading scenarios shows the benefits of careful design and maximising capacity utilisation rate in the refrigeration technology as much as possible. There is an optimal loading point where the amount of product loaded is maximised whilst also ensuring that it can achieve and remain at the desired temperature set point. Too much food and the system will not get cold enough. The cold room scenarios in Figure 6 (orange marker in middle and right-hand-side bars) show the difference in two loading scenarios for ColdHubs:

1. Loading 3 tonnes once per week
2. Loading the optimal amount (2.2 tonnes) every day

There is more than a four-fold reduction in emissions per unit of food in scenario 2 (optimal loading) compared to scenario 1 (3 tonnes once per week), and while this may not be the most appropriate scenario for every real-world situation, it highlights the benefit of maximising the usage of the cooling units. Oversizing the equipment can lead to a significant increase in emissions per kg of food cooled. Much of the cooling requirement comes from having to cool the food from ambient temperature to the internal temperature of the cold room and often the energy required to maintain the food at the set point is low in comparison.

Therefore, we recommend the following approaches to system design:

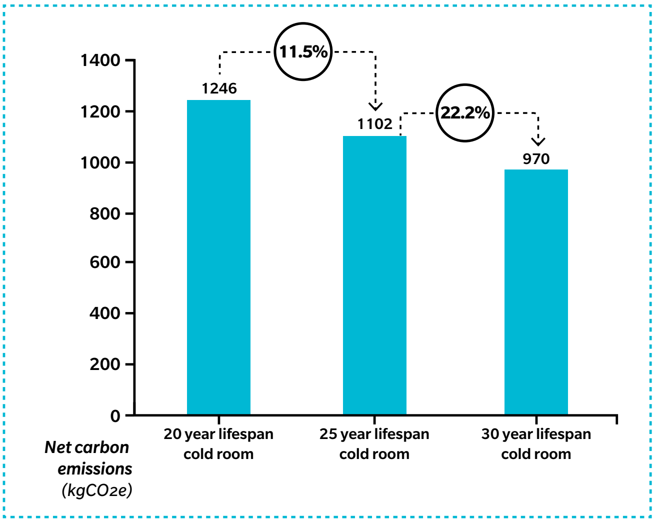
1. Size the system to the amount of food to be cooled and do not oversize
2. Consider the frequency of loading. If the desired loading frequency is only once per week, design the system in line with time taken to cool products initially. If the size of system is reduced, it will take longer to cool but overall climate impact will be reduced. However, you should make sure that you do not spoil the food
3. Consider precooling the food (eg by putting it in the shade for a few hours before putting it into the cold room, or by putting it in at cooler times of day)
4. Consider combining cooling requirements with other businesses close by to benefit from economies of scale or investigate cooling as a service business solution viability

2. Optimise system lifetime

> **"Maximise the lifetime of your system by using reliable, easy to maintain components. This avoids the need to replace the entire system too early"**

Within the world today there is still a tendency towards a 'throwaway' culture, with low initial cost being prioritised over future longevity. This analysis has shown that by increasing the lifetime of the system, one can dramatically cut emissions per year of operation. Figure 7 shows the emission-saving potential for extending the lifetime of the ColdHubs' cold room from 20 up to 30 years.

Figure 7: Emissions reduction for extending the lifetime of ColdHubs' cold room from 20 to 30 years



This considers the full replacement of various major components (eg, batteries, inverter and refrigerant), however does not include any additional emissions for the replacement of minor parts (for example compressor service parts). It is also possible that to ensure the longer lifetime is achievable, extra PV panels might be added to compensate for the 0.5% degradation per year. However, we expect that these additional emissions will be relatively minor and that the values quoted are a good representation of the possible savings.

There are potential arguments against increasing the system lifetime too much, the most significant being obsolescence. It might be the case that after the original lifetime of the system it might be more carbon friendly to recycle the old system and purchase a newer, more efficient system. These arguments are difficult to consider, with the state of the industry challenging to estimate at the present time, and are perhaps more relevant for grid connected systems. However, it is a subject that is worth consideration as the market develops. It is possible to design systems in such a way that inefficient or obsolete components can be replaced while still using much of the original system. For example, Selfchill's modular approach allows the cold room structure to be re-used, with the cooling units and parts of the solar power production system being replaced as they reach the end of their serviceable lifetimes.

This analysis leads to following recommendations:

1. Consider the lifetime of the system with regards to the embodied emissions. If a cold room's technical life in the field is increased, it can provide considerable emission savings per year of use
2. Use components which are high quality, reliable and easy to repair to maximise their lifetime. This should be combined with improving the local capacity to carry out these repairs to maximise the serviceable life

3. Consider adopting a modular design which would allow parts which have longer lifetimes to be re-used with new components

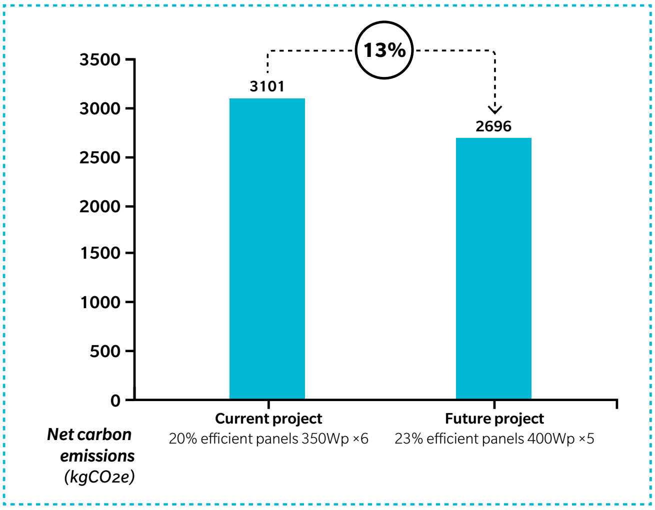
3. Use high efficiency solar panels

> **"Choose solar panels with high efficiencies to reduce the number of panels required"**

For each of the three technologies, the solar power system makes up a larger proportion of the emissions (greater than 50% for all three technologies). Within this, the solar panels have the largest emissions, followed by the emissions from battery storage (covered in the next section).

Efficiencies for solar panels can vary greatly with typical values around 15% to around 20%. Mono-crystalline and multi-junction cell panels can increase this further, with systems efficiencies of 23% readily available. By increasing the efficiency of the panels, this allows fewer to be used to produce the same amount of energy. If it is possible to produce the same size panels without any increase in emissions, significant carbon savings can be made as demonstrated in Figure 8. However, these high efficiency solar panels are often more expensive, and this additional cost must be balanced with the additional benefits in carbon mitigation.

Figure 8: Emission savings from using higher efficiency solar PV panels in the SelfChill cold room



Recommendations:

1. Use high efficiency solar panels to reduce the total number of panels used where possible
2. Encourage development in higher efficiency panels as well as investment in scaling up manufacture of these which will bring down the cost to affordable levels

4. Prioritise thermal (ice) storage over chemical batteries

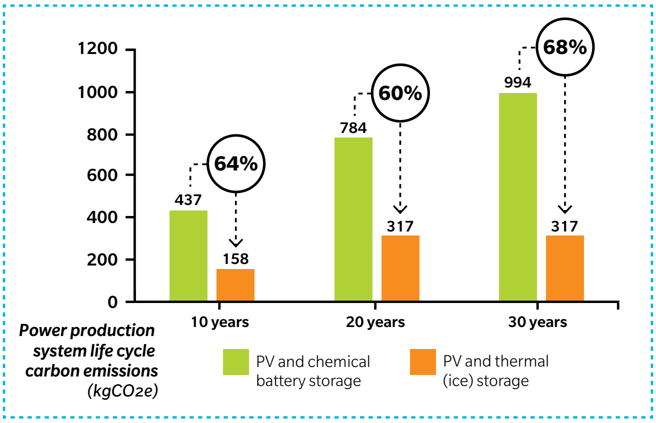
> **"Use thermal (ice) storage wherever possible to reduce the impact from chemical batteries. Where this is not possible, consider using hybrid battery banks to reduce cost and climate impacts. Develop re-use, refurbishment and recycling capacity for lithium-ion batteries in developing countries."**

Energy storage is a key component in off grid systems, which must store excess energy for use when there is no energy generation. This can be done in two ways: chemical storage using batteries or thermal storage typically using ice (and hybrid combinations of both).

The lowest environmental impact as well as the most economically feasible option is from thermal storage using ice. Ice is frozen during the day when there is lots of solar energy available. This ice then melts during cloudy periods or overnight when no solar electricity is generated. This melting provides the cooling to maintain the cold room at a low temperature. Cooling units that rely purely on thermal storage are called solar direct drive (SDD) systems. Some cold rooms utilise a hybrid system, using ice based thermal storage and a minimal amount of chemical storage to run fans which transfer cool air to the cooling area resulting in a significantly smaller climate impact when compared to pure chemical storage. As noted in the section 'Technology summaries', an important distinction here are the advantages of an SDD system over an off-grid system that uses chemical batteries or operates in hybrid mode by using a mix of chemical batteries and diesel generator or on-grid back-up services. The latter case will have more emissions and have higher energy reliability issues.

Figure 9 shows the difference in emissions between the SureChill refrigerator's power production system using ice storage and a baseline system using lead acid batteries; the thermal storage part effectively has no emissions.

Figure 9: Emissions for PV power production system for SureChill's refrigerator with thermal storage and a baseline system utilising chemical batteries for various lifetimes[9]



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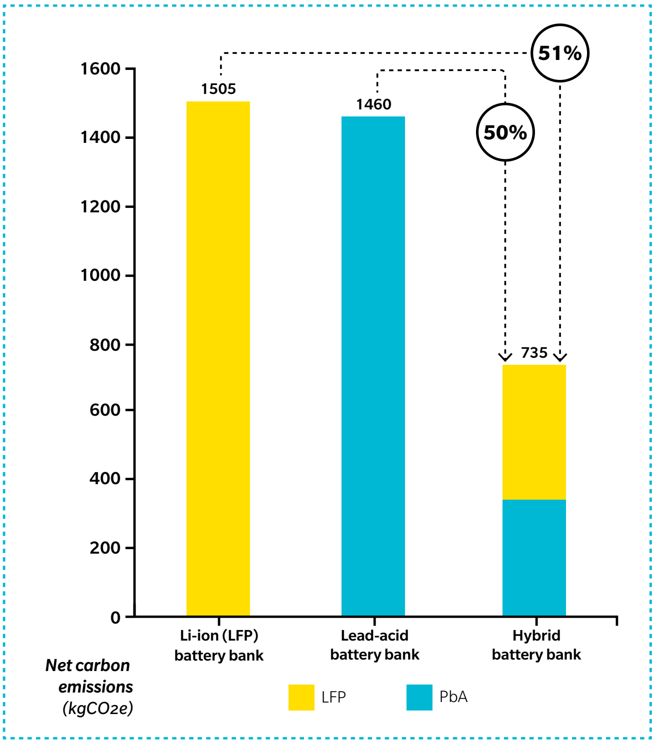
[9] It should be noted that in the 10-year cases, we have attributed only 50% of the solar panels emissions as we assumed they have been re-used for the remainder of their lifetime. A typical lifetime of a solar PV panel is at least 25 years.

There are a range of battery chemistries available to consumers in the current market. The two main ones to note in the off-grid industry are lead acid and lithium-ion. Lead acid batteries are less costly; however, they have shorter lifespans, are bulkier and cannot charge as quickly as lithium ions (although this last point is less important for off-grid refrigeration usually). There is a shift towards lithium-ion in many applications at the moment, which has also raises questions over human rights and environmental issues around the mining of the raw materials needed for various lithium-ion chemistries.

Our analysis has shown that the emissions from lead acid and lithium-ion systems are broadly comparable (see Figure 10), principally due to the fact that lead acid recycling is very well developed, whereas for lithium-ion technologies it is not. As the recycling rate of lithium-ion batteries improves, this will likely swing the emissions in favour of these systems, however this will likely take some years, especially in developing countries where the recycling industries are less well established.

Figure 10: Comparison of emission from an equivalent storage system of lithium ion, lead acid and a hybrid battery bank for SelfChill's cold room



Note: SelfChill uses a small battery pack as it includes thermal storage, therefore overall emissions from chemical batteries is in general, low.

An interesting emerging concept is the use of a hybrid system which uses both lead acid and lithium-ion batteries in tandem. The lithium-ion batteries generally do most of the heavy lifting, performing most of the discharging and charging which they are designed for, with the lead acid only used during longer periods of less generation (as back-up). This enables you to improve the lifetime of the lead acid system and also reduce the size of the Lithium-ion system, reducing both overall emissions and costs.

Recommendations

1. Encourage the use of ice storage instead of batteries. The climate impact and cost is significantly less
2. Our research suggests that lithium-ion batteries and lead acid batteries currently have a similar climate impact due to the good recycling rates of lead acid and poor recycling rates of lithium-ion. Therefore, significant investment should be made into lithium-ion battery re-use, refurbishment and recycling strategies to reduce their impact which would then likely prove the more climate friendly option
3. It is worth considering hybrid (lead acid and lithium-ion) battery systems for affordability and lower climate impacts

5. Maximise re-use and recycling

> **"Always recycle the components of the system where possible, and focus on developing higher quality recycling facilities in developing countries.**
>
> **Making the manufacturer at least partly responsible for end-of-life recycling can be a more efficient mechanism than expecting the sector to evolve as a pro-recycling ecosystem. Manufacturers are also best placed to re-use and repurpose used components and systems and especially in service-based business models, could be best placed to bear the burden of recycling."**

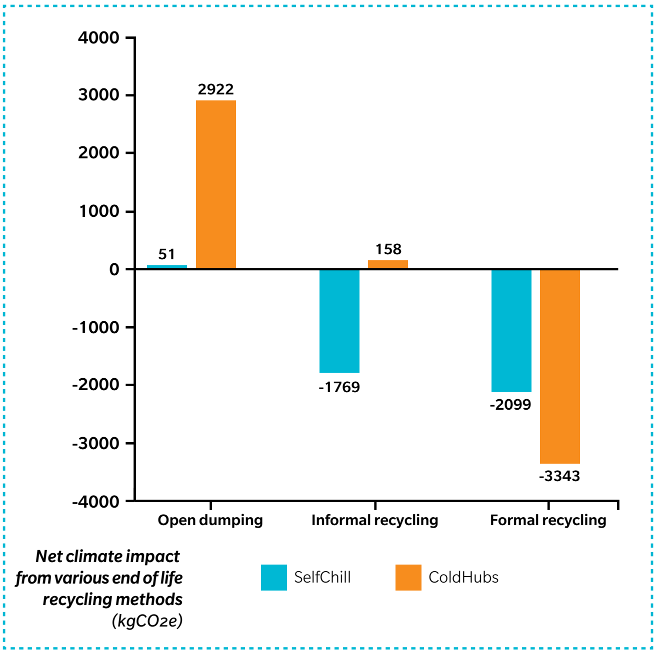
End-of-life management is an integral part of the circular economy and can help reduce emissions within low-carbon cooling technologies. Within this work, three disposal methods were explored: open dumping, informal recycling and formal recycling.

Open dumping is the case where components from the system are taken to landfill, which can have harmful impacts to the local environment through contamination by heavy metals and other materials used in cooling technologies. It also results in the release of fluorinated gases if used in the system, causing considerable carbon emissions due to their high global warming potential (GWP).

Informal recycling is the most common recycling method in Sub-Saharan Africa, where local recyclers manually extract valuable metals such as steel, aluminium, copper, and lead, and sell them to local collection agents for recycling at the nearest smelting facility. By recovering these materials rather than letting them go to landfill, accessibility and price-competitiveness of secondary materials within the local market is improved, in turn lowering manufacturing emissions and the cost for local production. Despite informal recycling, many materials and components still end up at landfill sites. Fluorinated gases if used in the system are also released during the manual dismantling process. Figure 11 shows there is a significant emission reduction potential from informal recycling when compared with open dumping scenario.

Formal recycling involves an organised collection process, comprising a mix of manual and mechanical dismantling and recycling using appropriate safety procedures. In this scenario, it is possible to maximise resource recovery. If appropriate equipment is available, refrigerant and blowing agents can also be captured. These facilities minimise health and environmental impacts in recycling vicinities and help provide a safe working environment for workers. Figure 11 shows a relatively small additional emissions gain from formal recycling compared to informal recycling. The scope of this analysis does not include the impact from non-greenhouse gases such as black carbon (from burning of end-of-life electronics to recover valuable materials) which could be significant under informal recycling conditions. There are also other impacts such as health and environmental impacts related to natural resource pollution that occur under informal recycling conditions, analysis of which is beyond the scope of this research. Therefore, the merits of formal versus informal recycling should not be established purely on the basis of carbon emissions analysis.

Figure 11: Net emissions from the various recycling methods for the SelfChill and ColdHubs cold rooms



It should be noted that the key difference in emissions between the two technologies is the impact of higher climate impact refrigerant and blowing agents. ColdHubs used higher carbon impact refrigerant and blowing agents which are released in the open dumping and informal recycling scenarios. This is discussed more in subsequent sections.

Recommendations

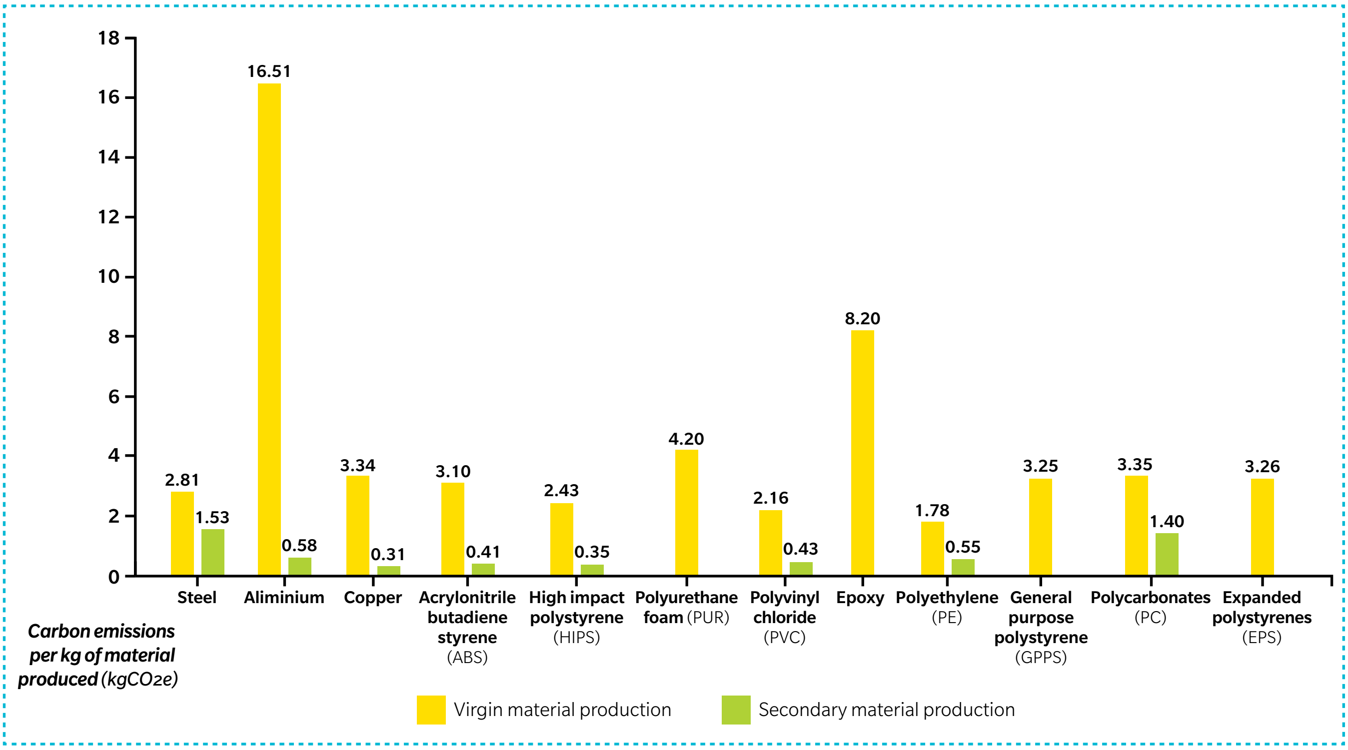
1. Informal recycling can provide significant carbon emissions reduction and resource recovery potential compared to open dumping methods, however there are still significant environmental and health impacts it does not address
2. Formal recycling has a further carbon emissions reduction from capturing refrigerant and blowing agents and recycling materials that informal recycling can't cover. It also has better health and environmental impacts for the neighbouring community and recycling workers
3. Making the manufacturer at least partly responsible for end-of-life recycling can be a more efficient mechanism than expecting the sector to evolve as a pro-recycling ecosystem. Manufacturers are also best placed to re-use and repurpose used components and systems and especially in service-based business models could be best placed to bear the burden of recycling
4. To promote a circular economy it should be ensured that all materials used in a product can be re-used, refurbished or recycled

6. Account for the carbon impact of materials at design stage

> **"Choice of materials especially virgin versus secondary materials can have a significant impact on the carbon footprint of refrigeration technologies. To achieve net zero targets, it is important to consider climate impact from mining, other raw material extraction processes and production"**

Within these technologies, the largest contribution to emissions is in the raw material extraction and manufacturing phases. The creation of virgin materials (i.e. those directly produced from extracted minerals), can have significantly higher emissions when compared to using recycled (or secondary) materials. To highlight this, Figure 12 shows the emissions from both virgin and secondary production for different materials used in Surechill refrigerators. Where it is possible to recycle these materials, you can see a significant reduction in emissions with particularly large savings for aluminium and copper.

Figure 12: Carbon emissions from the production of unit weight (1 kg) of materials from virgin processes and recovery from recycling



Recommendations

1. Use recycled materials as much as possible
2. Educate product designers and engineers on the climate impacts of various materials. This will allow them to better mitigate the climate impacts
3. Build local recycling facilities, especially formal recycling facilities. This can increase accessibility and price-competitiveness of secondary material to the local market, benefiting the supply chain of secondary materials

7. Choose refrigerants and blowing agents with a low global warming potential

"Choose low carbon impact refrigerant and blowing agents wherever feasible"

High carbon impact gases[10] are used as refrigerants in cooling units and blowing agents in the production of rigid insulation boards. Within cooling technologies, these gases contribute to emissions during the in-use phase, where a relatively small amount leaks out, and at the end of the product's life, where the majority can be released when the system is sent to landfill or recycled informally. The silver lining is that the adoption of low carbon impact gases for use in these applications is improving. Figure 13 and Figure 14 show the significant emission savings from the careful selection of refrigerant and blowing agents, with natural alternatives reducing emissions by over 99% compared to some hydrofluorocarbon (HFC) products. It should be noted that there may be some loss of performance by using these alternative gases, however, this is considered to be minimal in many cases and technology is constantly improving to nullify any performance gap.

In cooling technologies, while climate impact from refrigerant choice is often considered, the impact of using fluorinated gases as blowing agents is often overlooked, even though they can contribute significant emissions, especially in larger systems such as cold rooms. Therefore, it is suggested that there should be an equal (or even greater) focus on blowing agents compared to refrigerants to research novel, low carbon impact alternatives.

On occasions where low carbon impact gases are not available, these systems should be recycled using facilities capable of capturing these gases at the disposal stage so that they are not released into the environment.

Finally, there are materials which occur naturally and have very good insulative properties (eg sheep's wool, cellulose, hemp, various types of agricultural waste). These have a very low carbon impact, are more accessible in low-resource settings and should be investigated as alternatives to rigid insulation boards.

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[10] Often defined as high global warming potential (GWP) gases.

Figure 13: Emission summary for various blowing agent which could be used in ColdHubs' cold room

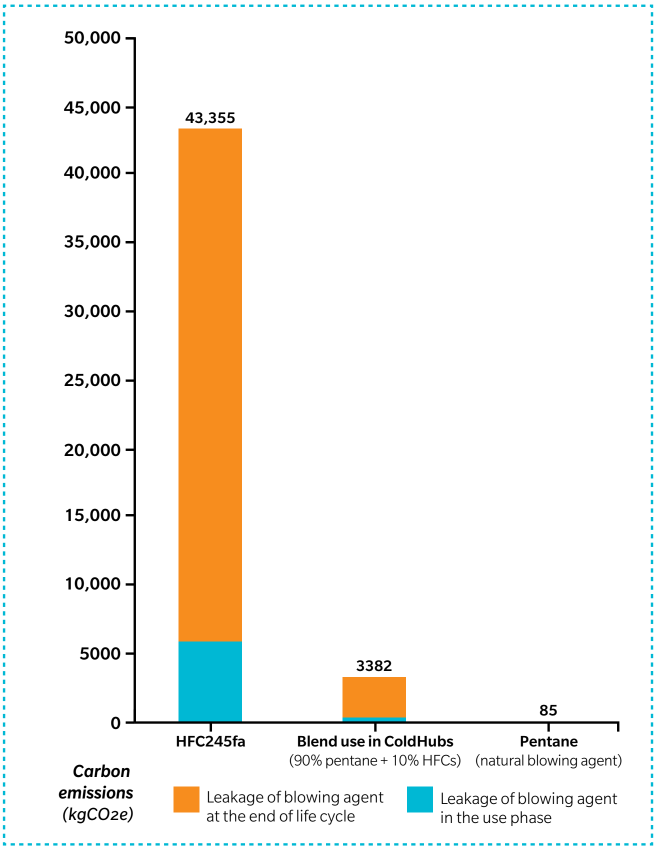
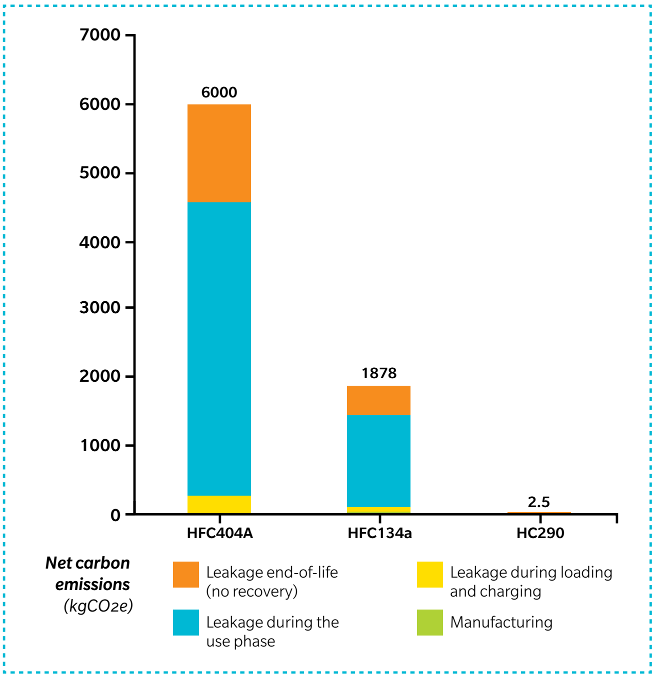


Figure 14: Emission summary for various refrigerants that could be used with the ColdHubs' cold room



Recommendations

1. Where possible, use low carbon impact refrigerants and blowing agents
2. If high carbon impact gases are used, the system should be disposed of at a facility which can capture these gases before they have a chance to release into the atmosphere
3. There should be more research and development into natural insulation materials

8. Cooling technologies are particularly effective at mitigating food waste emissions in developing countries

> **"Food waste emissions are significantly higher than the emissions for constructing a cold room or a refrigerator. The development of the cold chain to mitigate post-harvest losses in developing countries is key to reducing emissions in these countries. The use of lower carbon refrigeration technologies will maximise this benefit."**

As mentioned in the introduction, food waste is a major contributor to global emissions. In developing countries, around half of all food is estimated to go to waste. When food biodegrades it can release methane, a potent greenhouse gas around 25 times as powerful as carbon dioxide. There are additional embodied emissions from the food production process that are also wasted that can also be considered.[11] Therefore, by reducing food waste, we can dramatically reduce global emissions. Cold storage can greatly mitigate this by helping food stay fresh for longer and avoid spoiling before it even reaches consumers.

In this analysis, the potential avoided emissions from reducing food waste through the use of cold storage technologies has been estimated. The quantity of food as well as the associated emissions from food waste can vary dramatically depending on a number of factors, such as the type of food, its stage in the food supply chain and the location. The cold room technologies considered in this analysis are most applicable for the post-harvest handling and storage stages, at farms or close to local markets. There are no limitations on what type of food can be stored in a cold room, but based on the feedback from local installers, fruits and vegetables are the most common commodity in the areas of interest (Sub-Saharan Africa and South Asia).

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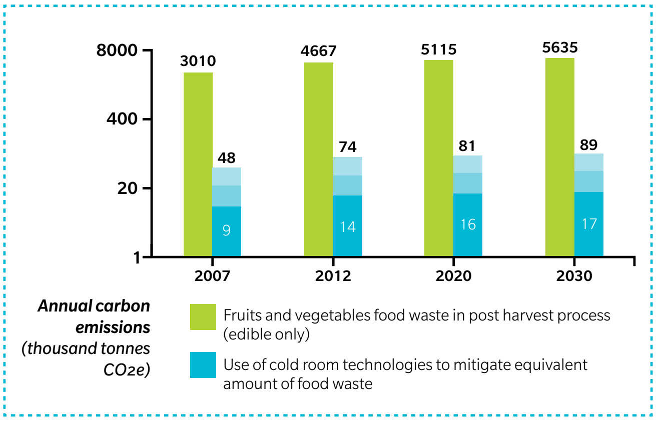
[11] Please note that we have only included decomposition emissions in this analysis.

Using data from the Food and Agriculture organisation of the United Nations (FAO), who produced a series of reports on global food waste and its associated carbon footprint with data from 2007, the total amount (in kg) of food waste for fruit and vegetables in the post-harvest and storage stages were estimated. Using assumptions from FAO's 'towards sustainability' scenario it was possible to project food wastage figures up to 2030.

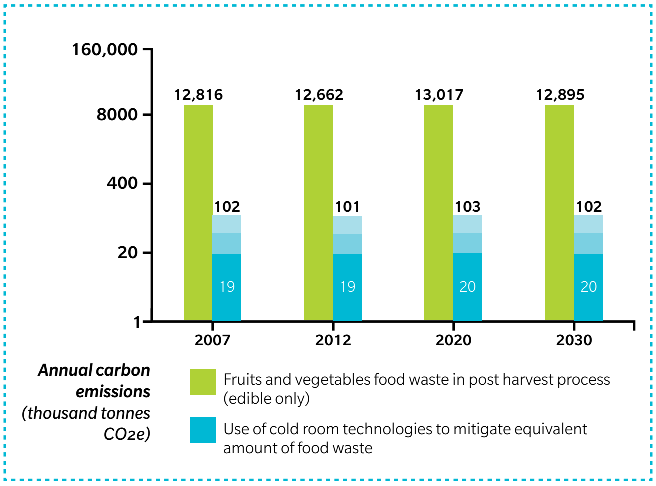
To convert the amount of food waste to equivalent carbon emissions, an emission factor of 20kg methane emissions per tonne of food waste for shallow dumping and 40kg methane emissions per tonne of food waste for deep dumping, was used. This is a conservative estimate as, in reality, there would be further emissions savings by avoiding the need to plant additional crops to replace any wasted food in the face of a growing population. However, regarding embodied emissions in food waste, it is beyond the scope of this work considered here.

Figure 15: Food waste emissions (from decomposition) compared to equivalent cooling technologies needed in Sub-Saharan Africa



Please note the logarithmic axis for carbon emissions.

Figure 16: Food waste emissions (from decomposition) compared to equivalent cooling technologies needed in South Asia



Please note the logarithmic axis for carbon emissions.

Figure 15 and Figure 16 compare the emissions from food wastage in the absence of cold storage with the emissions that would be incurred by installing and using a sufficient level of cold storage in Sub-Saharan Africa and South Asia, respectively. Please note the logarithmic axis for carbon emissions. The orange bars in the graphs represent the emissions from the decomposition of fruit and vegetable waste in the post-harvest stage per year in both regions that would occur in the absence of cold rooms. The green bars represent the annual carbon emissions associated with an equivalent number of cold rooms required to mitigate the fruit and vegetable food waste. The dotted box in the green bar shows the range of emissions for cold room technologies assessed in this study, with the lower end of the dotted box denoting emissions from the SelfChill cold room (at 3.5 tonnes per week loading rate) and the higher end of the dotted box indicating emissions from the ColdHubs cold room (at the higher loading rate emission scenario of 3 tonnes per week). The graphs show the staggering contrast between positive emissions from cold room installations and the emissions that can be avoided with cold room installations. If cold rooms were used to mitigate this food waste, the annual carbon emissions would only be 0.3% to 1.6% of current levels from food waste.

Final thoughts

The work carried out in this project serves as a key resource in identifying emission hotspots within refrigeration systems for off-grid areas in developing countries and the findings can be used by anyone in the refrigeration industry to design more climate-friendly appliances in the future.

Key recommendations include:

- Carefully plan the size of the cooling system based on the expected loading scenario to avoid oversizing
- Once the appliance or cold room is built, maximise the utilisation rate to minimise emissions per unit of cooling energy
- If utilisation rate is not an issue, a bigger appliance or cold room will result in much lower levels of carbon emissions per unit of cooling energy than a smaller one
- Maximise the lifetime of cooling system to reduce emissions per year of use; repairability is an important strategy to keep lifetime emissions low
- Choose solar panels with high efficiencies to reduce the number of panels required
- Use thermal storage (ice storage) as an alternative to chemical batteries to reduce storage emissions
- Develop re-use and recycling facilities to enable the safe recovery of materials from appliances. In particular, re-use and recycling efforts should focus on lithium-ion batteries. This will help minimise emissions of systems where complete substitution of chemical batteries with thermal storage is not feasible
- Avoid the use of primary or virgin materials where feasible – use recycled (secondary) materials to minimise the carbon impact and promote a circular economy
- Use low carbon impact refrigerants and blowing agents which can have significant carbon savings

The authors are extremely grateful to the three grantees of the LEIA programme: SureChill, SelfChill and ColdHubs, for all their assistance in this project. The grantees are using the results of this study to help inform low-carbon design of upcoming refrigeration models. For example, ColdHubs plans to develop a thermal storage based cold room.

It should be noted that there are some limitations to the analysis presented here. This analysis only covered carbon emissions and did not cover other impacts such as pollution from particulate matter (like black carbon). Some of these impacts are not considered in this study but have important implications in certain contexts. For example, there are significant health and environmental benefits under formal recycling over informal recycling, while carbon emissions gains are only modest.

It should also be noted that the emissions presented here will change in the future, as extraction and manufacturing processes become more carbon efficient with time. However, the authors expect that these numbers will remain valid for a number of years, and many of the key messages will remain relevant for even longer.

It is worth reiterating the arguments of the final point on food waste emissions versus emissions from cold storage as this begs an interesting argument: “Is any type of cold storage (i.e. even a high climate impact cold storage) better than no cold storage at all?” to which the answer is undeniably yes. This being said, there is an important opportunity here to create systems with low carbon impacts from the very start. The key limitation here is the supply chain within developing countries which may limit some of the more carbon friendly technologies (eg DC compressors, low carbon impact gases and systems which run on climate friendly refrigerants). There should be considerable efforts made here to allow these to become the go-to systems. What is more, the carbon friendly systems are often cheaper in the long term, with solar PV being cheaper than diesel and thermal storage (just water!) being cheaper than chemical batteries. By enabling these low-carbon technologies there is the opportunity to unlock significant economic benefits for users of these technologies in Sub-Saharan Africa and South Asia.

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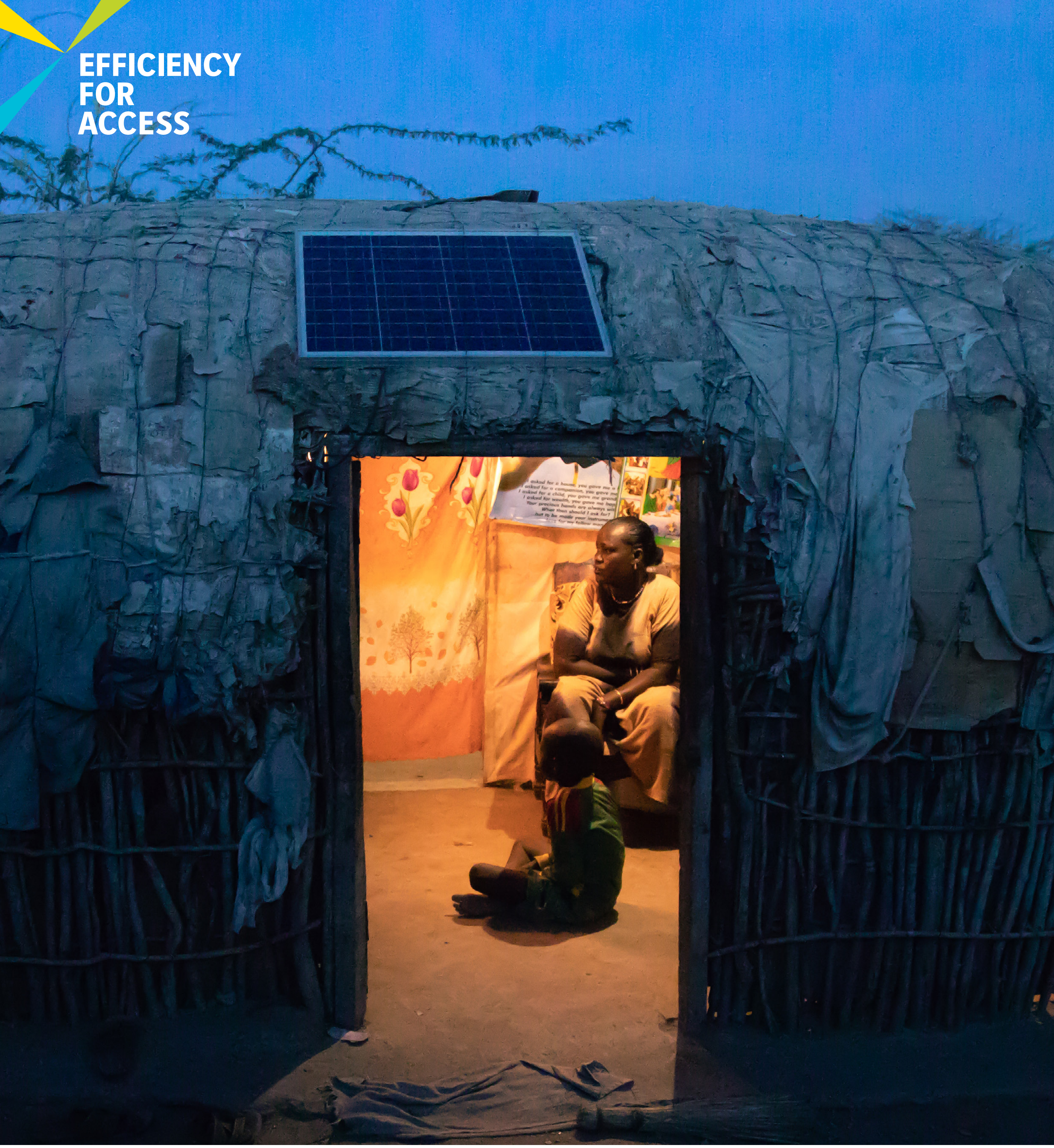

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