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

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EFFICIENCY FOR ACCESS COALITION

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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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ACRONYMS & ABBREVIATIONS

BC	Black carbon
CaaS	Cooling as a Service
CFC	Chlorofluorocarbon
DC	Direct Current
EOL	End-of-Life
GHG	Greenhouse Gas
GWP	Global Warming Potential
HCFCs	Hydrochlorofluorocarbons
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCI	Life Cycle Inventory
LCIA	Life Cycle impact Assessment
LEIA	Low Energy Inclusive Appliances
LFP	Lithium ferrophosphate
NMC	Lithium nickel manganese cobalt oxide
ODP	Ozone Depletion Potential
PAS	Publicly Available Specification
PbA	Lead acid
PCB	Printed Circuit Board (PCB)
PV	Photovoltaic
WEEE	Waste Electrical and Electronic Equipment

Large areas in rural pockets of many developing countries, especially in Africa, South Asia, and South-East Asia, have no or unreliable access to grid electricity.

Among other things, this lack of reliable energy 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 because it cannot be stored or transported at a low temperature. 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 15.3% of 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. Enabling access to cold storage can therefore be a powerful tool in mitigating climate change.

However, even though enabling cold storage can help in lowering emissions in developing countries, cooling technologies themselves have been responsible for some significant climate impacts in the past, 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, use of fluorinated gases as refrigerants and blowing agents continues. This has high global warming impact. In addition, system design and material choice also contribute to climate impact.

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

This report is a longer technical document that describes methodological details alongside summarising climate related insights. The authors have developed a shorter note titled, 'Note for policy makers: Life cycle GHG emissions assessment of off- and weak-grid refrigeration technologies', meant to assist policy makers in incentivising the development of least carbon off- and weak-grid refrigeration technologies suitable for developing countries. The primary aim of the policy maker note is to deliver the key insights from the main technical report, 'Life cycle GHG emissions assessment of off- and weak-grid refrigeration technologies' developed by the LEIA programme, in an accessible manner. These insights are bucketed intro 8 categories as shown in schematic below. The authors recommend readers keen to access a quick summary of this report to access the policy maker note here.

Figure 2: Key learning points related to their position within the circular economy

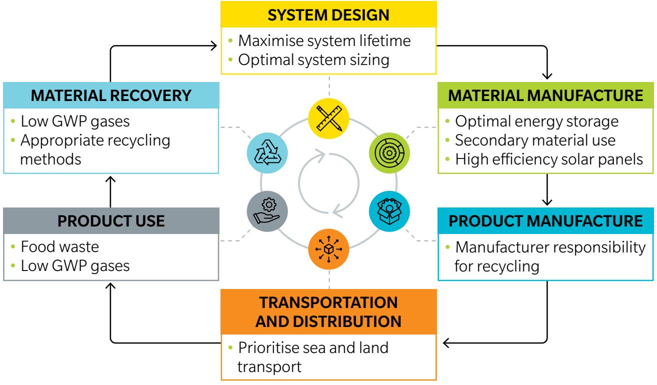
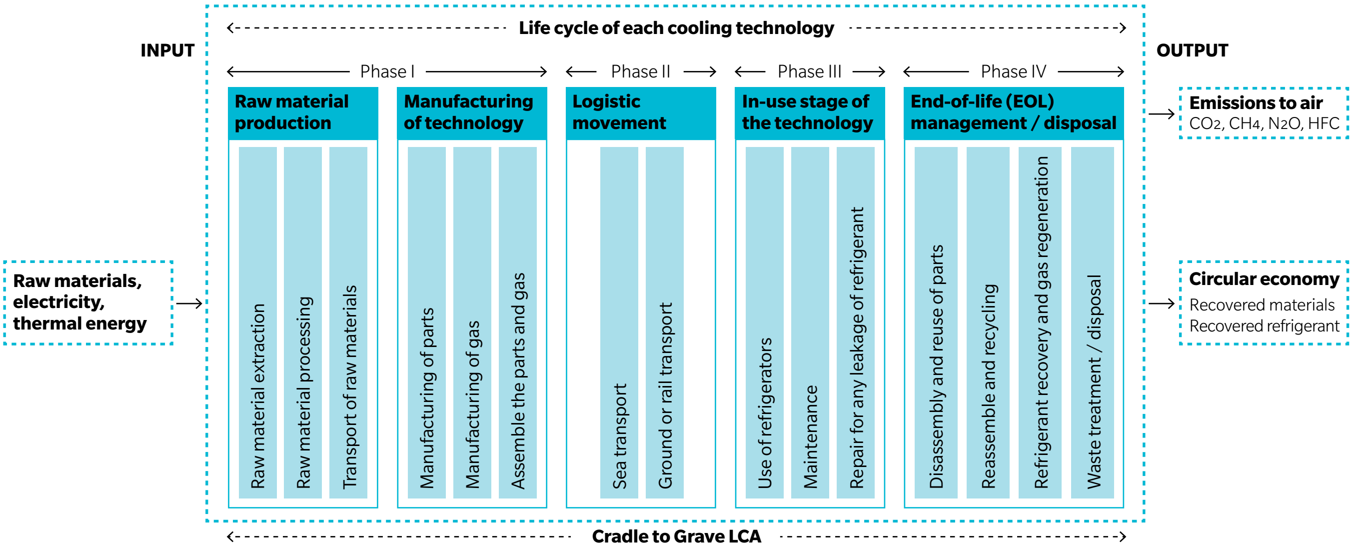


Figure 1: Cradle to grave life cycle emissions covering all the stages of a products lifetime



In the paragraphs below, we detail and synthesize the combined findings across these three technologies with implications for the climate impacts of off-grid cooling technologies generally. The technology summaries have been used to develop key scenario analyses that have important insights to offer for development of low carbon cold chain infrastructure. These analyses and insights are detailed in Sections 2.4, 3.2 and 4.2 in this report.

Technology summaries

Three technologies were examined in this project which are all produced by organisations that have recieved grant funding from the LEIA programme. We are extremely grateful to all three companies who provided full details of all the components of their systems which enabled a thorough analysis of each product.

1. SureChill refrigerator

SureChill are a fridge manufacturer who originally specialised in vaccine fridges. The refrigerator examined in this report is their 65 L refrigerator designed specifically for the off-grid domestic market. It is a solar direct drive (SDD) system, meaning that is 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 DC components their system is extremely efficient, enabling it to use very little energy to run.

Figure 3 shows the greenhouse gas emissions from the SureChill fridge, with the majority of emissions coming in the extraction and manufacturing stages. One of the key features of battery-free off-grid systems are their low emissions during the in-use phase as once the solar power system is made it has no subsequent emissions until the recycling stage. The solar power system and the main body of the fridge 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.

By comparing the SureChill refrigerator to a baseline version (i.e. a typical, low-cost alternative powered by alternating current (AC) in the same market), it was possible to identify key emission savings points. For example, the use of the thermal ice storage instead of a typical battery reduced the overall impact of the PV power production system by around 65%. This meant that the entire solar power system for an equivalent baseline system generated around 50% more emissions than the entire SureChill refrigerator (440 kg CO_2-eq compared to 300 kg CO_2-eq). Similarly, by using low GWP refrigerants and blowing agents, the SureChill refrigerator can reduce the climate impact from these by around 25 times (600 kg CO_2-eq for the baseline blowing agent and refrigerant compared to 25 kg CO_2-eq for SureChill). Overall, this produces a fridge with emissions around 25% those of a standard system for a 10 year lifespan of the fridge.

2. SelfChill cold room

SelfChill have 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 power 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 20m^3 and stores 500 kg of food per day.

Figure 3: Emission summary for SureChill 65 L refrigerator

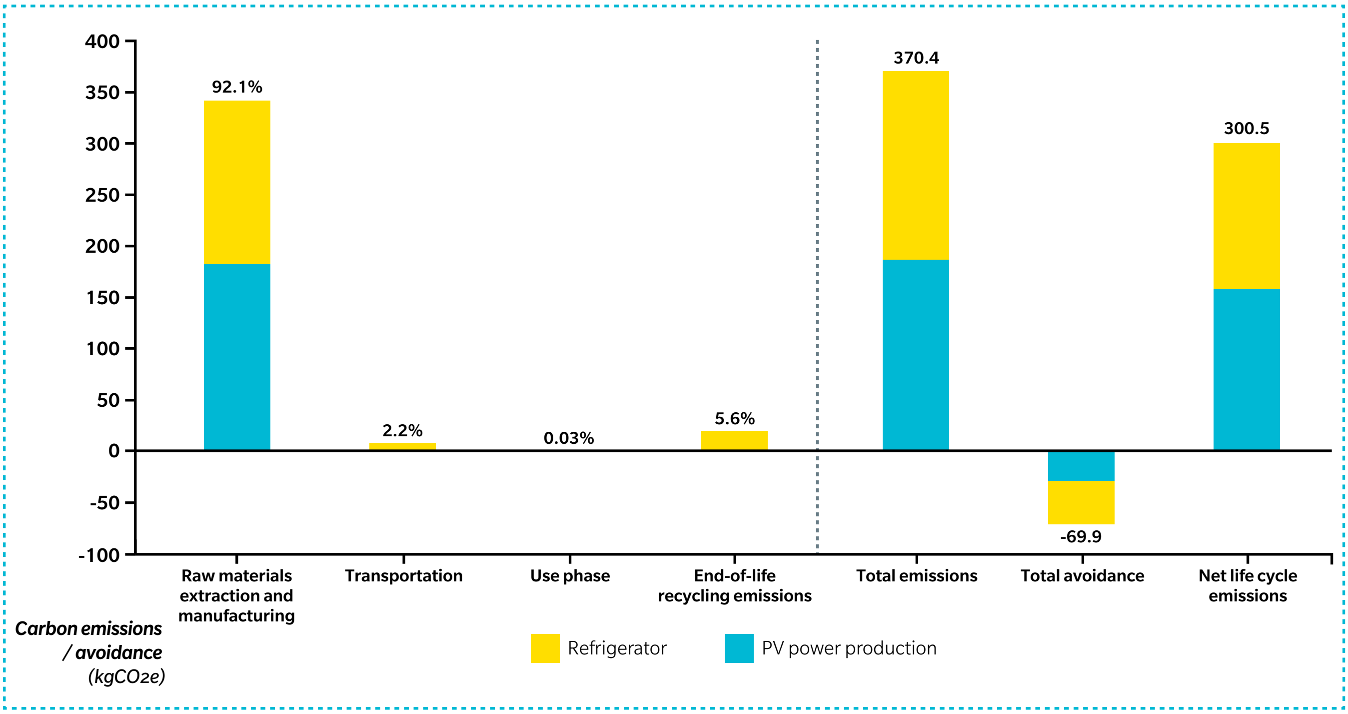


Figure 4 shows the overall emissions for the SelfChill cold room, with again the majority of emission coming in the extraction and manufacturing stages.

As with SureChill, the SelfChill system greatly benefits from thermal storage and low GWP refrigerants, with emissions for their refrigerant reducing emissions by almost 100% compared to other currently used refrigerants (for context, HC600a produces 2 kg CO_2-eq compared to 1900 kg CO_2-eq for HFC134a and 5900 kg CO_2-eq for HFC404A). SelfChill is considering using an innovative hybrid battery system, which uses both Li-ion and lead acid batteries together, to power the fans and electronics within their system which can reduce the emissions by around 50% compared to just Li-ion or lead acid batteries by themselves. This would reduce both emissions as well as cost, providing greater economic benefits for customers. Finally, SelfChill are currently investigating the possibility of a net-negative cold room, using carbon negative materials (such as mud bricks) to build the structure.

Figure 5: Emission summary for ColdHubs cold room

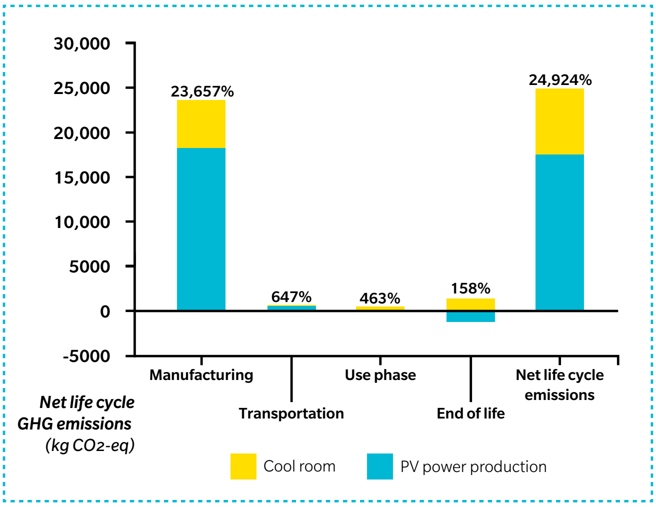
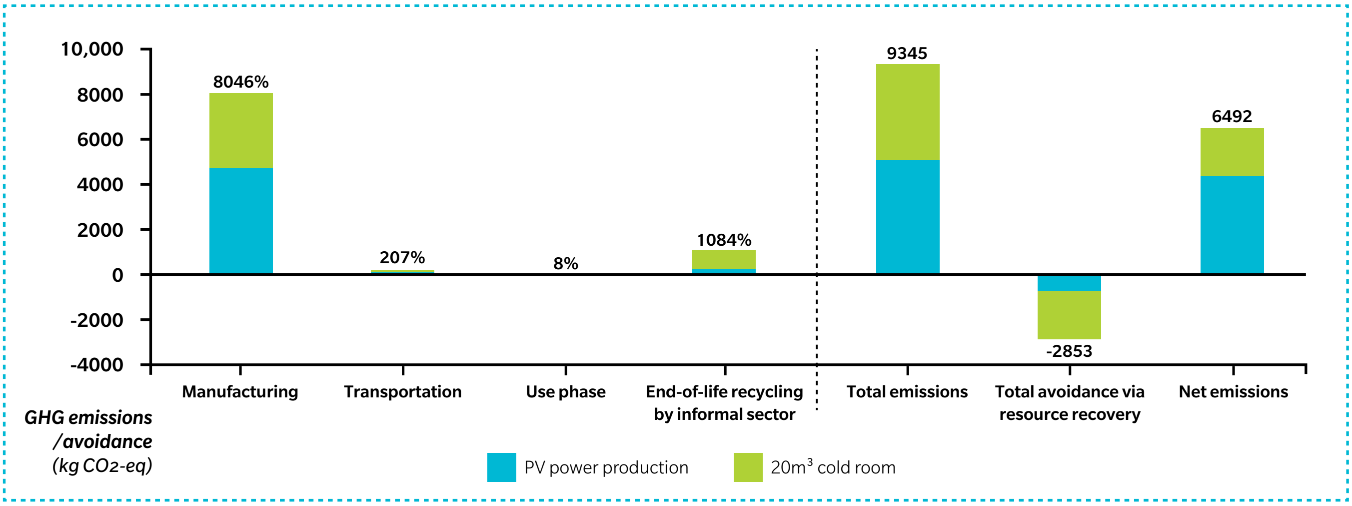


Figure 4: Emission summary for SelfChill cold room



3. ColdHubs cold room

The model developed by ColdHubs considered in this report also has an internal volume of 20 m^3, however it uses off the shelf components within its cooling system. They use a cooling unit that is typically used in on-grid refrigeration applications and have added an inverter to the solar power production system to make it compatible. Energy storage is exclusively provided 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 utilization, filling it with around 2 tonnes per day. This allowed an interesting comparison of emissions at varying capacity utilisation levels.

Figure 5 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. ColdHubs in its latest cold storage unit designs, is considering incorporating ice storage.

This ColdHubs system analysis highlighted some key emission hotspots which could be reduced in such systems. The use of lead acid batteries contributed 2800 kg CO_2-eq to the system, 40% 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. ColdHubs also have their systems installed in various use cases; in some locations around 3 tonnes of food are loaded per week and in another around 2.2 tonnes are loaded per day (around 15 tonnes per week). In the latter case, the cold room is being used to its maximum limit and emits four times fewer emissions per unit of cooling energy required or per kg of food compared to the lower loading scenario. In the maximum loading scenario the cold room emits 77 g CO_2-eq/kWh while the lower loading scenario emits 309 g CO_2-eq/kWh.

Introduction and motivation for this research

Large areas in rural pockets of many developing countries especially in Africa, South Asia and South-East Asia have no or unreliable access to grid electricity.

940 million (13% of the world) did not have access to grid electricity in 2016.[1] Even in areas with grid power, electricity access is unreliable and insufficient for continuous refrigeration due to the outpaced demand growth. Among other things, lack of reliable energy access makes it challenging to provide access to vaccines and food storage services.[2] As an example, 50% of the food produced in developing countries goes to waste because it cannot be stored or transported at a low temperature.[3] Access to energy-efficient and affordable cooling systems would improve food security and reduce food wastage and food-related illness in remote areas of developing countries. Furthermore, provision of adequate off-grid cooling services in remote areas would enhance business opportunities and local economic growth, directly contributing to improving communities' well-being. Last mile provision of these services is critical to ensure community resilience in the face of macro-economic shocks caused by COVID-19 or climate change.

Food losses across the agricultural supply chain cause an increase in GHG emissions resulting from agricultural production. This includes indirect emissions from land use change, and emissions from extra food production required to make up for food losses to ensure true food security. Depending on publication source, food losses and waste in supply chain and by consumers accounts for 6 – 8% of anthropogenic GHG emissions. Therefore, enabling access to cold storage for food could be a powerful tool in the climate mitigation toolbox, especially if efforts are made to deploy the lowest carbon cold chain infrastructure possible. Climate change is a global issue of increasing importance and urgency; the 2021 Intergovernmental Panel on Climate Change (IPCC) report indicates that a 50% - 80% reduction of global greenhouse gas (GHG) emissions by 2050 from 2000 is required to avoid severe and enduring climate change.[4] The 2023 IPCC report underlined the importance of urgent action with a focus on low-income and marginalized communities to deliver a "livable" future.

Given a substantial majority of rural regions would be accessing cooling services for the first time, this sector is expected to add significant positive emissions even if the most energy efficient, clean energy-based technologies were to be deployed. The following are some of the key areas where additional mitigation benefits could occur if a greener off-grid cooling infrastructure were deployed:

- Modern cooling technologies are not widespread in rural areas, particularly outside of the countries' economic centres. They are expensive and have a high carbon footprint owing to their high and diverse materials demand, use of fluorinated gases and high energy demand. The food cold chain sector alone is responsible for 1% of global GHG emissions due to use of fluorinated gases as refrigerants[5] and as blowing agents.[6] Use of low GWP refrigerants as far as feasible can help minimise such emissions.
- Abiotic resources depletion, i.e. rare and precious metals, is another serious threat to the environment. Recovery of resources from end-of-life refrigerators would contribute to abiotic resource savings, local economic development, and the circular economy.
- In addition to low carbon material selection and green system design, Cooling as a Service (CaaS), or another a pay-per-service model for clean cooling systems could be an example of an environmentally sustainable business model. Use of such models in certain applications enables the twin benefit of facilitating end-user affordability while creating environmental benefits. This is because the customer is able to avoid by instead paying on a use-only basis. The steep upfront costs entailed in owning an individual system and has to pay on a use basis alone. At the same time, such models could prove to be more environmentally sustainable as a single system is used by multiple users, thus decreasing the amount of materials and energy needed for manufacturing individual level systems.[7] Additionally, given the system is managed by the energy service provider, the provider has an incentive to undertake preventative maintenance and timely repairs, leading to a scenario where the maximum possible technical life of the system could be attained. Such systems are also likely to be designed in the most energy efficient way, leading to reduced energy consumption.

Similarly, material recovery and recycling at system end-of-life can help avoid carbon emissions that would otherwise have occurred in producing a corresponding amount of material required for producing new cooling systems. If these new systems were to be powered by conventional electricity, this would result in emissions beyond those required for material extraction and production. Reuse, refurbishment, recycling, and recovery of resources from end-of-life cooling technologies not only enhance resource efficiency, but they also have other social benefits like local economic development, job creation and can make the off-grid appliance sector more circular. In most existing studies, carbon emissions and avoidance potentials from the manufacturing and end-of-life management phases have been ignored.

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[1] Efficiency for Access (EforA), 2019. Off-grid refrigeration technology road map. Available at https://efficiencyforaccess.org/publications/off-grid-refrigeration-technology-roadmap

[2] McCarneya, S., Robertsonb, J., Arnaudc, J., Lorensond, K., LloydUsing, J., 2013. Solar-powered refrigeration for vaccine storage where other sources of reliable electricity are inadequate or costly. Vaccine, 31, 6050-6057

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

[4] ITF, 2008. Greenhouse gas reduction strategies in Transport sector. Available at 08ghg.pdf (itf-oecd.org)

[5] Refrigerant is a compound typically found in either a fluid or gaseous state. It readily absorbs heat and provide refrigeration effect by combining with compressors and evaporators. A blowing agent is a substance which is capable of producing a cellular structure via a foaming process in a variety of materials that undergo hardening or phase transition, such as polymers.

[6] Ravishankar, M., Bordat, S.and Aitken,D.2020. Net ZeroCold Chain for food. Available at https://prod-drupal-files.storage.googleapis.com/documents/resource/public/Net_zero_cold_chains_for_food.pdf

[7] The Lab. 2019. Cooling as a Service. Available in https://www.climatefinancelab.org/project/cooling-service/

All of this made it imperative that we undertake a comprehensive cradle-to-grave carbon assessment of representative, off-grid cooling technologies that appear low carbon to the best of our understanding and compare their carbon footprint with more baseline cooling technologies. Use of these results to estimate what the maximum possible mitigation benefit could be at a sector level if such technologies were deployed, while taking into account the emission mitigation benefits from avoided perishable food (only including fruits and vegetables) waste during post-harvest process, would help us design the most optimum and green cooling access interventions.

Carbon assessment literature pertains to the off- and weak-grid sectors, and there is an over focus on mitigation benefits from diesel displacement and use of energy efficient technologies, and a more system and business model level environmental evaluation is often ignored.

To evaluate the environmental performance of off-grid cooling systems, a life-cycle approach can be a useful method to design appropriate cooling access interventions that develop the market sustainably while minimising carbon and other environmental emissions. Although life cycle-based assessments have been documented in on-grid cooling systems,[8] applying the Life Cycle Assessment (LCA) concept to support environmental decision-making in developing weak and off-grid cooling technologies has not yet been well documented at the international level. To make up for this research gap, the LEIA programme undertook this research to assess the overall climate impact from the full life cycle of off-grid domestic refrigerators and walk-in cold rooms.

This research is also one of the first of its kind, as it is being provided as a technical assistance to the grantees of the LEIA programme R&D fund. This LCA analysis is being done for the following three types of cooling technologies of the LEIA R&D fund grantees:

- SureChill's 65L Solar Direct Drive (SDD) DC refrigerator
- Solar Cooling Engineering's (SCE) SelfChill Kit Cold Room 20m^3
- ColdHub's 20m^3 Cold Room

A technical description of each of these technologies can be found in Chapters 2 and 3.

These technologies were selected as they are representative of key solar based off-grid refrigerator and 20m walk-in cold room technologies being sold commercially in rural regions in sub-Saharan Africa. A life cycle assessment of these alongside an assessment of more baseline technologies would help identify the biggest possible emissions mitigation benefit by transitioning the sector toward such technologies.

The remaining report is organised into 6 chapters. Chapter 1 includes a description of methods, Chapters 2, 3 and 4 summarise analysis and findings from LCA on SureChill's 65L Solar Direct Drive (SDD) refrigerator, SelfChill's 20m^3 cold room and ColdHub's 20m^3 Cold Room respectively. Chapter 5 provides projections of emissions for the off-grid sector by extrapolating emissions from the 3 technologies and Chapter 6 reflects on key conclusions.

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[8] UN, 2021. Technical Guidelines for energy efficient refrigeration applications. United for Efficiency (U4E). Available in https://united4efficiency.org/wp-content/uploads/2021/06/GPP-Tech-Spec_Refrigeration_2021-11-15.pdf

Chapter 1: Methods

This section provides a detailed description of the methodology used in the study including a development of life cycle assessment framework for the assessment. This section goes on to describe the various boundary conditions for the analysis.

1.1 Introduction to Life Cycle Assessment (LCA)

Product and service carbon footprint assessments, including life cycle assessments (LCA) of the associated carbon emissions, are rapidly becoming an integral part of new product development and eco-design practices. LCA approach has been widely used in many sectors since the methodology was standardised in the ISO guidelines. For the purposes of this research, the assessment of carbon emissions from off-grid refrigeration technologies is conducted in accordance with ISO14040 and ISO14044 standards, which are globally recognised standards for similar studies.[9,10]

According to ISO 14040, LCA is an environmental tool used to assess potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, transportation, use, and disposal. LCA is a well-known technique for assessing the environmental aspects and potential impacts associated with a product, service, or function by compiling an inventory of relevant input materials, energy used and output emissions of a product system. LCA is also useful for estimating possible carbon emissions and mitigation options from a product or service. By applying LCA, priorities can be identified more easily, and policies can be targeted more effectively on carbon mitigation targets to achieve maximum benefit relative to the effort expended. Moreover, this approach can be considered an essential tool for evaluating both direct and indirect emissions caused by embodied carbon related to energy and material input in upstream processes. By assessing the GHG emissions of a product / service throughout its entire life cycle, 'hot-spots' can be identified easily, and then cost and emission reductions can be planned at the design stage.

By applying the LCA approach, it is possible to isolate carbon impacts of different materials, processes and design strategies and use this information to prioritise interventions against them based on their individual carbon impact. The concept of LCA can be used to identify environmental 'hot spots'[11] and use this knowledge to design more environmentally friendly off-grid refrigerators and cold room systems. This information could help provide useful policy guidance for promoting circularity and eco-labelling by enabling comparison of different cooling systems.

As defined by ISO 14040/44, the LCA framework consists of four major phases. These are (i) goal and scope definition; (ii) inventory analysis; (iii) impact assessment; and (iv) interpretation. Typical life-cycle stages of a product and related inputs and outputs are shown in Figure 6. The scope of any LCA study should cover the function of the product system(s) under analysis, the system's functional unit, its system boundaries, allocation procedures, the type of indicators use for impact assessment, data requirements, assumptions, limitations etc.[12] Each of these factors are explained in the following sections.

1.2 Defining a functional unit

Defining an appropriate functional unit is an important step in an LCA-based assessment. It expresses and identifies the operational unit of the analysis, a reference to which the input and output data are normalised (in a mathematical sense). It is used as a basis for selecting one or more alternative product systems that might provide these function(s). The functional unit enables different systems to be treated as functionally equivalent to allow reference flows to be determined for each of them.[13] In Layman's terms, a functional unit provides a consistent measure for analysis, effectively allowing us to compare parts of or an entire system.

It is challenging to define a functional unit to compare the emissions from the various refrigerators and cold rooms due to the variations in the physical size as well as the use of different types of refrigerants. For example, the emissions for a refrigerator are an order of magnitude smaller than a cold room and not directly comparable. However, when we calculate emissions per functional unit, we are able to directly compare them more easily and understand the variations. Within this report we have used a number of different functional units to illustrate key areas, however not all will facilitate comparison between the different systems due to different assumptions which are explained below:

- **PV power production:** 'kg of CO_2-eq emissions per unit of electricity (kWh) produced'. This enables comparison between the emissions of the different power production systems, for example to other solar energy systems, grid power or any other electricity source emissions. In the case of this report, this includes emissions from production of PV panels, mounting system, solar array cables and chemical battery storage where applicable.
- **Refrigerator emissions:** 'kg of CO_2-eq emissions from the particular refrigeration unit considering all the phases of life cycle including specified years of operational time/use phase with a specific set point temperature'. This allows comparison to another fridge of the same size, cooling load, lifespan and set point temperature in a common location. In this report, this allows us to compare the SureChill fridge to an equivalent baseline system.
- **Cold room:** 'kg CO_2-eq emissions to storing one tonne of food under the given setpoint temperature in the cold room'.

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[9] ISO (2006a) International Standard Organization. Environmental management - Life cycle assessment - principles and framework. Reference number ISO 14040:2006

[10] ISO (2006b) International Standard Organization. Environmental management - life cycle assessment - requirements and guidelines. Reference number ISO 14044:2006(E), Geneva

[11] Hotspot; A life cycle stage, or phase which accounts for a significant proportion of the impact of the functional unit

[12] McDougall, F.R., White, P.R., Franke, M and Hindle, P. (2001). Integrated Solid Waste Management: A Life Cycle Inventory, 2nd edition, Blackwell Science

[13] Guinée, et al., 2001. Life Cycle Assessment—An Operational Guide to the ISO Standards. Ministry of Housing, Spatial Planning and the Environment (VROM), and Centre of Environmental Science, Leiden University (CML): The Netherlands

This will allow comparison to other systems operating with the same internal temperature set point and in a common location. It will also give end users an idea of the emissions produced by storing their food in these particular cold rooms.

- **Per cooling unit:** 'kg CO_2-eq emissions per kWh of cooling energy provided'. This will enable comparison across all the technologies seen in this report, as well as providing a means for other refrigeration providers to compare their systems to these. Previous functional units have to use fixed variables; but utilising the cooling energy can account for variations in the following:
  - Climate region – higher temperature regions will have higher emissions
  - Set point temperature – a lower set point temperature will have higher emissions
  - Food temperature – high food entry temperatures will have higher emissions
  - Amount of food cooled – more food cooled per day results in higher emissions
  - Size of system – larger systems will have larger thermal losses due to increased surface area

  We have used this functional unit to compare the different cold rooms and fridges (which may be located in different regions, have different food temperatures and have different volumes of food used).

1.3 Defining the system boundary

The specification of system boundaries is one of the most important steps in an LCA. The system boundary needs to be clearly defined for each product under assessment and shall include all of its material life cycle processes. Depending on the scope of the study, the system boundary can be designed from cradle-to-gate, cradle-to-grave or cradle-to-cradle as defined below:

- Cradle-to-gate: from raw material extraction to factory gate
- Cradle-to-grave: from raw material extraction through product use and disposal
- Cradle-to-cradle: similar life cycle approach to products but goes one step further to ensure that all materials used in production can be reused as a nutrient for enabling circular economy.

This study will focus on estimating carbon emissions and identifying opportunities for their avoidance from cooling technologies from cradle-to-grave of the system. In such an approach, at least 95% of the anticipated life cycle GHG emissions and removals associated with the functional unit can be incorporated within the system boundary for the assessment. The cradle-to-grave-based LCA framework and system boundary for the off-grid cooling technologies, including the major life cycle phases to be studied, is illustrated in a simplified manner in Figure 6. The life cycle assessment of the off-grid cooling technologies includes two major parts, namely, solar power production unit (solar panels, mounting structures, power electronics and battery storage if applicable) and the cooling technology (refrigerator or cold room) itself. Life cycle phases include raw material production, manufacturing, logistical movements, use / operation and maintenance stage, and end-of-life disposal. Investigating relative impact from each phase of the life cycle of the whole system and individual sub-components would be useful to identify the critical processes / hotspots that would contribute to the highest emissions.

The cut-off criteria to be applied in the system boundary conditions to avoid the need to pursue insignificant inputs and outputs in the system are as follows:

1. All energetic inputs to the process stages are recorded, including fuels, electricity, steam and compressed air
2. Each excluded material flow must not exceed 1% of mass, energy or environmental relevance for each unit process[14]
3. The sum of the excluded material flows in the system must not exceed 5% of mass, energy, or environmental relevance[14]

1.4 Identification of life cycle phases and their implications

The life cycle phases of the solar powered cooling technologies considered in this study include the manufacturing phase, transportation of the parts, assembling and installation, use phase and end-of-life (disposal) phases. To distinguish between use of grid electricity and electricity from photovoltaic (PV) panels used to power the cooling system during its use phase, the authors of this report performed life cycle assessment on PV power production system. For the PV systems, a functional unit of 'kg of CO_2-eq emissions from generating 1kWh power' was considered. The net emissions from PV panel power production represent the emissions with respect to the different phases of the life cycle. Often LCA analyses overlook emissions analysis at the product sub-assembly level which is essential for policy and decision-making processes. To make up for this literature gap, this research also investigates the climate impact of the cooling system at its sub-assembly level including the different components of the solar power system such as the PV panel, mounting system, inverter or electrical installation etc.

Raw Material Extraction and Processing

This stage in the life cycle of a product / system includes the extraction of all types of materials involved in the entire life cycle of the cooling systems. The mining of ores and minerals are the main activities considered in this stage. The inventory of raw materials extraction phase includes direct and indirect raw materials required to produce cooling systems. Raw materials such as fossil fuel in the production of electricity and energy used in the different life stages of the product are also considered. Data collection concerning different raw material extraction and

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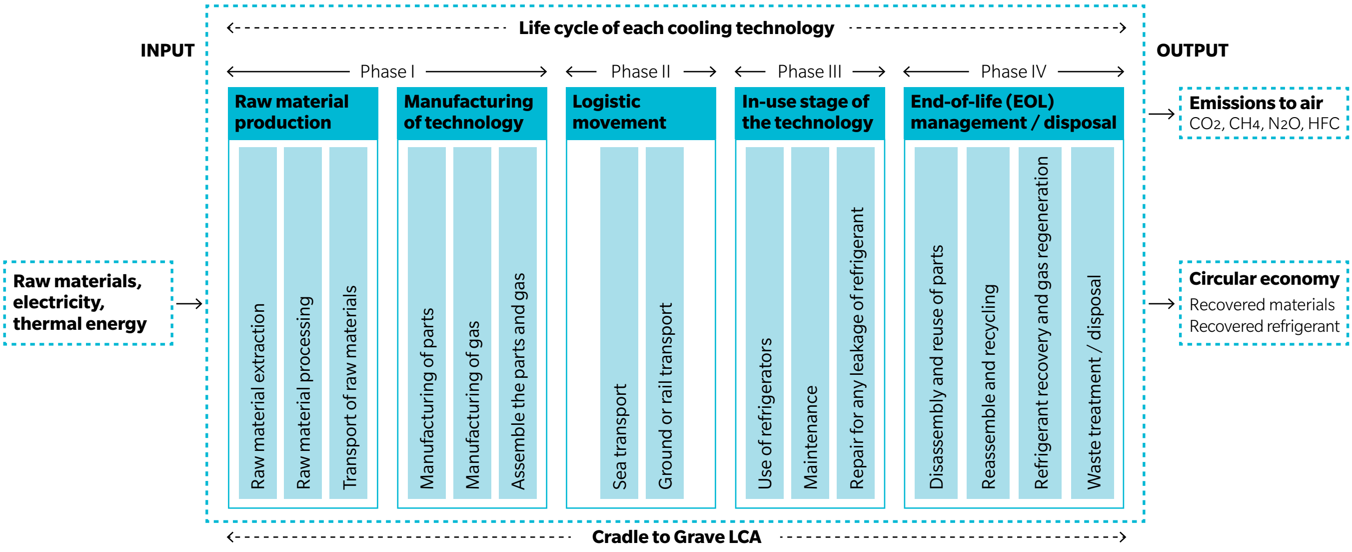
[14] World Steel Association, 2017. Life cycle inventory methodology report for steel products. Available in www.worldsteel.org

processing is a complex task. Different literature sources such as LCA databases[15] need to be used to find the emission factors. Raw materials extraction phase can be considered as one of the phases that would create serious environmental impacts of the product life cycle. Therefore, the amount of raw materials required for cooling systems have been accounted for with careful consideration in this research.

Figure 6: LCA framework for assessing the climate impact from each cooling technology



Manufacturing and implementation

The manufacturing phase involves all the processes including conversion of raw materials into a particular component of the cooling system considered in the LCA. Apart from the manufacturing processes at the plant where the product is made, this stage should also account for the production of ancillary materials[16] required for the manufacturing process. As far as the PV power production process is concerned, manufacturing phase in this research includes a carbon assessment of PV panels production, mounting system and storage system and other relevant power system components. Manufacturing of the PV system emits a significant amount of carbon due to both direct (energy consumption for manufacturing) and indirect emissions caused by embodied carbon related to energy and material production required in upstream processes. Manufacturing refrigerators and cold rooms includes raw material extraction, component manufacturing, assembling, transportation, and installations. Each of these phases requires a significant amount of energy and materials that contribute to GHG emissions and have been considered in this study.

Logistical movement

Every stage of the life cycle is directly linked with logistical movements. Transportation can be characterised as the delivery of materials or energy between different operations at various locations. Transportation of cooling equipment and supporting components (e.g. refrigerator, PV panels, mounting structures, parts of the cold room) requires considerable energy, and emissions from this phase also need to be accounted for. The severity of climate impact varies with the mode of transportation, transportation distance, the efficiency of fuel consumption of vehicles etc. The basic data related to the mode of transportation, transportation distances, type of vehicle used and their fuel efficiencies etc. was collected via a survey conducted with the manufacturers of the cooling systems considered in the study. In this study, an online tool developed by EcoTransIT[17] has been used to estimate the GHG emissions for the different logistical paths of the cooling equipment and supporting system.

Use phase

Direct carbon emissions occur due to energy use required for the use/operational phase of the off-grid refrigerators and cold rooms. Most refrigerators also contribute to emissions due

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[15] LCA data base is large collection of inventory data/information of a product or service

[16] Ancillary materials are raw materials used for the manufacture but that are not intended to be present in the final product. For example, cardboard and plastic required for packaging of manufactured products should be accounted

[17] EcoTransIT World. 2020. Available in https://www.ecotransit.org/index.en.html

to the leakage of fluorinated gases used in refrigerants and blowing agents used in insulation materials. The longevity of the use phase of the cooling system is key to optimising resource efficiency given the significant emissions incurred during phases defined in previous sections. Emissions from the use phase of off-grid sector are highly dependent on the energy efficiency of the cooling system and the lifespan of the PV system. Therefore, this study includes a sensitivity analysis using different assumptions for energy efficiency of the cooling system and the lifespan of PV panels to estimate the GHG emissions and related climate impact from the use phase.

End-of-Life Management (EOL)

Three primary disposal methods practised at the end of the life cycle of Waste Electrical and Electronic Equipment (WEEE), namely, open dumping, informal recycling and formal recycling. At present, end-of-life management options for WEEE, including the end-of-life refrigerators/cold rooms, are limited to open dumping or partial recovery of materials by informal recyclers in most of the developing countries including Africa.[18] Informal activities in the WEEE recycling chain include collection, manual dismantling, open burning to recover metals and open dumping of residual fractions. Implementing a proper recycling mechanism supports the recovery of valuable metals like aluminium, silver and copper and enhance circular economy opportunities. Climate impact from these primary disposal options have been assessed using the available emissions factors in the literature.

Designing out waste, ensuring the longevity of manufactured products and materials and recycling is the key to transformation from a linear to a circular off-grid appliance sector. Investigating the potential for valuable material recovery from end-of-life cooling systems would be useful for policy-supporting information. A significant volume of ferrous metals, non-ferrous metals (such as aluminium, copper, zinc, lead) and plastic are used in manufacturing of PV systems and refrigerators/cold rooms. Production of these resources via the virgin production process chain is energy-intensive and can cause carbon emissions and resource depletion. Carbon removal/savings via reuse or recovery of resources/materials at the end of the life cycle is one of the important steps in the carbon mitigation target. For example, avoided carbon emissions through resource recovery can be credited as for eliminating a corresponding amount of carbon emissions through materials production in conventional processes. Therefore, this study includes a detailed assessment of carbon emissions/savings potentials from end-of-life PV power production and cooling systems.

End-of-Life recycling and resource recovery from cooling technologies are beneficial from the perspective of energy consumption, mineral conservation of the virgin production processes. For instance, primary production of paper requires 40% more energy than secondary production.[19] Furthermore, aluminium has enormous recycling potential. Copper is one of the main components of cooling systems, and the production of primary copper causes eight times greater environmental impact than secondary copper. Recycling copper seems to be the most appropriate option to reduce the environmental burden, as it is 100% recyclable.[20] On average, copper products contain more than 30 percent recycled content, which significantly reduces the energy demand and GHG emissions associated with copper production.[21]

Polyurethane rigid foam is the insulating material that has been most widely used throughout the world for refrigerators and cold rooms as a robust, strong, lightweight and affordable material with excellent insulation properties. The most common types of gases used as blowing agents in polyurethane materials are HCFC-22, HCFC-141b and blend of HCFC-142b with HFC-134a. Although all of these gases have either zero or relatively low ODP compared to CFCs,[22] they have very high global warming potential. Blowing agents for foams are used in significant quantities; proportions of 2% to 20% by input mass are common.[23] End of life management of polyurethane foam needs to be done in an appropriate way to avoid emissions of harmful substances. However, dumping in landfills or burning after the disposal is currently the most common method of disposing of polyurethane waste as there is no market value for the foam. Recycling is an excellent alternative to landfills, but despite some effort from producers and legislative units in developed countries, it is still not the predominant method of waste disposal.[24]

1.5 Life Cycle Inventory Assessment (LCI)

The life cycle inventory analysis (LCI) is the bedrock of LCA and has been conducted for various types of data collected from different sources in a systematic way. This analysis involves intensive data collection and calculation procedures to quantify the relevant inputs and outputs of a product or service over its whole life cycle (cradle-to-grave). All the required inputs and outputs related to carbon emissions are collected from different sources with respect to each phase of the life cycle, such as raw material extraction, manufacturing of refrigerators, logistic movements, use stage of the refrigerators and end-of-life (EOL) management (reuse, recycling). Input/output analysis is also carried out regarding each sub-system (refrigeration unit and refrigerant) within the main life cycle phases. Logistic movement

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[18] Cool Coalition, 2021. Opportunities to Address Used Cooling Product Imports into Africa. Available in https://coolcoalition.org/opportunities-to-address-used-cooling-product-imports-into-africa/

[19] BIR, 2020. Recycling plastic, Facts, Data, Policy recommendations. Bureau of International Recycling. Available in https://www.bir.org/publications/facts-figures Accessed 29 October 2020

[20] Jingjinga, et al., 2019. Environmental benefits of secondary copper from primary copper based on life cycle assessment in China. Resources, Conservation & Recycling, 146 (35-44)

[21] Copper Alliance, 2022. Recycling. Available in https://copperalliance.org/policy-focus/climate-environment/recycling/

[22] HCFC-141b has an ODP of 0.11,10 times less ODP than CFC-11. Other HCFCs have an ODP of zero

[23] PlasticEurope, 2019. The Circular Economy for Plastics – A European Overview. Available in https://www.plasticseurope.org/en/resources/publications/1899-circular-economy-plastics-european-overview Accessed 01 November 2020

[24] Datta J., Włoch M. 2017. Recycling of Polyurethanes. In: Sabu T., Datta J., Haponiuk J., Arunima R., editors. Polyurethane Polymers: Blends and Interpenetrating Polymer Networks. Elsevier; Amsterdam, The Netherlands: pp. 323–358

is linked with each and every phase, and therefore any carbon emissions related to different modes of transportation such as rail, sea and ground are assessed at this step. The below inventory Table 1 summarises the list of all material and energy inputs and outputs required for the LCA study.

Table 1: Material and energy inputs and outputs required for the LCA study

LIFE CYCLE PHASE	PROCESS	DATA SOURCE	DATA CATEGORY
PV panel manufacturing	Raw material extraction	Ecoinvent* + published literature	Generic**
	Raw material processing	Ecoinvent + published literature	Generic
	Manufacturing of PV panels and supporting structures	Ecoinvent + published literature	Generic
	Specifications of the PV panels supporting structure	Interviews with vendors of refrigerator / cold room manufacturers	Specific**
Refrigerator / cold room manufacturing	Raw material extraction	Ecoinvent + published literature	Generic
	Raw material processing	Ecoinvent + published literature	Generic
	Manufacturing of parts	Manufacturer	Specific and critical
	Mass balance and material composition of each part	Interviews with refrigerator / cold room manufacturers	Specific and critical
	Assembly of parts	Interviews with refrigerator / cold room manufacturers	Specific and critical
Refrigerant / blowing agent production	Raw material extraction	Ecoinvent + published literature	Generic
	Manufacturing of gases	Ecoinvent + published literature	Generic
	Production of gas blend	Ecoinvent + published literature	Generic
Transportation	Logistical movement by ground and sea	Published literature	Generic
Refrigerator and cold room use phase	Energy consumption	Interviews with refrigerator / cold room manufacturers	Specific and critical
	Maintenance	Interviews with refrigerator / cold room manufacturers	Specific and critical
	Gas leakage rate	Interviews with refrigerator / cold room manufacturers + published literature	Specific and critical
End of Life (EOL) Refrigerator / Cold room	Energy consumption for disassembling	Interviews with e-waste recyclers companies + literature	Specific and critical
	Re-use of parts	Interviews with e-waste recyclers	Specific and critical
	Recycle and material recovery	Interviews with e-waste recyclers	Specific and critical
	Final disposal	Interviews with e-waste recyclers	Specific and critical
End of Life (EOL) Refrigerant / blowing agent	Recovery of PV panels and the refrigerator	Published literature	Generic
	Regeneration	Published literature	Generic

* Ecoinvent is the world's most consistent & transparent life cycle inventory database
** Generic data is secondary data obtained from open literature, and specific data is the primary data obtained from directly by companies or manufactures

Primary data across the various life phases described in Table 1 was gathered through a customised survey administered to the manufacturers of the three cooling technologies considered in the study and interviews with e-waste recyclers based in Africa. In addition, the authors relied on the Ecoinvent databases (version 3.7) and published, peer reviewed literature for gathering other pieces of data necessary for the LCA modelling, see Table 1. Priority is given to the primary data in the analysis since primary data relates to the technology in question directly and is therefore more accurate than the secondary data. For example, gathering energy consumption data for manufacturing of a refrigerator at factory level would cultivate a more accurate carbon footprint estimation than the published literature data on carbon emissions from manufacturing of a fridge, without knowing the energy sources used.

1.6 Life Cycle Impact Assessment (LCIA)

At this stage of the life cycle assessment, both carbon emissions to the atmosphere and removals from the atmosphere are accounted for in the assessment of the overall GHG emissions of the cooling technologies. Carbon emissions are estimated as GHG due to direct emissions and embodied carbon linked to energy use, combustion processes, process operations, transportation etc. GHG emissions are calculated as kg of CO_2-eq with respect to the different items and for the entire cooling system. Primary energy consumption for raw material extraction, manufacturing and operating the cooling system are closely linked with CO_2 emissions, the primary source of GHG emissions. Moreover, other GHG emissions (e.g. CH_4, N_2O) from transportation and operation of machineries are also significant, especially due to fossil-based energy utilisation.

Furthermore, potential GHG savings via resource recovery from end-of-life cooling systems are credited back to estimate net carbon emissions. This is because they lead to avoidance of emissions that would have otherwise occurred in the process of producing equivalent amount of materials through conventional processes. Global Warming Potential (GWP) values recommended by the IPCC in value units of 100 years are utilised for aggregating net climate impact from different GHG (e.g. CO_2 - 1, fossil methane CH_4 - 25; nitrous oxide N_2O - 298).[25] IPCC has not yet finalised the GWP value for Black Carbon (BC), and therefore, the net climate impact from BC emissions is not considered in this study.

The overall climate impact from a particular cooling system is dependent on net GHG accounting, looking at both emissions and indirect downstream GHG savings throughout the life cycle. Therefore, net GHG emissions should be calculated as shown below to make decisions and policy recommendations.

Gross and net GHG emissions from cooling system can be calculated as follows:

$$\text{GHG Gross} = \sum (Q_i\,MP \times EF_i) + \sum (Q_i\,T \times EF_i) + \sum (Q_i\,M \times EF_i) + \sum (Q_i\,U \times EF_i) + \sum (Q_i\,EOL \times EF_i)$$

$$\text{GHG Net} = \text{GHG Gross} - \sum (Q_i\,PAMR \times EF_i)$$

Where; Qi – Magnitude of ith GHGs from MP – Material Production, EFi – Equivalency Factor of ith GHGs. T – Transportation / logistic movements, M – Manufacturing, U – Use phase, EOL – End of Life disposal, PAMR – Potential Avoidance via Material Recovery

1.7 Functional unit – emissions per unit cooling energy

It is useful to define the functional unit for which you can compare across the various technologies within this report and also for other companies who could use this method to assess the emissions from their own technology.

To allow comparison between technologies we have calculated the GHG emissions per kWh of cooling energy. This metric accounts for different system volumes, climate regions, food storage levels, food entry temperature and set point temperatures for which the other metrics / functional unit used so far do not. For each cooling technology the total cooling energy is made up of the following components:

- $E_{thermal}$ – thermal losses through the walls of the fridge / cold room. This is determined by the difference between the internal and external temperatures, together with the insulation levels
- $E_{thermal} = A \times \Delta T \times \lambda / L \times t$

  where; A = Area (m^2), ΔT = Thermal difference (°C), λ = Thermal conductivity (W/(m°C), L = Thickness of the insulation (m), t = time (h)

- $E_{infiltration}$ – thermal losses through the opening and closing of the door to the cold room. Cold air inside the fridge/ cold room is replaced with warm air from outside which has to be cooled
- $E_{infiltration} = V \times c \times \Delta T$

  where; V = Volume of infiltrated air(m^3), c = Heat capacity (Wh/m^3 °C), ΔT = Decrease of temperature (°C)

- E_{food} – the thermal energy required to cool the food within the fridge/cold room. Food is usually loaded when warm and the fridge/cold room has to cool it to the desired temperature
- $E_{food} = m \times c \times \Delta T$

  where; m = Mass of the product (kg), c = Heat capacity (Wh/kg °C), ΔT = Decrease of temperature (°C)

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[25] Forster et al., 2007. Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Rep. (pp. 129–234). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press

Chapter 2:
Carbon Footprint Assessment of Off-grid Refrigerators: SureChill Solar Direct Drive DC Refrigeration Technology

In the 1980s, solar refrigerators were introduced for vaccine storage in areas without electricity, to address the problems created due to gas and kerosene refrigerators.[26]

However, one of the major downsides in terms of affordability, timely repair and the carbon footprint of solar refrigerator technology has been the large battery systems that were required to store the sun's energy for use during the night and cloudy periods. These batteries have a relatively short lifetime of 3 to 5 years, and replacements are expensive and sometimes unavailable for local purchase in low-income countries. In addition, batteries can fail due to improper design, misuse, poor installation, overuse of the refrigerator, overload of the refrigerator resulting in prolonged running cycles, lack of maintenance (e.g. topping up of acid in certain lead acid technologies) and delayed repairs.[27] For these reasons, solar refrigerators are often not the most viable technology when compared with their conventional counterparts.

In recent years, solar direct-drive refrigeration technologies have been developed which remove the need for these battery storage requirements. They use solar power to freeze water or other phase change materials that act as thermal storage devices. During the night and cloudy days, the refrigerator uses the ice bank for cooling and maintaining the setpoint temperature. The direct-drive refrigerator is directly connected to the photovoltaic panels and can run on low voltages. There is an increasing demand for Solar Direct Drive refrigeration systems as they help avoid the issues associated with units with batteries.[28]

2.1 SureChill Refrigeration Technology: 65L SDD DC refrigerator

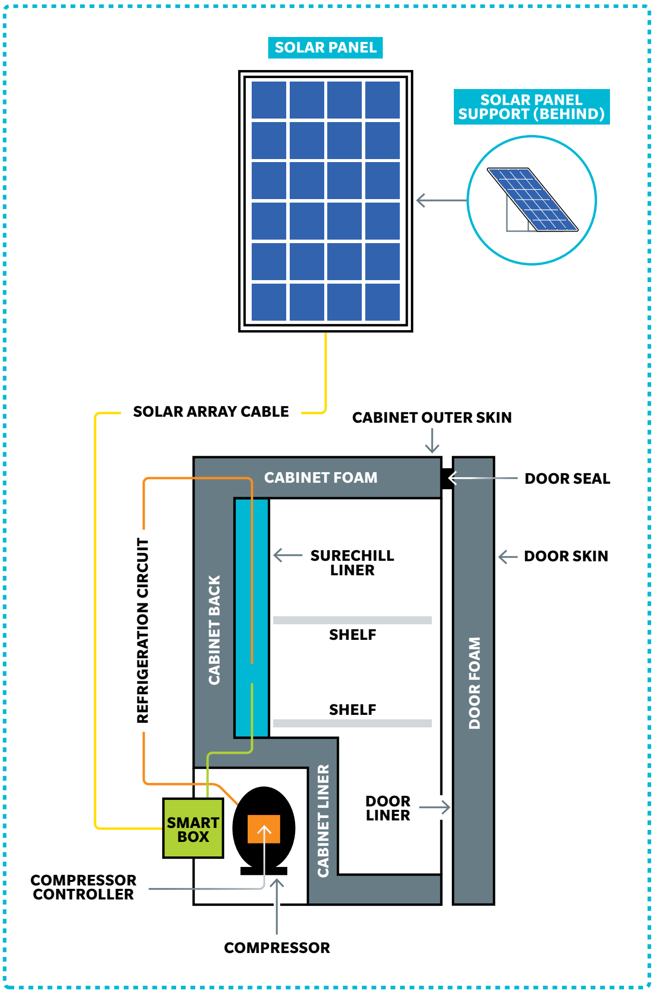
To assess the climate impact from off-grid DC refrigerator, a refrigerator model by the SureChill refrigeration company was considered. Despite being new to the market, the SureChill SDD refrigerator is one of the lowest carbon footprint off-grid refrigerators that is widely available commercially. This appliance is intended to be used in households and small businesses such as small shops, offices, farmhouses and hotels. The volume of the fridge (65L) is not the most common size for off-grid refrigerators, with the Verasol fridge database suggesting two peaks around 100L and 55L. However, to demonstrate one of the most sustainable industry examples, the technology itself took precedence over the right size in the selection process. To address this size discrepancy, the authors use 100L as the size for projecting whole-sector GHG reduction potential in Chapter 5.1, linearly scaling from the 65L SureChill SDD refrigerator.

The major components of the solar-powered DC refrigerator are shown in Figure 7. These are the PV panels, mounting structures, smart box and the refrigerator itself. The system is manufactured in China and transported to Africa for sale. For the purposes of this study, Kenya is considered as the end-user destination.

2.2 Life Cycle Carbon Assessment of SureChill DC refrigeration model

This part of the study aims to estimate GHG emissions across the life cycle of a typical off-grid solar power refrigerator in Africa. Based on the information provided by SureChill, the warranty period for solar panels and fridge is 25 and 10 years, respectively. However, the serviceable life of the system could be extended to 30 years with careful handling and maintenance. The geographic boundary for computing emissions from transport of the PV panels and refrigerator was considered from the manufacturing hub in China to the final consumer in Kenya. The functional unit for the LCA assessment was defined as the climate impact from the complete life cycle of a 65L off-grid domestic refrigerator used for ten years (24 hours/day). Given the extremely low rate of e-waste recycling in Africa, it is assumed that the refrigerator will be informally recycled at the end-of-life.[29]

Figure 7: SureChill off-grid DC refrigerator (Home and Small Business model)



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[26] WHO, 2013. Drive solar vaccine refrigerators— a new choice for vaccine storage. Available in https://apps.who.int/iris/bitstream/handle/10665/254715/WHO-IVB-17.01-eng.pdf?sequence=1

[27] UNICEP, 2016. Solar Direct Drive Refrigerators and Freezers. Cold chain support package. Available in https://www.unicef.org/supply/media/4396/file/E003-solar-direct-drive-refrigerators-freezers-procurement-guidelines.pdf

[28] UNICEP,2020.Cold Chain Support Package. Procurement Guidance. Available in https://www.unicef.org/supply/media/6276/file/E003-solar-direct-drive-refrigerators-freezers.pdf

[29] According to data from the 2017 Global E-Waste Monitor, less than 1% of e-waste is collected and recycled in Africa annually

2.2.1 Life Cycle GHG emissions from PV power production system

The basic technical specifications of the solar power production system and estimated GHG emissions are presented below. The life cycle stages of PV power production include production of raw materials, manufacture of components, transport to the operating operation site, use phase and end-of-life recycling phase.

The life cycle emissions (kg of CO2-eq) are calculated as follows:

Life cycle GHG emissions from PV system =
GHG emissions from module manufacturing +
GHG emissions from manufacturing mounting structures +
GHG emissions from manufacturing electric installations (cables, inverters) +
GHG emissions from transportation +
GHG emissions from end-of-life management

GHG emissions from raw material extraction and manufacturing of solar panels: The SureChill refrigerator is powered by two polycrystalline 120 Wp solar panels. The total mass of a single panel including its frame is 8.4 kg. The Ecoinvent database (version 3.7) is used for the energy and emissions data related to raw material extraction and manufacturing of the PV panels. The detailed GHG emissions estimation is presented in Annex A. The net GHG emissions per m^2 of polycrystalline panel production are 199.15 kg CO2 eq, resulting in the two 120 Wp panels used emitting 296.66 kg CO2-eq (1.49 m^2 of panel area).

GHG emissions from raw material extraction and manufacturing of supporting structure: A tilted mount indicated on the roof in Figure 7 is the mounting system for the solar PV system. The total mass of the mounting system is 2.4 kg, and the composition is 95% aluminium and 5% steel. As plant-specific information was not available for estimating energy and material consumption, the authors referenced the Ecoinvent database. GHG emissions from the supporting structures of two 0.745m^2 panels amounted to 53.86 kg CO2-eq.

GHG emissions from raw material extraction and manufacturing of solar array cables: The PV panels and the smart box are connected using a 6 mm^2 gauge cable. The total mass of the cable is 2.4 kg, and is made from 30% plastic and 70% copper. Data for cables with a similar composition were taken from the Ecoinvent database to estimate the GHG emissions for their production. The estimated GHG emissions from the production of 2.4 kg of solar array cable is 15.33 kg CO2-eq. Detailed calculations are presented in Annex A.

GHG emissions from logistical movement: The manufacturing location of the solar panels in the SureChill case study are unknown. Therefore, it was assumed that the PV panels, supporting structures and cables are manufactured in China and transported to the project location in Kenya. With the help of EcoTransIT World software, GHG emissions from the logistical movement of PV panels were estimated for the China-Kenya route. The total emissions from the logistical movement of PV panels and supporting structure was estimated as 3.85 kg CO2-eq (see Table 2).

Table 2: GHG emissions from logistical movement of PV panels and supporting structures

TRANSPORT ROUTE	DISTANCE (km)	MODE OF TRANSPORT	GHG EMISSIONS (kg CO2-eq)
Manufacture (Hafei, China) to the Wuhu Port in China	125	By truck	0.181
Port in China (Wuhu) to port in Kenya (Mombasa)	11958	By ship	2.225
Port in Kenya (Mombasa) to Nairobi warehouse	485	By truck	0.645
Nairobi warehouse to the selling point	485	By truck	0.796
TOTAL GHG EMISSIONS			**3.846**

GHG emissions from end-of-life management of PV solar panels: The current levels of waste from solar PV modules do not yet justify the widespread operation of recycling facilities for these products.[30] At present, only about 10% are recycled worldwide due to the lack of regulations, with only a few commercial PV recycling facilities existing today, mostly in Europe. At present, informal recycling is the most common approach in African countries including Kenya. Components with valuable metals are collected and pre-processed by informal recyclers and sold to local facilities as recovered materials from end-of-life electronics. Therefore, informal recycling was used as the end-of-life disposal method in this study. In addition, this study includes a scenario analysis to account for differences in climate impact from two other waste management options:

1. 100% open dumping or landfilling without any form of material recovery
2. formal recycling

Informal recycling or the current scenario: In this scenario, only part of the materials from the PV panels, supporting structures and solar array cables are recycled since informal recyclers are mainly interested in highly valuable metals such as steel, aluminium and copper. It was assumed that informal recyclers would collect easily removable parts such as aluminium frames from PV panels, supporting structures made of 95% aluminium and 5% steel and copper fractions from solar array cables. Copper cables are burned out to extract the copper fraction and get rid of the plastics. The extracted materials are sold to middlemen or waste aggregators who in turn sell these materials to the smelting facilities to recover secondary resources. The total mass of the PV system is 21.5 kg, in which 5.35 kg are easily removable metals that are assumed to be collected by informal recyclers. Total GHG emissions, avoidance and

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[30] IEA, 2018. Life Cycle Inventory of Current Photovoltaic Module Recycling Processes in Europe. International Energy agency. Available in https://www.researchgate.net/publication

net emissions-related to informal recycling activities are summarised in Table 3. The estimated net impact is -53.15 kg CO_2-eq, and the resulted net negative value indicated that informal recycling activities contribute to GHG savings significantly through resource recovery.

Table 3: Summary of GHG emissions, emissions avoidance and net emissions from informal recycling - current scenario

DESCRIPTION	MASS OF MATERIAL (kg)	GHG EMISSIONS FROM RECYCLING (kg CO_2-eq)*	GHG EMISSIONS AVOIDANCE THROUGH RESOURCE RECOVERY (kg CO_2-eq)	NET GHG EMISSIONS (kg CO_2-eq)
Transportation	5.354	0.198	-	0.198
Recycling of aluminium frame of PV panels	1.344	0.640	17.976	-17.336
Recycling of supporting structures	2.400	1.390	34.170	-32.780
Recycling of copper from cables	1.610	1.345	4.578	-3.233
TOTAL EMISSIONS		**3.574**	**56.725**	**-53.151**

*This is the emissions from burning of end-of-life items to extract valuable metals (e.g., burning of copper wire to extract the copper) in the field and use of fossil fuel and grid electricity for recycling and resource recovery at the factory

Life cycle GHG emissions from PV power production components in the informal recycling scenario

The life cycle GHG emissions for the PV power production components is 373.3 kg CO_2-eq (see Figure 8). 80% of the GHG emissions arise from the manufacture of the panels, with the mounting system, cables, logistical movement and end of life recovery at 14%, 4%, 1% and 1% respectively. Material recovery by the informal sector from the PV system contributes to savings of 56.7 kg CO_2-eq, approximately 15% of the total emissions from the PV power production system. These emission savings are shown as a negative value in Figure 8. The estimated net life cycle GHG emissions from the PV system amounts to 316.6 kg CO_2-eq.

The typical lifespan of a PV system is 20-30 years. Total electricity production potential from 10 years, 20 years and 30 years lifespans PV systems is 3,426kWh, 6,685kWh and 9,784kWh respectively. Based on the life cycle emissions, the GHG emissions potentials per kWh electricity production in different lifespans of PV system were estimated, see Annex A for more details. The estimated GHG emissions from the PV system in SureChill model is 92 g CO_2-eq/kWh if the PV panel lifespan is 10 years, 47 g CO-eq/kWh if it is 20 years and 32 g CO_2-eq/kWh if it is 30 years. With proper maintenance, if the PV system is used for 30 years or 20 years instead of 10 years, GHG emissions per unit of electricity production can be reduced by 65% and 32%, respectively (see Figure 9).

Figure 8: Life cycle GHG emissions from PV system in the current scenario with informal recycling

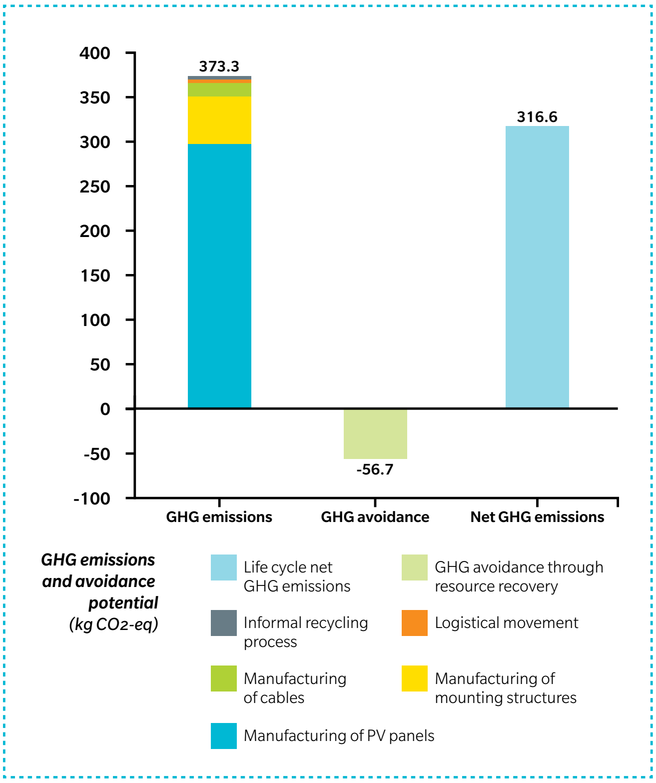
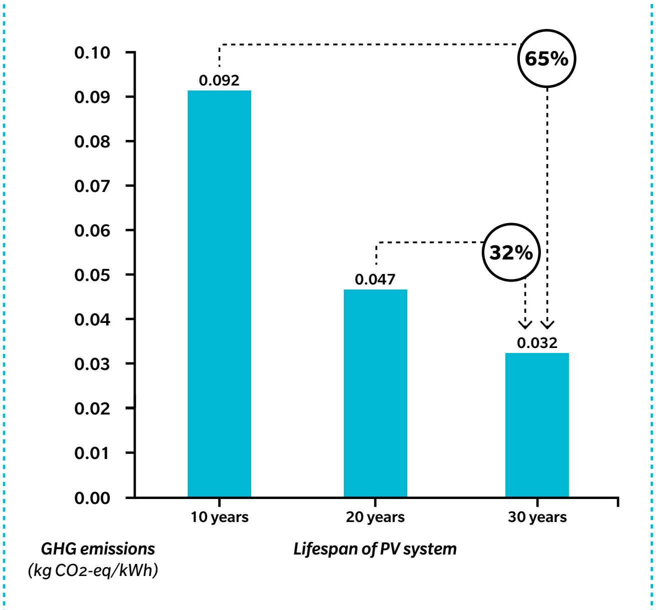


Figure 9: Life cycle GHG emissions per kWh of electricity production in difference lifespans of PV system



2.2.2 Life Cycle GHG Emissions from SureChill 65L Refrigerator

The smart box and the 65L domestic refrigerator are the two major items considered in the inventory analysis related to the refrigeration process. Detailed inventories associated with the smart box and the fridge are presented in Annex A.

Life cycle GHG emissions from smart box

Manufacturing of the smart box: Smart box is useful for 1. adapting the output from the solar panels to a suitable input for the refrigerator's compressor, 2. regulating temperature, 3. providing an interface to whatever pay-as-you-go system is being used.[31] This study accounts for the life cycle GHG emissions of this component. GHG emissions with respect to manufacturing major sub-components of the smart box are calculated and presented in Table 4. Total GHG emissions from the manufacturing of the smart box are 19.35 kg of CO2-eq.

Table 4: GHG emissions from raw material extraction and manufacturing of major components in the smart box

MAJOR PARTS OF THE SMART BOX	MASS (g)	GHG EMISSIONS (kg OF CO2-eq)	GHG EMISSIONS PER UNIT MASS
Polycarbonate outer box	320	1.58	Production of 1 kg of PC: 3.25 kg CO2-eq[32]
Printed circuit board (PCB)	127	17.74	Production of 1 kg of PCB: 139.6 kg CO2-eq[33]
Wire (copper)	30	0.03	Production of 1 kg of copper wire: 0.882 kg CO2-eq/kg of copper wire[33]
TOTAL	**477**	**19.35**	

GHG emissions from the logistical movement of the smart box from the manufacturing hub to the project location are negligible as the smart box weighs less than 1 kg.

End-of-life management (informal recycling of the smart box): At present, the informal sector recovers portions of the materials using simple tools like hammers, screwdrivers and chisels. For the smart box, it was assumed that only the copper portion would be extracted from the copper wire by burning, and the polycarbonate outer box and PCB will be disposed of in a landfill or kept aside. The net GHG emissions from recovering copper from end-of-life copper wire is 0.005 kg CO2-eq per 30g of copper wire.

Therefore, the net life cycle GHG emissions (manufacturing emissions and end-of-life recycling emissions) were calculated to be 19.35 kg CO2-eq.

Life cycle GHG emissions from 65L SDD DC refrigerator: This DC refrigerator's total mass is 30 kg and it has a design setpoint temperature of 4-6 °C. The approximate energy consumption is 182 Wh/day to maintain the setpoint temperature at an average ambient temperature of 32°C. If the ambient temperature rises to 43°C, the power consumption increases to 200 Wh/day. Detailed specifications of the SureChill 65L DC refrigerator are presented in Annex A alongside life cycle inventories from the questionnaire survey and literature sources.

GHG emissions from the manufacturing phase: The mass balance of the refrigerator provides the key information required for estimating the climate impact from the manufacturing phase and is presented in Annex A. Model-specific inventory related to material consumption for manufacturing the chosen refrigeration model was prepared based on the data obtained from SureChill. The material composition of each component of the fridge and the corresponding amount of GHG emissions from raw material extraction and processing is summarised in Table 5 from a variety of literature sources (see Annex A).

The total GHG emissions from raw materials extraction and production for the fridge amounted to 121.98 kg CO2-eq (see Table 5). Of the total emissions, 48% emissions are caused from extraction of three major metals required: steel, aluminium and copper. The emissions from the production of packaging materials are 6.86 kg CO2-eq, resulting in total emissions for the SureChill domestic refrigerator and its packaging being 128.83 kg CO2-eq (see Table 5).

Plant-specific data is not available with respect to material and energy consumption during the manufacturing phase. Therefore, the authors have used published literature sources to provide the required information. Xiao et al.[34] conducted a study that represents the production and disposal of conventional AC refrigerator with approximately 61 kg in mass. It has an envisaged lifetime of 10 years and is manufactured in China. The data set used in this paper has been extrapolated for estimating energy and material consumption during the production phase of SureChill's refrigeration model.

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[31] Information from SureChill expert via personal communication

[32] Plastic Europe, 2005. Polyurethane Rigid foam. Eco-profiles of the European Plastics Industry. Available in https://www.plasticseurope.org/en Assessed 06 December 2020

[33] WARN, 2019. Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model https://www.epa.gov/sites/production/files/2019-06/documents/warm_v15_electronics.pdf

[34] Xiao, R., Zhang, Y., Liu, X., and Yuan, Z., 2015. A life-cycle assessment of household refrigerators in China. Journal of Cleaner Production, 95, 301-310

GHG emissions arise in the manufacturing and assembly phase from the burning of fossil fuels to produce thermal energy and grid electricity to power equipment. Using the data in the Xiao et al. study,[34] the required energy for manufacturing the SureChill fridge is presented in Table 6. The total emissions emitted during the manufacturing process comes to 10.126 kg CO_2-eq, with the largest portion of emissions (52%) from the production of the cabinet and door of the fridge.

Total GHG emissions from the manufacturing phase are estimated by aggregating the GHG emissions from raw material extraction and production and GHG emissions from fridge manufacturing. This amounts to a total of 138.96 kg CO_2-eq.

GHG emissions from the logistic movements: The refrigerator is manufactured in Hefei, China and transported to the project location in Kenya. The emissions for transporting the 32.8 kg fridge with its packaging were estimated using EcoTransIT World software and totaled 5.96 kg CO_2-eq.[17] Marine transport accounts for 57% of the emissions, with the remaining 43% due to ground transport by trucks.

GHG emissions from the use phase: During the use phase, any direct climate impact would occur from the leakage of gases used as refrigerants and in blowing agents. SureChill's domestic refrigerator uses R600a (isobutane) as the refrigerant and cyclopentane as the blowing agent; both gases have low global warming potential values.[35] SureChill's careful design seeks to avoid any refrigerant leakage during the refrigerator's use phase as they are hermetically sealed. However, in around one in a hundred systems, there is a catastrophic leakage of refrigerant where it all leaks out. Therefore, an average leakage rate of 1% has been assumed, amounting to 0.001 kg CO_2-eq of GHG emissions. It is expected that approximately 6% of blowing agent can be emitted during the use phase, which amounts to 0.12 kg CO_2-eq of GHG emission during the ten-year lifetime of the fridge.

Table 6: GHG emissions from the manufacturing of the domestic fridge

TYPE OF ENERGY USE	**PRODUCTION OF CABINET AND DOOR**	**ASSEMBLY OF CABINET AND DOOR**	**INFECTION MOULDING (SHELVES/ DRAWERS)**	**COMPRESSOR**	**ASSEMBLY**	**FINAL ASSEMBLY**	**TOTAL GHG EMISSIONS** kg CO_2-eq
Electricity (kWh)	1.900	1.100	0.237	1.118	0.000	0.503	4.858
Natural gas (m^3)	0.220	-	-	0.0475	-	-	0.267
Steam (kg)	1.152	-	-	-	-	-	1.152
Compressed air (m^3)	1.950	1.130	0.244	0.010	0.000	0.517	3.850
TOTAL GHG EMISSIONS (kg CO_2-eq)							**10.126**

Table 5: Material composition of 65L domestic off-grid refrigerator and GHG emissions with respect to different material extraction and processing of different parts. Mass of each type of materials (in kg) derived based on Xiao et al study. GHG emissions estimated based on the emission factors presented in Annex A

TYPE OF MATERIALS	**COMPRESSOR**	**COMPRESSOR CONTROLLER**	**STEEL MOUNTING FOR COMPRESSOR**	**REFRIGERATION CIRCUIT**	**CABINET BACK**	**CABINET OUTER SKIN**	**CABINET FOAM**	**CABINET LINER**	**DOOR SEAL**	**DOOR SKIN**	**DOOR FORM**	**DOOR LINER**	**SHELVES**	**SURECHILL LINER**	**CRISPER DRAWER**	**PLASTIC TRIM**	**TOTAL WEIGHT OF EACH METAL/ MATERIAL (kg)**	**TOTAL GHG EMISSIONS FROM RAW MATERIALS EXTRACTION** (kg CO_2-eq)
Steel	3.277	-	0.750	-	0.857	4.802	-	-	-	1.900	-	-	3.600	-	-	-	15.186	42.672
Aluminium	0.347	-	-	0.502	-	-	-	-	-	-	-	-	-	-	-	-	0.849	14.020
Copper	0.276	0.175	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.276	1.509
Polyurethane foam (PUR)	-	-	-	-	-	-	2.940	-	-	-	0.588	-	-	-	-	-	3.528	14.829
Acrylonitrile butadiene styrene (ABS)	-	-	-	-	-	0.098	-	-	-	-	-	-	-	-	-	-	0.098	0.305
High Impact Polystyrene (HIPS)	-	-	-	-	-	-	-	1.900	-	-	-	0.600	-	-	-	-	2.500	6.076
Polyvinyl Chloride (PVC)	-	-	-	-	-	-	-	-	0.291	-	-	-	-	-	-	-	0.291	0.629
Epoxy	-	0.175	-	-	-	-	-	-	-	-	-	-	0.400	-	-	-	0.575	4.715
Polycarbonates (PC)	-	0.175	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.175	0.586
Polyethylene (PE)	-	-	-	-	-	-	-	-	-	-	-	-	-	4.200	-	1.250	5.450	9.685
General purpose polystyrene (GPPS)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.770	-	0.770	2.503
Printed Circuit Board (PCB)	-	0.175	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.175	24.446
TOTAL MASS OF EACH COMPONENT	**3.900**	**0.700**	**0.750**	**0.502**	**0.857**	**4.900**	**2.940**	**1.900**	**0.291**	**1.900**	**0.588**	**0.600**	**4.000**	**4.200**	**0.770**	**1.250**	**30.048**	**121.976**
Expanded Polystyrene Foam (EPS)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.016	6.574
Corrugated cardboard	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.832	0.284
TOTAL GHG EMISSIONS																		**128.834**

[35] Global warming potential values of R600a (isobutane) and cyclopentane are 3 kg CO_2-eq/kg and 11 kg CO_2-eq/kg respectively

GHG emissions from end-of-life refrigerator management (informal recycling): The refrigerator is designed to last at least ten years. There is a 'secondary market' for used refrigerators where they are passed on or sold to another household or kept and used as a second refrigerator.[36] Therefore, in reality, a significant number of domestic fridges tend to be used for as much as 20 or 30 years. Thus, end-of-life scenarios were assessed for refrigerator lifetimes of 10, 20 and 30 years in the scenario analysis.

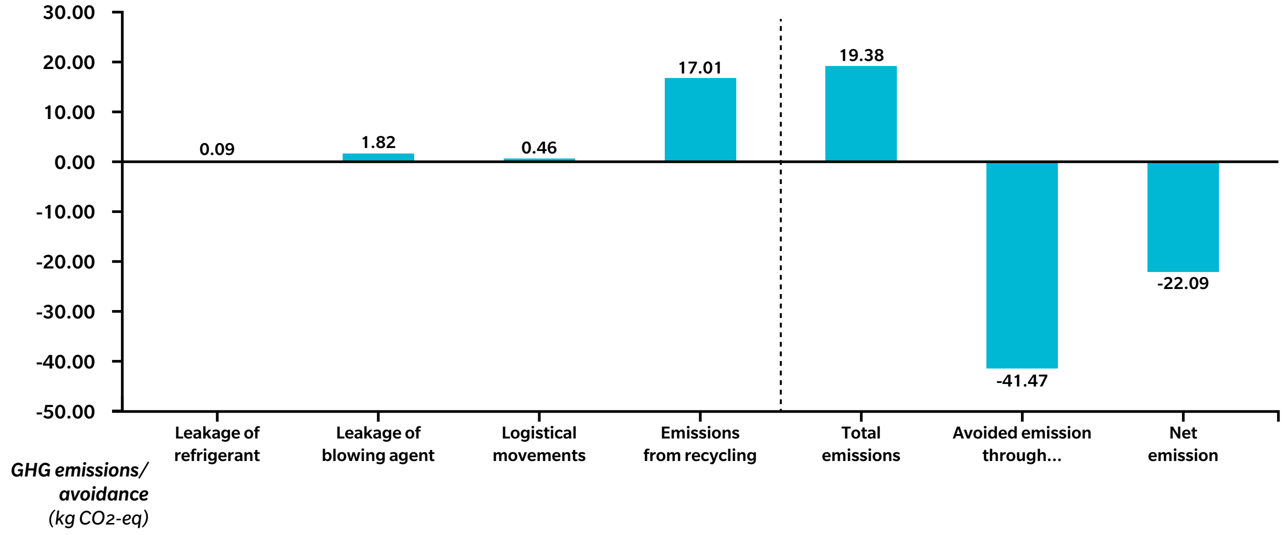
As far as the climate impact from informal recycling of the end of the SureChill fridge is concerned, it was assumed that informal recyclers only recover the components with valuable metals such as steel, aluminium and copper after manual dismantling. The refrigerant and blowing agent is released into the atmosphere during the manual dismantling process. The recovered metal fraction is sold to the local collection agents and transported to the smelting facilities. Most of the metals are assumed to be recycled at existing smelting plants in Kenya. It was assumed that informal recyclers would at least recover 75% of steel, aluminium and copper,[37] and other components of the fridge will be disposed of at nearby dumpsites. The total end-of-life GHG emissions from recycling activities and the release of refrigerant and blowing agents at the disposal phase amount to 19.38 kg CO_2-eq. The total GHG emissions avoidance due to the recovery of resources is 41.47 kg CO_2-eq. The estimated net GHG savings from the SureChill 65L refrigerator's informal recycling is -22.09 kg CO_2-eq, see Figure 10.

2.2.3 Net life cycle GHG emissions from 65L SureChill SDD DC refrigerator

The net life cycle GHG emissions are estimated by aggregating the emissions from different life cycle phases. The use phase of the fridge is less than half of the lifespan of the PV system. Therefore, 50% of the emissions from solar power production is considered as the emissions related to the energy consumption during the 10 year lifespan fridge. It is assumed that the PV system and the refrigerator will be informally recycled at the end of its life, since this is currently the most prominent practice of e-waste management in Kenya, and more broadly in Africa.

GHG emissions are estimated according to the different phases of the life cycle. It should be noted that manufacturing of the PV system, raw material extraction, processing and manufacturing of the refrigerator and the smart box resulted in a considerable 92.1% of life cycle GHG emissions. GHG emissions from transportation phase of PV systems and refrigerators contributed to only 2.2% of life cycle emissions. Emissions from the use phase are negligible as solar energy is used as the energy source. The climate impact from the blowing agent during the use phase amounts to 0.03% of life cycle emissions. The remaining 5.6% emissions are from leakage of blowing agent and the refrigerant during the disposal phase and energy consumption for recycling activities at the end of the life of the PV system and the refrigerator. Considering all these emissions, the total life cycle GHG emissions from the refrigerator is estimated to be 370.4 kg CO_2-eq. As a result of resource recovery from end-of-life cycle recycling by informal recyclers, there is a possibility for the avoidance of emissions amounts of up to 69.9 kg CO_2-eq. The net life cycle GHG emissions after accounting for the savings/avoidance potential amounts to 300.5 kg CO_2-eq for a fridge with a ten year lifespan (see Figure 11).

Figure 10: GHG emissions, savings and net emissions from informal recycling of end-of-life SureChill refrigerator



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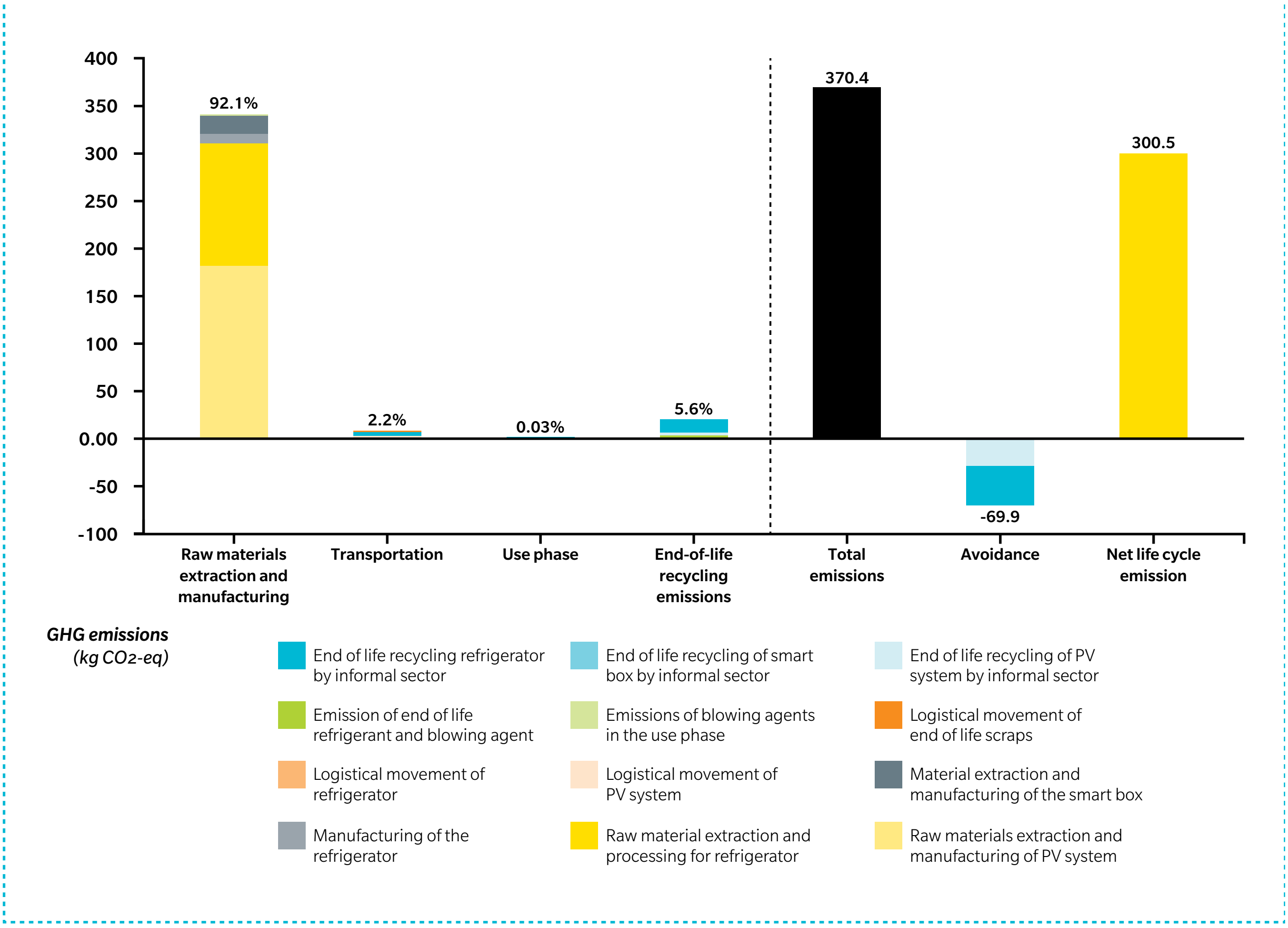
[36] United4efficiency. 2017.Climate Friendly and Energy-efficient Refrigerators. Available in http://united4efficiency.org

[37] Murakami, S., Terazono, A., Abe, N. Moriguchi, Y. and Miyakawa, H. 2006. Material flows of end-of-life home appliances in Japan. J Mater Cycles Waste Manag (2006) 8:46–5

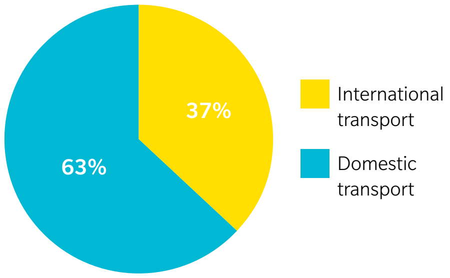
Figure 11: Total GHG emissions, GHG emissions avoidance and net emissions from a 65L SDD DC fridge (including the smart box) with a 10-year lifespan



As shown in Figure 11, transportation produced 2.2% of the overall emissions. In this case, GHG emissions from logistical activities are insignificant compared to other phases of the life cycle. That being said, it is useful to investigate the breakdown of emissions from different types of transport to identify any additional and easy to achieve emission mitigation opportunities. Shipping has been identified as one of the fastest-growing sectors in terms of GHG emissions. As reported by IPCC, ships carried around 80% (8.7 Gt) of internationally traded goods in 2011 and produced about 2.7% of global CO_2 emissions.[38]

GHG emissions from transport logistics depend on transportation mode, fuel used, fuel consumption efficiency, and transportation routes. The SureChill fridge is assembled and imported from China via maritime shipping and transported to the project location in Kenya. Sea transport caused the highest emissions among the different logistical movements, amounting to 58% of the total emissions from transportation. International transport resulted in 63% of total emissions from logistical activities since further transportation overland is needed to reach the fridge from manufacturing location to the port in China. The remaining 37% GHG emissions arise from domestic transportation, see Figure 12. These results indicate that international transport contributed to the significant share of emission from logistical movements. Manufacturing those items at the local level could help lower emissions from the logistical activities while creating other co-benefits such as job creation and provide boost in local manufacturing capacities.

Figure 12: GHG emissions from international transport vs domestic transport needs



With careful management, most domestic refrigerators could be utilised for over 20 years. Therefore, a similar approach is

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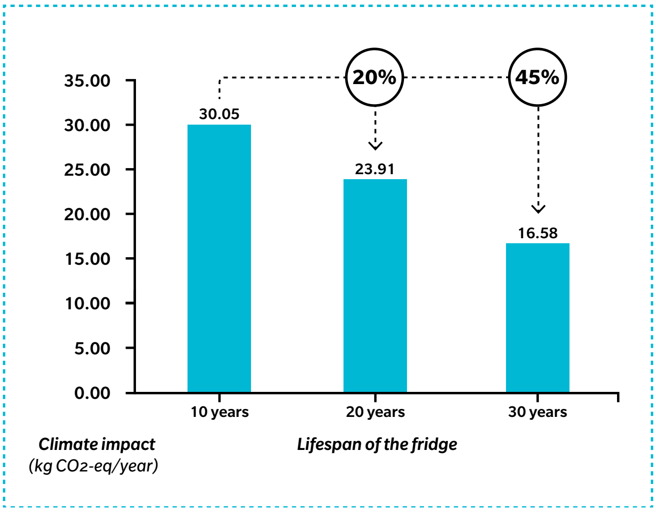
[38] IPCC, 2014: Transport. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

followed to estimate net life cycle emissions for 20 years and 30 years lifespans under the informal recycling option. In these scenarios, it was assumed that the smart box used in the refrigerator needs to be replaced every ten years. Further, it was assumed that the same PV system can be used to power the 20 and 30 year fridge lifespans. Although the warranty period of the PV system is 25 years; it could be used up to 30 years with proper maintenance.[39] Total life cycle emissions from PV power production was allocated among the manufacturing and end-of-life disposal phases of the refrigerator for the 20 year and 30-year lifespans. The estimated net GHG emissions from the fridge life cycle for a 20 year and 30 year lifespan are 478.13 kg CO_2-eq and 497.50 kg CO_2-eq, respectively. This analysis results revealed that life cycle GHG emissions from SureChill 65L domestic refrigerator vary from 300-500 kg CO_2-eq for 10-30 years of lifespans.

Net GHG emissions per functional unit are estimated to compare the climate impact from the three different refrigerator lifespans. The functional unit is GHG emissions from 65L DC fridge for one year operation period. The estimated result is shown in Figure 13. The result revealed that expanding the fridge's usage life for 20 and 30 years contributed to 20% and 45% GHG emissions reduction respectively on an annual basis compared to 10 years lifespan fridge. This analysis result revealed the significant impact of expanding the product life on GHG mitigation.

Figure 13: Comparisons of GHG emissions from 65L domestic fridge per year operational period under different lifespans



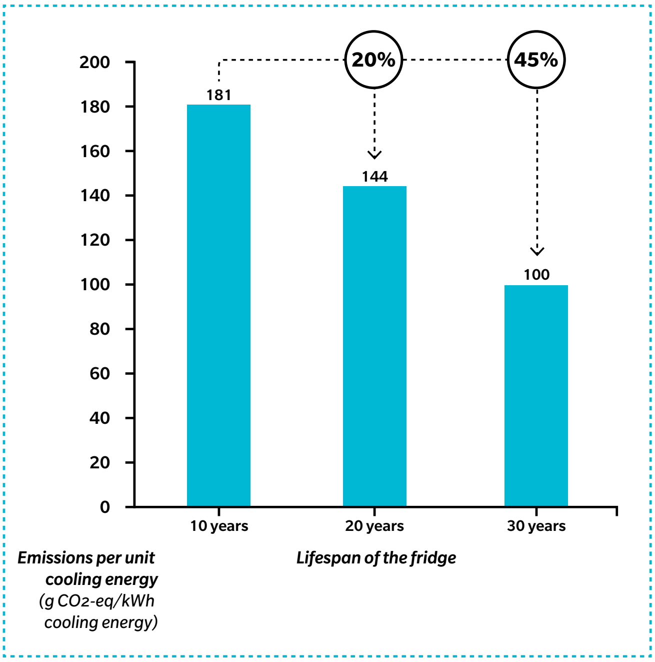
2.2.4 GHG emissions per kWh cooling energy

The general method for calculation of the GHG emissions per cooling energy unit can be found in Section 1.7. For the SureChill refrigerator, the cooling energy is calculated using an hourly fridge usage model which calculates the thermal losses, infiltration losses and food cooling energy required. Full details of the model can be found in the 'Refrigerator energy consumption and component sizing' section in Annex A. The following assumptions were used for the analysis:

- Fridge thermal energy determined using lab test data provided by SureChill giving an electricity use at different temperatures and a typical COP for the fridge
- Climate conditions for Lagos, Nigeria. Average ambient temperature of 27°C
- Internal set point temperature of 5°C
- Air infiltration losses calculated as 30% of the thermal losses as given by Khan et al.[40]
- 6.5 L of food to be cooled per day
- Initial food temperature of 15°C

The total cooling energy required was found to be 180 kWh per year. Figure 14 shows the emission comparison of the 10-, 20- and 30-year lifespans. These values can in theory be compared to any other cooling system.

Figure 14: Comparison of GHG emissions per unit cooling energy for SureChill domestic fridge



2.3 GHG Emissions from baseline scenario and its comparative assessment with SureChill's technology

2.3.1 Baseline Scenario Analysis

The baseline scenario is also known as 'reference' or 'benchmark' or 'non-intervention' scenario. Such a scenario depicts a sector in which no new environmental policies are implemented apart from those already in the pipeline today; or in which these policies have an indiscernible influence regarding the questions being analysed.[41] This analysis is important to make a comparison with

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[39] This is based on interview with expert from SureChill.

[40] Khan, M.I.H and Hasan M.M. Afroz, 2014. An Experimental Investigation of Door Opening Effect on Household Refrigerator; the Perspective in Bangladesh. Asian Journal of Applied Sciences, 7: 79-87. DOI: 10.3923/ajaps.2014.79.87, URL: https://scialert.net/abstract/?doi=ajaps.2014.79.87

[41] European Environmental Agency, 2020. Baseline Scenario. Available in baseline scenario — European Environment Agency (europa.eu).

the intended technologies for the future. Identification of an appropriate model for base scenario analysis is important, which could represent a conventional, less environmentally friendly, cooling system. As reported in a recent market survey, the off-grid market favours smaller refrigerators. In general, people need a cooling solution that helps them keep fresh produce and leftovers for only one or two days. Therefore, the average preference size for the 50–80L is considered for establishing a base model for comparison with the SureChill fridge.

As far as energy consumption is concerned, the average AC refrigerator consumes approximately 1 to 2.5 kWh per day,[42] which represents a significantly higher energy consumption demand when compared with its SureChill counterpart. Based on insights from off-grid suppliers in Africa and Asia, small off-grid refrigerators need to decrease in price to approximately USD 200 and operate on less than 40 Wp for these products to be viable for the rural, off-grid customer.[42] Most off-grid refrigerators utilise a battery bank to store energy. The size of the components in a solar power system are selected to satisfy the need for reliable operation during the times of the year when the system is under greatest stress. This might be when the refrigerator is most used or when there is least sunshine or some other event. What this means is that for most of the year the system has excess generation and energy storage capacity.

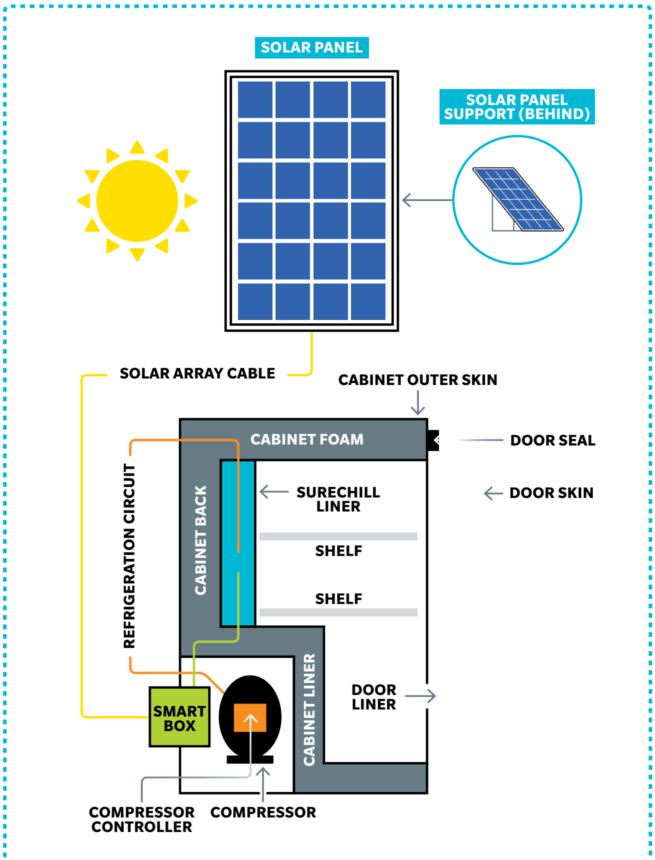
Considering the types of off-grid fridges available in the market, and in discussion with SureChill, the authors identified a 65L DC refrigerator powered by a battery bank as the reference scenario to be compared with the SureChill SDD DC refrigeration model. The technical specifications considered for such a baseline fridge are as follows:

- The fridge is powered by a lead acid battery bank
- Refrigerant used is R134, a hydrofluorocarbon, which is the most common type of refrigerant used in off-grid refrigerators[43,44]
- HFC-245fa is considered as the blowing agent, which is the most common type of blowing agent used recently to replace HCFCs[45]
- The lifespan of the baseline fridge is assessed for 10, 20 and 30 year lifespans
- Informal recycling is considered as the end-of-life disposal option

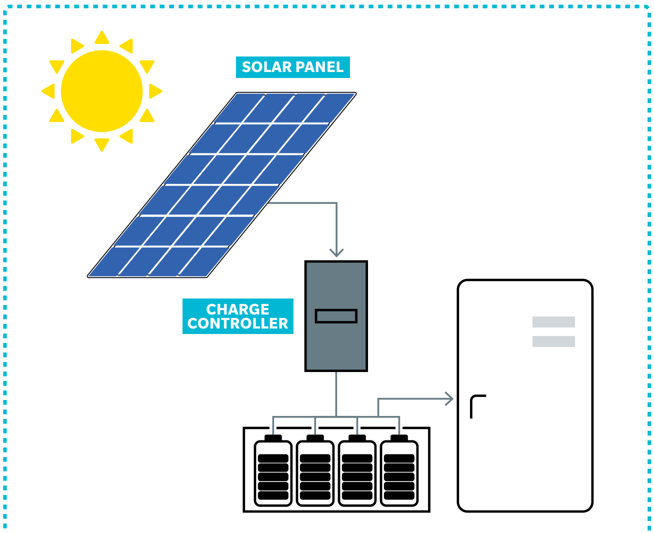
Different types of battery banks available in the market have been assessed in the baseline scenario and compared with the thermal storage system in the SureChill case to enable a comprehensive understanding of the potential climate benefits of using thermal storage over conventional battery storage.

Three types of batteries that are commonly seen in the off-grid solar products sector are considered in this study. These are lead acid (PbA), lithium ferrophosphate (LFP) and lithium nickel manganese cobalt oxide (NMC) batteries. Battery sizes, charge controller and PV panel sizes are derived under different lifespans of the fridge by using an adapted version of the PV battery model produced by Energy Saving Trust, see Table 7. The detailed information on specifications and size calculation methodology is presented in Annex A.

Figure 15: Schematic diagram of SureChill domestic refrigeration (a) and baseline case (b)



(A) SURECHILL DOMESTIC REFRIGERATION



(B) OFF-GRID DC

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[42] WARN, 2019. Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model https://www.epa.gov/sites/production/files/2019-06/documents/warm_v15_electronics.pdf

[43] Phocos, 2020. 8 Considerations When Buying A New DC Refrigerator/Freezer. Available in https://www.phocos.com/industry-insights/8-considerations-when-buying-a-new-dc-refrigerator-freezer/

[44] Goyal.R. 2021. Phasing down HFCS in Off- and weak-grid refrigeration. Available in https://storage.googleapis.com/e4a-website-assets/Phasing-down-HFCs-in-off-and-weak-grid-refrigeration.pdf

[45] AGC, 2020. Evaluating Safety Performance Properties of Common Foam Blowing Agents. Available in https://www.agcchem.com/blog/foam-blowing-agent/foam-blowing-agent-safety/

Table 7: Sizes of the PV panels, battery bank and charge controller for the 3 different lifespans for the baseline refrigerator

FRIDGE LIFETIME	BATTERY TYPE	PV SIZE (Wp)	BATTERY SIZE (Wh)	BATTERY SIZE 12V (Ah)	BATTERY BANKS REQUIRED ACROSS FRIDGE LIFETIME[46]	CHARGE CONTROLLER (Wh)	CHARGE CONTROLLER 12V (Ah)
10	PbA	260	1860	155.0	2	325	27.1
10	LFP	260	1150	95.8	1	325	27.1
10	NMC	260	1150	95.8	1	325	27.1
20	PbA	280	1860	155.0	3	350	29.2
20	LFP	280	1150	95.8	2	350	29.2
20	NMC	280	1150	95.8	2	350	29.2
30	PbA	320	1860	155.0	4	400	33.3
30	LFP	320	1150	95.8	3	400	33.3
30	NMC	320	1150	95.8	3	400	33.3

GHG emissions have been estimated for different components (e.g., battery bank, charge controller) of the baseline refrigerator by referencing emissions factors available in published literature. GHG emissions from PV panels that would be in use under the different lifespans and different end-of-life treatment options were estimated for the baseline scenario and presented in Table 8.

Table 8: GHG emissions (kg CO2-eq) from the PV panels required to power the baseline refrigerator technology across the 3 lifespans

SCENARIO	LIFE CYCLE GHG EMISSIONS EOL: OPEN DUMPING WITHOUT ANY RECYCLING	LIFE CYCLE GHG EMISSIONS EOL: INFORMAL RECYCLING – CURRENT SCENARIO	LIFE CYCLE GHG EMISSIONS EOL: FORMAL RECYCLING – POTENTIAL FUTURE SCENARIO
GHG emissions from 240Wp ×2 panels – SureChill case (25 years warranty period)	369.71	316.56	311.81
Fridge lifetime 10 years: 260Wp panel* ×2	200.26	171.47	168.90
Fridge lifetime 20 years: 280Wp Panel ×2	431.33	369.32	363.78
Fridge lifetime 30 years: 320Wp panel ×2	492.94	422.08	415.75

*only 50% of life cycle emissions of the PV system was allocated for 10 years lifespan of the fridge

Life cycle inventory of PbA batteries was obtained from the Spanos et al (2015) study and used to estimate emissions from manufacturing and recycling.[47] It was assumed that batteries are imported from China, and emissions from different modes of transportation such as sea transport by ships and ground transport by trucks were found using the EcoTransIT World model 2020. Mining and smelting during lead production have significant environmental impacts. The lead content of a PbA battery is approximately 71% of the battery mass[47] and there is a possibility of recovering 80-90% of lead from end-of-life batteries. The emissions saved from recovering lead and other valuable metals such as copper and certain types of plastics like polypropylene (PP) informal recycling has been credited back as avoided emissions (see Table 9 and Table 10). Estimated net GHG emissions from PV power production with respect to the baseline case and SureChill model are presented in Figure 16.

Table 9 note: *PbA batteries are replaced when they reached the lifetime of the battery which is assumed to be 7.0 years **Informal recycling of lead acid battery shows a less negative value since the emissions from the recycling process are more or less same as avoided emissions through resource recovery. In the lead acid battery manufacturing process, 70% of the lead used for the batteries is retrieved from a recycling process, whereas 30% is made of new raw materials.[47] Thus, it was assumed only 30% of recovered lead is credited for avoiding the virgin lead production. ***Negative GHG emissions values indicate GHG savings, resulting in resources (lead, copper and plastic) recovery from end-of-life batteries in formal recycling and avoided virgin production of equivalent number of materials. Inventory data of material composition of PbA battery in Spanos et al (2015) study was used to estimate emissions from recycling.[47]

Table 9: Life cycle GHG emissions (kg CO2-eq) from PbA batteries required for different lifespan scenarios of the refrigerator

FRIDGE LIFETIME	SIZE OF THE PBA BATTERY (Wh) 12V, C20	*A)* NUMBER OF BATTERY SETS*	*B)* GHG EMISSIONS FROM MANUFAC-TURING (kg CO_2-eq)	*C)* EMISSIONS FROM TRANSPO-RTATION (kg CO_2-eq)	*D)* EMISSIONS FROM RECYCLING (kg CO_2-eq)			*E)* NET LIFE CYCLE EMISSIONS (kg CO_2-eq) / 550 WH BATTERY (B) + (C) + (D)			F) NET LIFE CYCLE EMISSIONS (kg CO_2-eq) FROM ALL THE BATTERIES (A) X (E)		
					100 % OPEN DUMPING	INFORMAL RECYCLING **	FORMAL RECYCLING ***	100 % OPEN DUMPING	INFORMAL RECYCLING **	FORMAL RECYCLING ***	100 % OPEN DUMPING	INFORMAL RECYCLING **	FORMAL RECYCLING ***
10	1860	2	110.71	10.40	0.00	-0.34	-5.11	121.12	120.77	116.01	242.23	241.55	232.02
20	1860	3	110.71	10.40	0.00	-0.34	-5.11	121.12	120.77	116.01	363.35	362.32	348.03
30	1860	4	110.71	10.40	0.00	-0.34	-5.11	121.12	120.77	116.01	484.46	483.09	464.04

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46 Batteries are replaced when they reached the lifetime of the battery. Estimated lifetime of LA, LFP and NMC batteries are 7.0 years, 13.6 years and 13.6 years respectively.

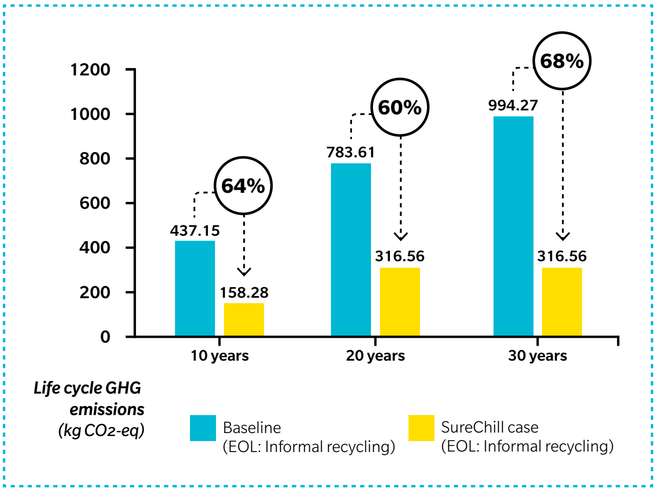
47 Spanos, C., Turney, C.D., and Fthenakis, V. 2015. Life-cycle analysis of flow-assisted nickel zinc-, manganese dioxide-, and valve-regulated lead acid batteries designed for demand-charge reduction. Renewable Sustainable Energy Reviews 43, 478–494

Table 10: Life cycle GHG emissions from charge controller required for different lifespan scenarios of the refrigerator

FRIDGE LIFETIME	**CHARGE CONTROLLER** PV POWER OUTPUT × 1.25 (W)	**GHG EMISSIONS FROM MANUFACTURING*** (kg CO_2-eq)	**EMISSIONS FROM TRANSPORTATION**** (kg CO_2-eq)	**EMISSIONS FROM RECYCLING** (kg CO_2-eq)			**NET LIFE CYCLE EMISSIONS** (kg CO_2-eq)		
				100 % OPEN DUMPING	INFORMAL RECYCLING**	FORMAL RECYCLING***	100 % OPEN DUMPING	INFORMAL RECYCLING	FORMAL RECYCLING
10	325 x 1	23.94	0.19	0.00	0.00	-3.11	24.13	24.13	21.02
20	350 x 2	25.79	0.20	0.00	0.00	-3.35	51.97	51.97	45.27
30	400 x 3	29.47	0.23	0.00	0.00	-3.83	89.10	89.10	77.60

*Life cycle inventory data for the charge controller is not available in the literature. Therefore, manufacturing data from a 500W inverter was used to derive emissions for manufacturing of the charge controller. b It was assumed that charge controllers are imported from China and emissions from different modes of transportation were found using EcoTransIT World model.[17] Authors collected values based on input/output data of 500W inverter from Ecoinvent, 2021.
**Mass of the charge controller is approximately 1 kg and there is hardly any significant mass of valuable metals that can be easily recovered by informal recyclers. Therefore, it was assumed that GHG emissions of informal recycling and resource recovery is negligible.

Figure 16: Comparison of life cycle GHG emissions from PV power production in SureChill and baseline scenario



Note: PbA battery used as the power storage mode in base case and end-of-life management option is informal recycling

2.3.2 Comparison of life cycle GHG emissions from 65L refrigerator and base scenario

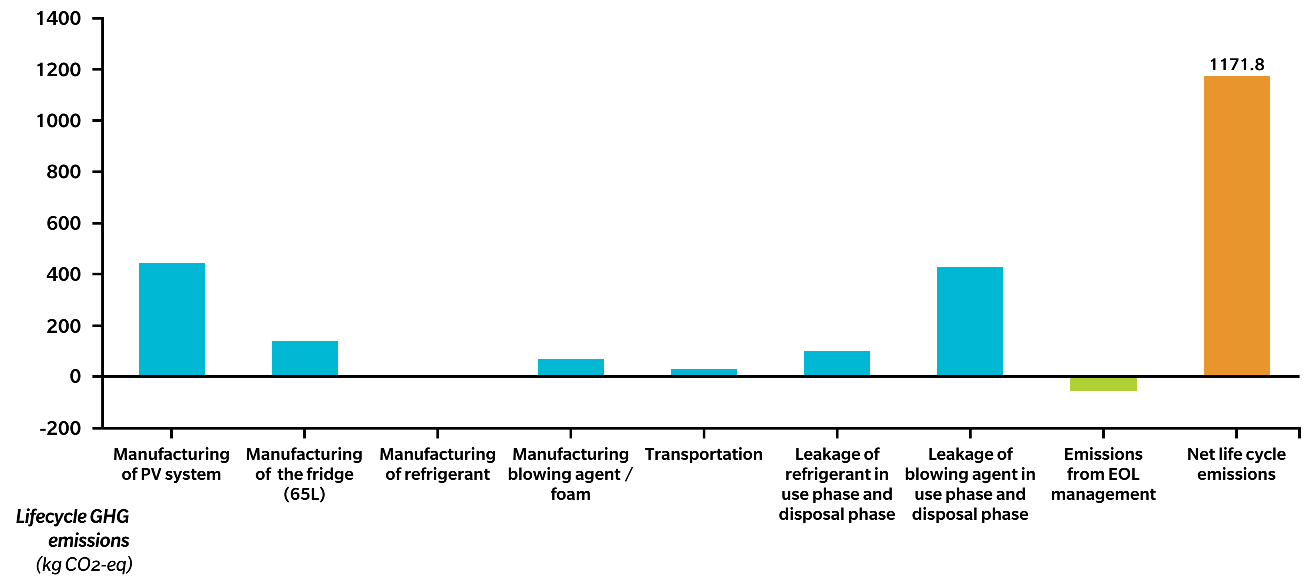
As specified previously, most of the refrigerator specifications (e.g. size, insulation materials) in the baseline scenario are the same as the SureChill fridge. It was assumed that the refrigerant in the baseline fridge was the HFC based R134a gas (70.85 g), and the blowing agent was HFC245fa (0.415 g). These type of fridges do not normally leak refrigerant during the use phase as they are hermetically sealed. However, in around one in a hundred systems, there is a catastrophic leakage of refrigerant where it all leaks out. Therefore, an average leakage rate of 1% has been assumed for all fridges. Thus, the total estimated amount refrigerant used in a baseline scenario is 71.56g of R134a.

At the end of the life cycle, it is expected that both refrigerant and blowing agent would escape into the atmosphere due to the unavailability of proper recovery methods under Kenya's existing disposal and treatment options. The climate impact caused due to the leaking of the blowing agents from the PU foam and refrigerant was estimated and is presented in Figure 17 alongside emissions from the other major phases. The estimated life cycle GHG emissions from the baseline scenario is 1,171.8 kg CO_2-eq. The highest percentage of GHG emissions in the baseline technology scenario, 38%, arises from the PV system manufacturing. Leakage of blowing agent, HFC245fa, into the atmosphere during the use and end-of-life disposal phases is responsible for 37% of the life cycle emissions. manufacturing. Leakage of blowing agent, HFC245fa, into the atmosphere during the use and end-of-life disposal phases is responsible for 37% of the life cycle emissions.

The total life cycle climate impacts from SureChill refrigerator and the baseline scenario are 300.5 kg CO_2-eq and 1,171.8 kg CO_2-eq, respectively (see Figure 18). This comparative assessment shows that with the appropriate design for energy savings and climate change mitigation, SureChill can result in 74% lower life cycle emissions than a baseline case.

Identifying emission hotspots would help identify and prioritise critical areas for climate mitigation actions from a life cycle perspective. This analysis helps identify three crucial emission hotspots in an off-grid refrigerator system. These are related to the choice of refrigerant, choice of blowing agent, and power storage method choice. As far as the refrigerant choice is concerned, the use of natural refrigerant (R600a) in SureChill fridge shows 99.9% lower emissions than utilising R134a refrigerant in the baseline case. Avoiding use of HFC gases as blowing agent is crucial in GHG mitigation. The use of cyclopentane in the SureChill fridge has a potential of emissions reduction by 96.6% as compared to use of HFC245fa as blowing agent in the baseline case. Thermal storage as a power-saving method would considerably contribute to emissions reduction as well. There are hardly any emissions with respect to the thermal storage (ice storage) in SureChill's fridge,but in contrast, the use of PbA battery bank in the baseline scenario resulted in emissions of 241.5 kg CO_2-eq. These results revealed that the thermal storage system in the SureChill case contributed to a 100% emissions reduction compared to the battery bank as a PV power saving option in the baseline case (see Figure 19).

Figure 17: Life cycle GHG emissions from the refrigerator in the baseline scenario for 10 year lifespans



The total life cycle climate impacts from SureChill refrigerator and the baseline scenario are 300.5 kg CO2-eq and 1,171.8 kg CO2-eq, respectively (see Figure 13). This comparative assessment shows that with the appropriate design for energy savings and climate change mitigation, SureChill can result in 74% lower life cycle emissions than a baseline case.

Figure 18: Comparison of life cycle GHG emissions of SureChill fridge and baseline scenario

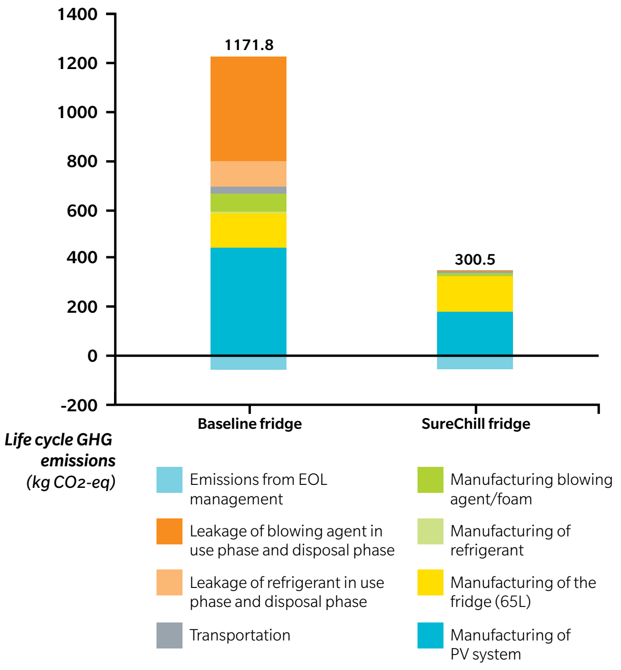
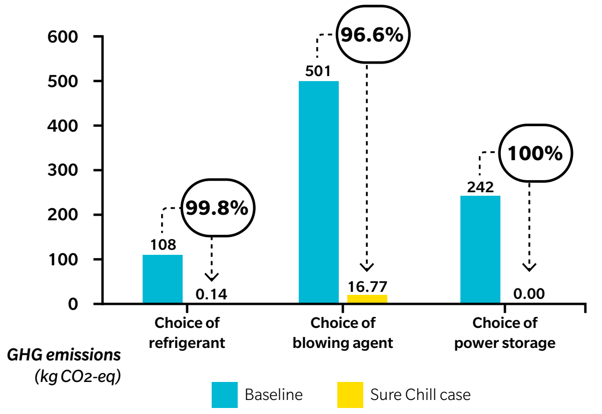


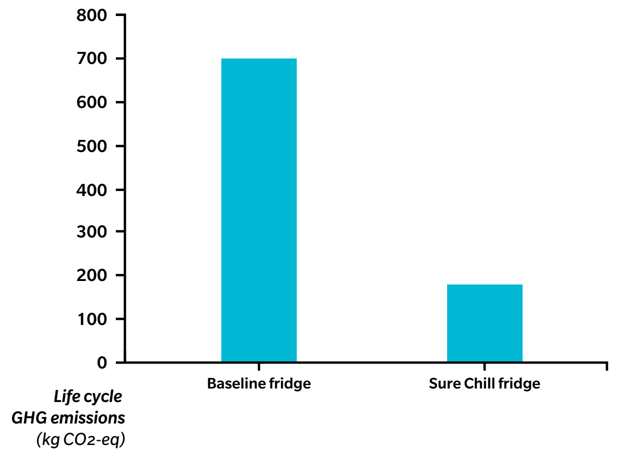
Figure 19: Comparative analysis of GHG emissions reduction potential from GHG hotspots of a technology such as that of SureChill compared to a baseline technology



2.3.3 GHG emission per kWh cooling energy

The emissions per unit cooling energy were calculated using the same method as in Section 2.2.4. Figure 20 shows the comparison between the 10-year lifespan scenarios for the baseline and SureChill refrigerators. This shows an almost four-fold reduction in emissions.

Figure 20: Comparison of GHG emissions per unit cooling energy between Surechill and baseline refrigerators



2.4 Scenario analysis for identifying GHG hotspots

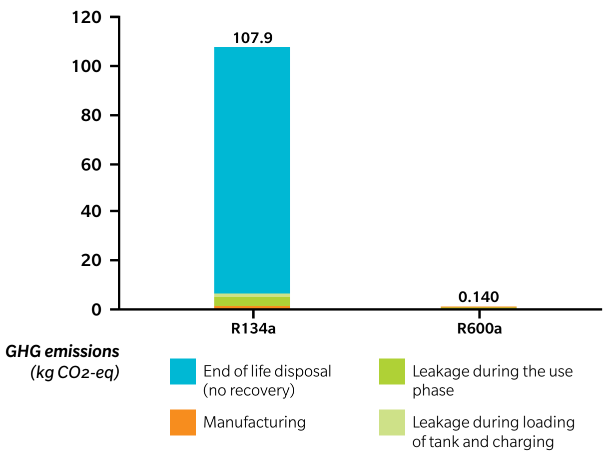
There are various factors related to off-grid refrigerators technologies that could significantly affect life cycle GHG emissions. Therefore, conducting a sensitivity analysis is useful to determine the ultimate climate impact with different manufacturing/management and end-of-life disposal options of the off-grid refrigerator.

2.4.1 The climate impact of different types of refrigerant

According to a recent publication by Efficiency for Access (EforA),[48] R134a, an HFC gas, and R600a, a natural refrigerant, dominate the refrigerants used in the off-grid refrigerator markets. The use of R600a is increasing due to its low environmental impact and superior thermodynamic performance and it is now the refrigerant gas of choice in domestic and small commercial refrigerators.[49] It is non-toxic with zero ODP (Ozone Depletion Potential) and has very low GWP (Global Warming Potential) with a value 3.[50] On the other hand, the GWP value of R134a is 1430, i.e. the global warming impact of 1 tonne of R134a in the atmosphere is 1,430 times more than global warming impact of 1 tonne of CO_2. 40% of the analysed refrigerator models use R600a, and more than 50% of manufacturers are still using the HFC gas, R134a.[48] While this study helps estimate the emissions impact during the use and end-of-life phases, the authors have estimated the life cycle impact of these gases by factoring in emissions during production and transport stages as well.

In general, the charge of R600a used as refrigerant in domestic and small commercial refrigerators is approximately 40–50% by mass when compared with HFC gases. In this study, the authors have used the formula proposed in the Goyal, R. 2021 refrigerant emissions study to estimate the charge mass of R134a.[48] This is 0.5282 x CL + 36.518, where CL is the volume of the refrigerator. According to this formula, the required amount of R134a refrigerant is 70.8g. In the SureChill case study, the amount of R600a refrigerant used is 30g which is 57.6% lower than the estimated R134a charge. It was assumed that 1% refrigerant would leak in the SureChill refrigerator in the use phase as unavoidable accidental leakages which need be topped-up. In the case for the baseline refrigerators, there is a good chance that they are not certified or fail to meet the off-grid refrigerator standard, therefore a conservative estimate of the amount of gas needed for top-up over the 10-year use phase of the fridge was taken at 1% of the gas-filled at manufacturing stage. Most fridges come to the recycling plants when they are completely broken down and the refrigerant has almost completely leaked. The small amount that may remain is released at the recycling stage. As there is no enforcement of any regulation to avoid leakages, the easiest way is to let the gas go, especially in the absence of any viable economic incentives.[51] The climate impact caused by R600a and R134a refrigerants to maintain the same level of coefficient of performance in a 65L domestic fridge is shown in Figure 21.

Figure 21: Effect of prominent types of refrigerant on GHG emissions of 65L DC fridge



The life cycle carbon impact from use of R600a and R134a amounts to 0.140 and 117.9 kg CO_2-eq, respectively. With the right incentives, if the off-grid refrigerator market could be transitioned to the natural refrigerant of isobutane (R600a) instead of HFCs refrigerant (R134a), it is possible to avoid 99.9% of climate impact caused from the use of R134a.

2.4.2 The climate impact of blowing agents

The primary reason for the high carbon impact of rigid foam insulation used in cold rooms and refrigerators is the use of a blowing agent. The blowing agent, HFC-245fa produces foams with the highest insulation value across any HCFC-141b alternative blowing agent in the construction market.[52] HFC gases have zero effect on the ozone layer, but they still have a high global warming

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[48] Goyal.R. 2021. Phasing down HFCS in Off- and weak-grid refrigeration. Available in https://storage.googleapis.com/e4a-website-assets/Phasing-down-HFCs-in-off-and-weak-grid-refrigeration.pdf

[49] Freeze Refrigerant. 2022. Refrigerant R600a Gas. Available in http://www.freezeref.com/index.php/products/refrigerant-r600a-gas/

[50] Ozon Action, United Nations Environment Programme, GWP, CO_2 (e) and the Basket of HFCs, n.d., https://wedocs.unep.org/ bitstream/handle/20.500.11822/26866/7878FS03GWPCO_EN.pdf?sequence=1&isAllowed=y

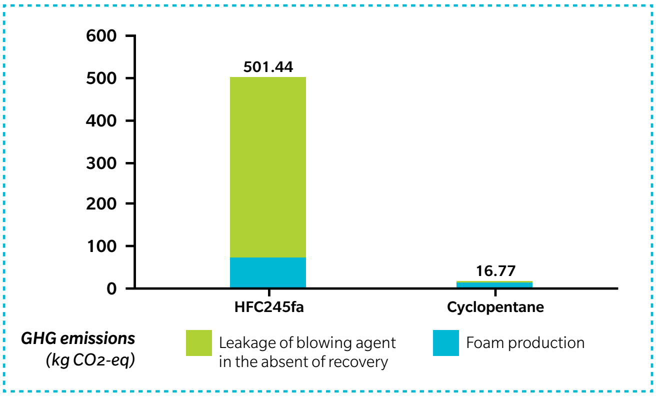
[51] Interviews with e-waste recyclers

[52] Bogdan, M., Williams, D. and Verbiest, P.2001. HFC245fa Spray Polyurethane Foam Systems Co-Blown with Water: A Quality, Cost Effective, Safe Substitute for HCFC141b. Journal of Cellular Plastics 37(1):58-71.

potential (HFC-245fa has a GWP of 1030).[53] Therefore, there is a trend of moving towards natural blowing agents that have zero effect on ozone depletion and extremely low global warming potential. This study includes a comparative analysis of the climate impact from use of cyclopentane, a hydrocarbon with the chemical formula C_5H_{10} and HFC245fa. Cyclopentane (GWP – 11) is a natural blowing agent used in the SureChill refrigerator, and is one of the most popular blowing agents used in cooling technologies.[54]

The estimation for the amount of blowing agent required for manufacturing PU foam for a 65L domestic fridge and its climate impacts is shown in Annex A. It is assumed that any remaining blowing agent in the foam at EOL will eventually find its way in the atmosphere, since there are limited commercial re-use applications for foam, and in the scenario that a fridge is recycled at a formal recycling facility in Africa, the foam is stacked and stored in warehouses. Approximately 6% of the blowing agent used in the foam insulation material of 65L domestic fridge is released during its use phase (10 years).[55] The remaining 94% is eventually emitted to the atmosphere by the product's end-of-life. The estimated emissions for the production of polyurethane foam using cyclopentane and HFC245fa as blowing agents for a 65L DC fridge are 16.77 kg CO_2-eq and 501.44 kg CO_2-eq, respectively, see Figure 22. The climate impact is high due to a lack of formal recovery method for blowing agents. The climate impact from use of HFC blowing agents accounts for approximately 85% of the life cycle emissions of PU foams, highlighting the significance of the choice of blowing agent. It is recommended that more measures are put in place to phase out use of HFC gases and transition the off-grid sector to natural blowing agents where feasible, as well as build e-waste recyclers to be able to recover environmentally harmful gases during fridge recycling.

Figure 22: GHG emissions from use of a natural gas and an HFC gas as blowing agents in the production of form required for a 65L domestic fridge



Given that 6% of blowing agent could be released during the use phase, and 94% remains at end-of-life, the climate impact of HFC blowing agents depends on the end-of-life (EOL) management strategy. HFC gases may be captured at EOL and incinerated leading to minimum possible emissions compared to those which are sent to landfills, which result in maximum possible emissions.

2.4.3 The climate impact of end-of-life disposal practices from solar power production unit

SureChill's total life cycle GHG emissions can be highly sensitive to the end-of-life treatment strategy as GHG can be released at this stage which increase emissions significantly. This study considers three main disposal methods: open dumping without any recycling, informal recycling, and formal recycling. This section details emissions impact under each of these three disposal scenarios.

Open dumping scenario: Much of the PV panel waste is often stored at the project location site or ends up in landfills. Heavy metals present in PV modules can result in significant environmental pollution if the panels are disposed at landfill. However, piling up PV panels and their supporting structures at the site or landfills by itself would not contribute to GHG emissions as there is no natural degradation process for metals at the landfill site. Transportation of panels and their supporting structures to a landfill site will result in marginal transport related emissions. Although various other types of harmful impacts would be caused by open dumping, GHG emission impacts under an open dumping scenario can be assumed as negligible.

Informal recycling (the most likely scenario presently): This scenario assumes that informal recyclers extract the valuable components which are mainly metals such as steel, aluminium and copper. A detailed emissions assessment of this scenario has been presented in Section 2.2.1. The estimated net impact from informal recycling of the PV system used in the SureChill case study is -53.15 kg CO_2-eq.

Formal recycling scenario: Formal recycling of solar PV modules is at a nascent stage globally. Implementing a proper recycling mechanism would support the recovery of all valuable metals like aluminium, silver and copper and make the off-grid appliance sector more circular. Total GHG emissions from end-of-life management of the PV system under the formal recycling scenario have been presented in Annex A. The estimated net GHG emissions from formal recycling of the PV system is -57.896 kg CO_2-eq, indicating GHG saving potential.

Comparative assessment of end-of-life management scenarios of the PV system: Net climate impact from different end-of-life scenarios are presented in Figure 23. Both informal and formal recycling processes have the potential for significant emissions avoidance due to resource recovery opportunities. Materials recovered at end-of-life can be used several times over and kept in circulation for as long to possible to minimise virgin materials extraction. Furthermore, improving the recovery rate of valuable metals, polymers, and ceramics used in the PV system (120Wp x 2 polycrystalline panels, 2.4 kg of mounting system and 2.3 kg solar array cable) would further enhance the emissions savings under a formal recycling scenario.

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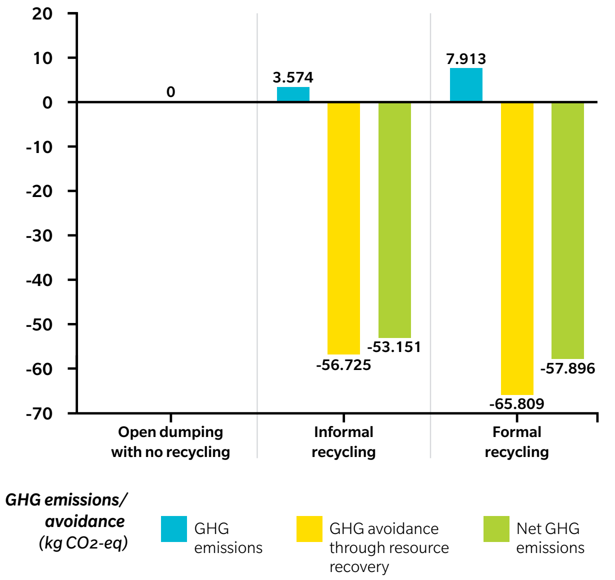
[53] Department for Business, Energy & Industrial Strategy, 2020. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020

[54] Vachon. C. and Gendron, R. Evaluation of HFC-245fa as an Alternative Blowing Agent for Extruded Polystyrene. Cellular Polymers 22(5):295-313

[55] Kjeldsen, P. And Charlotte Scheutz, C. 2003. Short- and Long-Term Releases of Fluorocarbons from Disposal of Polyurethane Foam Waste. Environ. Sci. Technol. 2003, 37, 5071-5079

Figure 23: GHG emissions from end-of-life disposal options of PV system



Net emissions saving values do not show a big difference between informal and formal recycling due to the assumptions made on the analysis of informal recycling. It was assumed that all valuable metal fractions are collected by the informal collectors and sent to the recycling facilities. However, there are numerous health and environmental implications in informal recycling settings due to the rough extraction processes often undertaken without appropriate protective gear. Burning plastic components to extract metal fractions in informal recycling situations emits significant amount of black carbon (BC), which has a 1055–2020 times warming effect as compared to CO_2 over a 100-year time horizon.[56] However, emissions estimation from BC is outside the scope of this study, therefore, these estimates do not include the climate impact from burning of plastics. In conclusion, informal recycling contributes to greater warming effects, and has adverse health and environmental consequences.

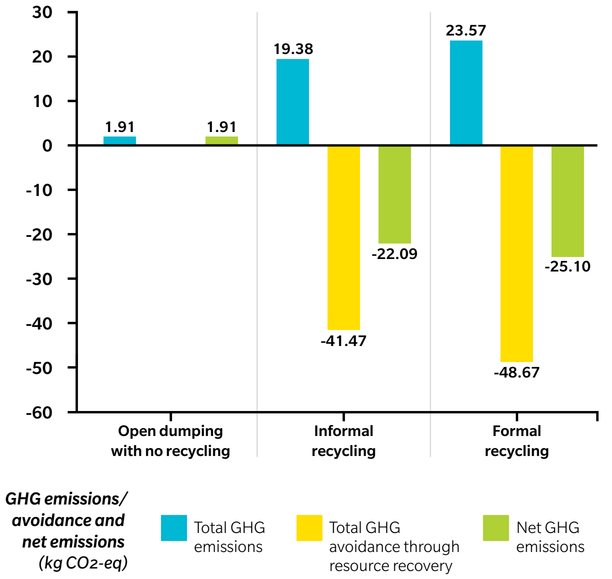
2.4.4 The climate impact of different end-of-life treatment options for a 65L SureChill refrigerator

Open dumping (without any recycling, formal or informal): Open dumping of the SureChill refrigerator at end-of-life will result in limited impact, as both the refrigerant gas and the blowing agent used are climate friendly. Leakage of refrigerant gas and blowing agent at this life cycle phase can emit as much as 1.91 kg CO_2-eq.

Informal recycling (often at a landfill site): An informal recycling scenario assumes manual dismantling and extraction process. Under this scenario, refrigerant gases and the blowing agent are released into the atmosphere during manual dismantling of the fridge. The recovered metal fraction would be sold to the local collection agents, who would, in turn transport metals to the nearest smelting facilities. Total end-of-life GHG emissions from informal recycling activities and the release of refrigerant and blowing agents at the disposal phase amounts to 19.38 kg CO_2-eq. The total GHG avoidance/savings due to the recovery of resources is -41.47 kg CO_2-eq. Based on these figures, the estimated net GHG savings from the SureChill 65L refrigerator's material recovery is 22.09 kg CO_2-eq (see Figure 24). In other words, net emissions are negative.

Formal recycling: Similarly, GHG emissions from the formal recycling route are estimated. This scenario assumes that all metals and plastic fractions such as steel, aluminium, copper, ABS, HIPS, PVC, PC, and part of the printed circuit board are recycled to recover valuable materials. Estimated net GHG emissions from formal recycling are -25.10 kg CO_2-eq. See Figure 24.

Figure 24: GHG emissions from end-of-life treatment scenarios for 65L domestic refrigerator



2.4.5 Life cycle GHG emissions from SureChill's PV power production by different end-of-life treatment options

As explained in the previous section, life cycle GHG emissions from PV power production highly depend on the end-of-life management plan. Therefore, life cycle GHG emissions from electricity production from SureChill PV power production system is estimated, considering the three disposal options discussed above.

Life cycle GHG emissions from PV power production with 100% open dumping at the end-of-life scenario: GHG emissions from a solar power production system in a SureChill case study would be 370 kg CO_2-eq. There are no GHG emissions associated with the use phase of the PV system. Therefore, net life cycle GHG emissions from PV power production can be considered as 370 kg CO_2-eq.

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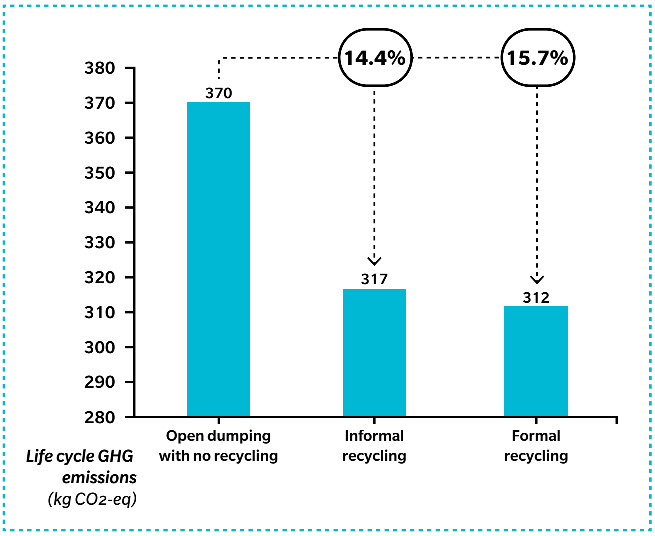
[56] European Environment Agency (EEA), 2016. EMEP/EEA air pollutant emission inventory guidebook 2016 – Emission factors. Available in http://efdb.apps.eea.europa.eu/?source

Life cycle GHG emissions from PV power production with informal recycling at the end of the life (most likely scenario as of now): Section 2.2 presents a detailed life cycle assessment under the informal recycling scenario. With the end-of-life informal recycling option, the estimated net life cycle GHG emissions from the PV power production system installed at SureChill case amounts to 317 kg CO2-eq (see Figure 25).

Life cycle GHG emissions from PV power production with formal recycling at the end of the life: A significant amount of emissions can be avoided through resource recovery by recycling all waste fractions. Formal recycling and resource recovery can lead to emissions savings of 65.8 kg CO2-eq. Therefore, net GHG emissions from the solar power system in the SureChill case resulted in 312 kg CO2-eq.

Comparing emissions from different end-of-life disposal options helps indicate the importance of recycling and resource recovery. For instance, informal recycling and formal recycling mechanisms can reduce emissions by 14.4% and 15.7% respectively when compared with the 100% open dumping of the SureChill fridge (see Figure 25). Although GHG savings from informal recycling show a similar range as formal recycling, the actual climate impact from informal recycling is expected to be higher (savings is lower) due to the emissions of black carbon (BC) from plastic burning in informal recycling activities. BC emissions and related climate impact have not been considered within this study's scope and should consider in future research.

Figure 25: Life cycle GHG emissions with different end-of-life treatment options of PV power production



2.4.6 Emission reduction potential by increasing serviceable life of the refrigeration system

Improving the usable life of a product or parts of products helps prevent the need for new materials extraction and reduces waste production. Designing products / parts to be more durable, repairable, and interoperable would help extend the technical and usable life of the product.[57] This section focusses on how the improved serviceable life contributes to emissions reduction.

GHG emissions per unit (kWh) of electricity production related to three lifespan scenarios were analysed. In the first scenario, the lifetime of PV panels is considered as ten years in the eventuality that some users will discard the PV systems along with the refrigerator at the end of the 10 years (given that the SureChill off-grid powered refrigerator warranty period is ten years). This is just an indicative scenario for comparison purposes with the most likely scenario being the use of the PV systems for 20-30 years. Total power production from two polycrystalline PV panels of 120 Wp capacity each, was estimated. It was assumed that at least four hours of peak sunlight would be received every day.

Further, it was assumed that the efficiency of the PV panel will fall by 0.5% each year as part of a natural degradation process.[58] The estimated electricity production from two 120 Wp PV panels would be 3426kWh for a ten year lifespan. Considering the total life cycle GHG emissions from PV system in 10 years and assuming end of disposal option is informal recycling (316.6 kg CO2-eq), the projected GHG emissions per kWh electricity production is 92g CO2-eq/kWh (see Table 11) Detailed calculation steps have been presented in Annex A.

However, ten years is an unrealistically short operating period for solar panels. As a general solar industry rule of thumb, solar panels last about 20-30 years, and the warranty period is often around 25 years.[59] The latest generation of panels can last up to 30-40 years.[60] Therefore, assessing GHG emission per kWh electricity of production from 20 years, and 30 years will reflect more realistic PV panel lifespans. The estimated GHG emission from 20, and 30 years of lifetime of two 120 Wp polycrystalline panels and the supporting system is 47 g CO2-eq/kWh, and 32 g CO2-eq/kWh, respectively, with the assumption of informal recycling of the panels at the end of the life cycle, see Table 11. If the lifespan is extended further with proper maintenance activities, GHG emissions per unit of electricity production can be further reduced.

The assessment results were compared with similar research information in the literature. For example, the Nugent and Sovacool[61] critical meta-survey on the LCA assessment of solar power production. In this study, a selection of 41 articles were evaluated and the PV literature did not account for power storage in the battery backup. The average life cycle GHG emissions for solar PV panels was found to be 49.9 g CO2-eq/kWh. Our potential GHG emissions from solar power production for the SureChill fridge is within the same range as those estimated in other published literature. In addition, estimated GHG emission factors from solar power production across 10-, 20-, and 30-years lifespans are very low compared to the grid emission factor (603 g CO2-eq/kWh) in Kenya.[62] Therefore, environmentally speaking, PV panels are the preferred solution over conventional grid power.

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[57] Cordella, M., et al. 2020. Improving material efficiency in the life cycle of products: a review of EU Ecolabel criteria. International Journal of Life Cycle Assessment, 25, 921-935
[58] Interview with refrigerator manufacturer
[59] Energysage, 2020. Smart Energy Decisions. Available in https://www.energysage.com/
[60] Greenmatch, 2019. Lifespan of solar power. Available in https://www.greenmatch.co.uk
[61] Nugent, D. and Sovacool, B.K. 2014. Assessing the life cycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. Energy Policy 65 (2014) 229–244
[62] Institute for Global Environmental Strategies (2020). List of Grid Emission Factors, version 10.8. Available at: https://pub.iges.or.jp/pub/iges-list-grid-emission-factors

GHG emissions per unit of electricity production under different lifespans would vary depending on the end-of-life cycle treatment. Therefore, GHG emissions per unit of electricity production under informal recycling and formal recycling mechanisms are also assessed, see Table 11. GHG emissions per unit of electricity production under informal and formal recycling options are noticeably lower than the 100% open dumping option. The GHG emissions per unit of electricity production from scenarios with informal recycling and formal recycling are similar. The reason is that informal recyclers collect most metals including aluminum, and metal recovery provides the highest levels of emissions savings compared with recovery of other types of materials.

Table 11: Life cycle of GHG emissions per kWh solar power production in different lifespan scenarios under different end-of-life treatment options

END-OF-LIFE CYCLE TREATMENT OPTION	**LIFE CYCLE GHG EMISSIONS PER UNIT OF ELECTRICITY PRODUCTION** (kg CO2-eq/kWh)*		
	10 YEARS LIFESPAN	**20 YEARS LIFESPAN**	**30 YEARS LIFESPAN**
Life cycle GHG emissions from PV power production with 100% open dumping	0.108	0.055	0.038
Life cycle GHG emissions from PV power production with informal recycling	0.092	0.047	0.032
Life cycle GHG emissions from PV power production with formal recycling (a potential future scenario)	0.091	0.047	0.032

*Life cycle GHG emissions per unit (kWh) calculation includes the emissions from PV panel, mounting system, solar array cable production, emissions from logistical movements and emissions from end-of-life treatment as mentioned in the table)

The assessment results show that expanding the PV system's serviceable life could considerably reduce GHG emissions per kWh. For instance, GHG emissions reductions per kWh from 20 year and 30 year PV system lifespans is 49% and 65% lower, respectively, than the ten year lifespan under the current disposal practice of informal recycling (see Figure 26). An extended warranty period and proper management of the PV system would be important aspects for an enhanced serviceable life and further GHG reduction potential.

In order to make a meaningful comparison, net GHG emissions per functional unit or 'GHG emissions from a 65L DC fridge for one year operational period', including emissions from both the PV system and the refrigerator are estimated to compare the climate impact from different refrigerators' lifespans. The estimated results with respect to the different lifespans under the current end-of-life disposal practice of informal recycling are shown in Figure 27.

The result revealed that extending the fridge's usage life to 20 or 30 years would contribute to a 20% or 45% GHG reduction, respectively, on an annual basis compared to a fridge with a 10 year lifespan. This result revealed that extending the product life has a significant GHG mitigation potential.

Figure 26: Life cycle GHG emissions per kWh electricity production from different PV system lifespans with informal recycling as end-of-life disposal

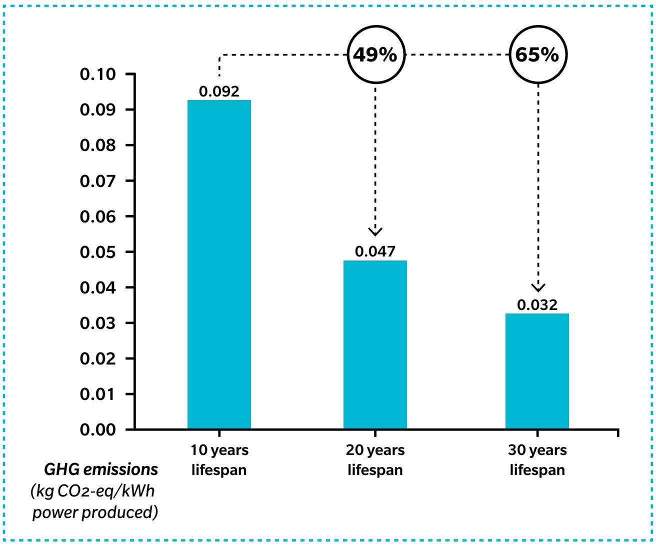
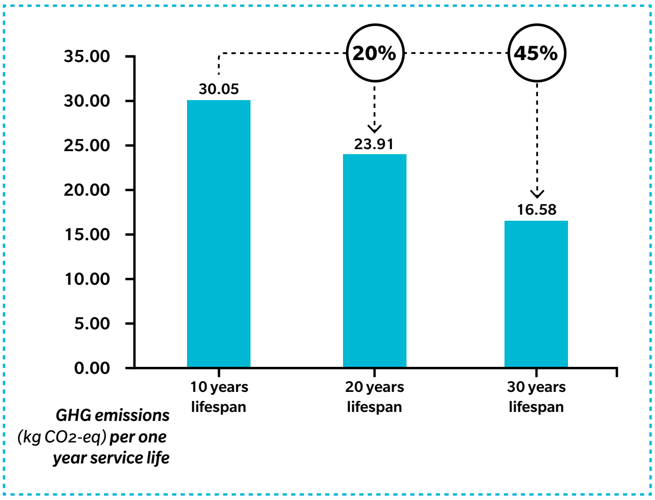


Figure 27: Comparisons of GHG emissions from 65L domestic fridge per year operational period under different lifespans (both the emissions of refrigerator and PV power production are included in life cycle GHG emissions of this fridge)



2.4.7 Comparative assessment of GHG emissions from an SDD fridge (SureChill) and fridges with batteries

Although incorporating a battery bank is an expensive option, most off-grid refrigerators still rely on them to run the fridge overnight and for periods with cloudy weather. Therefore, different types of battery banks available in the market were assessed in the baseline scenario relative to the thermal storage systems in the SureChill case to understand the potential climate benefits of a thermal storage option.

Three types of popular batteries in the off-grid market are considered in this study, namely, lead acid (PbA), lithium ferrophosphate (LFP) and lithium nickel manganese cobalt oxide (NMC) batteries. Lead acid batteries are the most popular type in the off-grid market. A detailed assessment of climate impact from PbA battery has been presented under the baseline scenario analysis in Section 2.2. This section focuses on evaluating the climate impact from using two types of lithium-ion batteries as opposed to using a Solar Direct Drive fridge (one that uses no battery) such as the SureChill fridge.

Lithium-ion batteries

Two major lithium-ion batteries are used in the off-grid market, lithium ferrophosphate (LFP) and lithium nickel manganese cobalt oxide (NMC). GHG emissions from manufacturing lithium-ion batteries are produced from the use of energy and materials during the manufacturing of positive electrode paste, negative electrode paste, electrolyte, separator, cell container, module and battery casing and electrode substrates. GHG emissions from the manufacturing of the above components were taken from the available data in the literature.[63] GHG emissions from the transportation of batteries were estimated, where it has been assumed that the battery is manufactured in China and transported to the project location in Kenya.

The recycling industry for lithium-ion batteries is not mature enough to become a universally well-established practice. Most lithium-ion batteries that are recycled undergo melting-and-extraction or smelting at high temperatures. These are highly energy-intensive processes. The plants are also costly to build and operate and require sophisticated equipment to treat the harmful emissions from smelting process. Despite the high costs ofbuilding such sophisticated recycling facilities, these plants do not recover all valuable battery materials. Due to these reasons, less than 5% of lithium-ion batteries are recycled today.[64] There are a few examples where used lithium batteries are being re-used in certain off-grid applications, however, overall there is limited recycling, formal or informal, for lithium-ion batteries.

There is a growing trend to replace the depleted lithium-ion (LFP) batteries with lithium-nickel manganese-cobalt-oxide (LiNiMnCoO2 or NMC) batteries due to unfavorable economics.[65] For this reason, in this study, the authors have estimated the life cycle GHG emissions from NMC batteries for comparison with LFP and PbA batteries.

Life cycle GHG emissions from different types of batteries

PbA batteries in Kenya are often informally recycled at the end of their lifetime, and a fraction of these are recycled by e-waste recyclers.[66] In contrast, lithium batteries are not usually recycled in an informal setting due to the inherent complexity in extracting valuable metals. Therefore, it was assumed that both LFP and NCM batteries are transported to and recycled in China under the formal recycling mechanism. GHG mitigation potential of resource recovery from the end-of-life batteries has been credited for PbA and LFP batteries. Material recovery rate for NCM battery is not available in the literature; therefore, life cycle GHG emissions for NCM batteries include only the emissions caused due to manufacturing, transportation, and recycling. An estimation of the battery size required to match the performance of SureChill's thermal energy store is summarised in Table 12. The estimated life cycle GHG emissions of the three types of batteries are summarised in Table 13 according to the different lifespans of the fridge.

Table 12: Specification of the batteries required for PV power storage for different lifespans of the fridge[67]

TYPE OF BATTERY	**FRIDGE LIFETIME**	**REQUIRED CAPACITY OF THE BATTERY** (Wh)	**NO. OF BATTERIES REQUIRED FOR THE FRIDGE'S LIFETIME**	**BATTERY'S ENERGY DENSITY** (Wh/kg)	**C) APPROX. WEIGHT** (kg/PER BATTERY)	**D) MANUFACTURING EMISSION** (kg CO_2/kg BATTERY)	**E) RECYCLING EMISSIONS** (kg CO_2/kg BATTERY) **(FORMAL RECYCLING)**
Lead acid (PbA)	10	1860	2	32[a]	58.125	1.905	0.508
	20	1860	3	32	58.125	1.905	0.508
	30	1860	4	32	58.125	1.905	0.508
Lithium iron phosphate – LFP (LiFePO4)	10	1150	1	88[b]	13.068	13.000	3.845
	20	1150	2	88	13.068	13.000	3.845
	30	1150	3	88	13.068	13.000	3.845
Nickel cobalt manganese lithium (NCM)	10	1150	1	112[b]	10.268	18.241	6.741
	20	1150	2	112	10.268	18.241	6.741
	30	1150	3	112	10.268	18.241	6.741

a: Energy density of lead acid battery[47]; b: Energy density of LFP and NCM[63]; c,d,e: Author derived values based on Spanos et al (2015)[47], Bettez et al., 2011[63], Zhu and Chen (2020)[68]

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[63] Bettez, G.M., Hawkins, T.R. and Strømman, A.H. 2011. Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-in Hybrid and Battery Electric Vehicles. Supporting Information. Environmental Science & Technology 45(12):5454

[64] Chen, W.S. and Ho, H.J. 2018 Recovery of Valuable Metals from Lithium-Ion Batteries NMC Cathode Waste Materials by Hydrometallurgical Methods CEN, 2021. Metals 2018, 8, 321; doi:10.3390/met8050321

[65] Battery university, 2021. Types of Lithium-ion. Available in https://batteryuniversity.com/article/bu-205-types-of-lithium-ion

[66] Interviews with e-waste recyclers based in Africa

[67] Batteries are replaced when they reached the lifetime of the battery. Estimated life time of PbA, LFP and LNMC batteries are 7.0 years, 13.6 years and 13.6 years respectively

[68] Zhu, L. and Chen, M. 2020. Research on Spent LiFePO4 Electric Vehicle Battery Disposal and Its Life Cycle Inventory Collection in China. Int. J. Environ. Res. Public Health, 17, 8828; doi:10.3390/ijerph17238828

Table 13: Net Life cycle GHG emissions (kg CO_2-eq/battery bank)[69] from different batteries used under different lifespans of the refrigerator

TYPE OF BATTERY	END OF LIFE DISPOSAL OPTION	LIFE SPANS OF THE REFRIGERATOR (YEARS)		
		10 YEARS	20 YEARS	30 YEARS
Lead acid battery	100% open dumping	242.23	363.35	484.46
	Informal recycling	241.55	362.32	483.09
	Formal recycling	232.02	348.03	464.04
LFP	100% open dumping	172.22	344.45	516.67
	Informal recycling	172.22	344.45	516.67
	Formal recycling	194.15	388.30	582.45
NMC-Lithium Nickel Manganese Cobalt Oxide (NMC)	100% open dumping	189.13	378.26	567.40
	Informal recycling	189.13	378.26	567.40
	Formal recycling	258.35	516.69	775.04

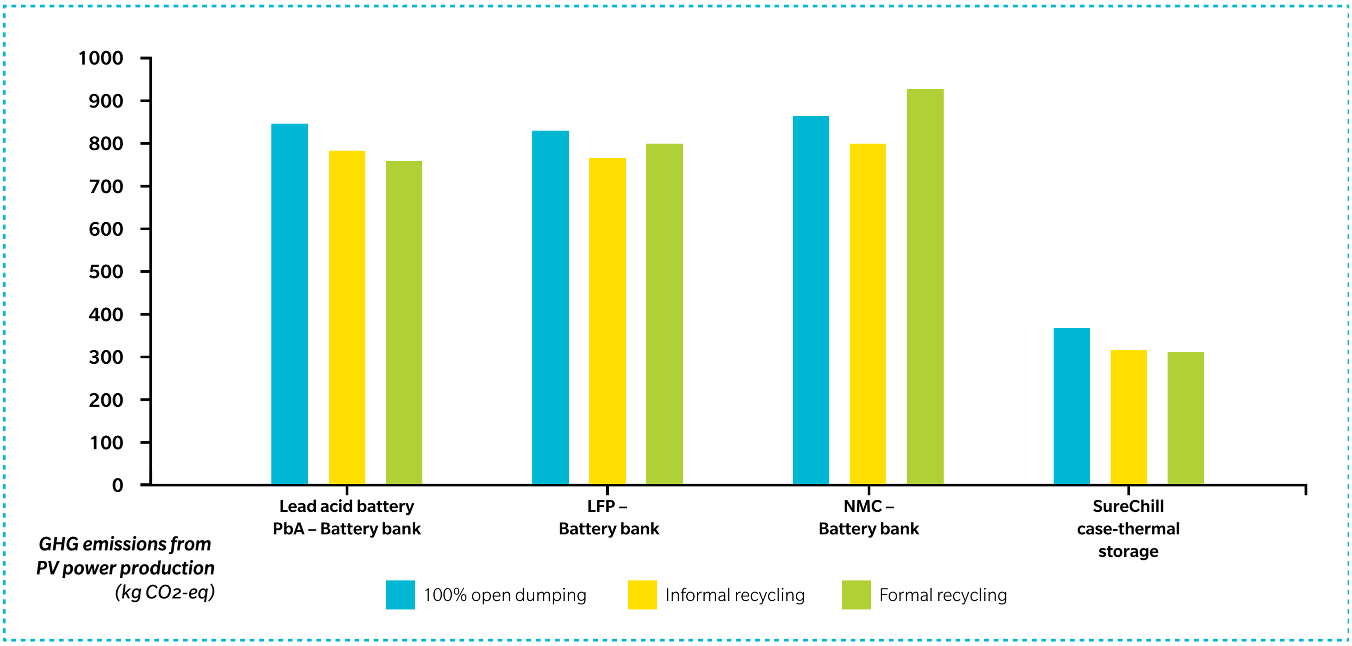
Note: a limited number of used lithium batteries are now being tested for efficiency and re-used in limited applications. However, there is no informal recycling mechanism for LFP and NMC batteries in Kenya. Therefore, net life cycle emissions from these batteries are same as the open dumping and informal recycling end-of-life disposal methods. For NMC batteries, data is not available on the recovery rate of the different elements in these batteries e.g., Li, CO, Ni etc., when recycled in a formal facility. Net life cycle emissions values under formal recycling are indicated as being higher than informal recycling. In formal recycling of LFP batteries and NCM batteries that are assumed to have been recycled in China, emissions from formal recycling appears to be high due to the fact that China's electricity production mainly relies on fossil fuels, resulting in a higher amount of GHG emissions.

The life cycle GHG emissions from PV power production with different battery banks was assessed and compared with the thermal storage option (see Figure 28). Resource recovery and the corresponding avoided GHG emissions were accounted for in formal recycling options of PbA battery and LFP but not in the case of formal recycling for NMC battery. According to the analysis, NMC batteries will cause the highest GHG emissions among the three battery types. Net GHG emissions in NMC batteries are likely to be slightly lower than the values in the table if the emissions avoidance via resource recovery is accounted for. The most significant GHG reduction can be achieved by using thermal storage instead of a battery, reducing emissions by 60%,59% and 60% compared to the use of PbA, LFP and NMC battery banks, respectively.

2.4.8 Potential emission savings from substituting virgin material use with recovered materials at the fridge's end-of-life

Mining and extracting abiotic resources such as the precious metals and fossil-based plastics used in the manufacturing of refrigerators contributes to significant GHG emissions. According to the mass balance, 50% of the fridge's mass consists of metals such as steel, aluminium and copper. The remaining 50% consists of different types of plastics and PCB. Significant GHG emissions are emitted from the virgin extraction of these metals and plastics. Total GHG emissions from the raw materials mined and the processing of materials required to manufacture and package a 65L SureChill fridge amounts to 128.8 kg CO_2-eq. The contribution

Figure 28: Life cycle GHG emissions from PV power production with different power storage modes with 20 years fridge lifespans



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[69] This is the total number of batteries required at a time to store power to operate 65L DC fridge

of the production of different types of virgin materials on GHG emissions at the manufacturing phase is presented in Figure 29. The highest GHG emissions are caused by steel, followed by plastics, PCB, aluminium, cardboard (used for packaging) and copper, see Figure 30. It was challenging to do a material specific assessment for PV panels because GHG emission estimates are aggregated across materials and presented on a per unit area basis in published literature.[70]

In contrast, recycling of electronic items, including refrigerators, could contribute to a significant amount of secondary resource extraction. Recently, waste electrical and electronic equipment (WEEE) has been recognised as a secondary source of various metals, including precious metals and other metals with limited supplies.[71] In addition, there is potential to recover sizable amounts of other materials including plastic. Recovered metals and other materials from appropriate recycling processes could be used to replace the production of virgin materials and metals leading to GHG emission savings in resource extraction. To help identify the emission savings potential of substituting virgin material production with recovered materials, values for material specific emissions from virgin production of each material and emissions from recycling an equivalent amount of material from an end-of-life refrigerator are presented in Figure 30. The virgin aluminium production process value chain shows the highest amount of GHG emissions. Recycling every bit of aluminium could contribute to significant emissions savings.

Manufacturing a 65L DC fridge from 100% virgin material would produce 128.8 kg CO_2-eq of emissions due the virgin material extraction. This value clearly demonstrates that recycling all types of metals and some plastics could contribute to significant GHG savings. Implementing an appropriate mechanism for the formal recycling of end of life refrigerators would maximize the amount of secondary resources that can be considered as secondary reserves.[72] GHG emissions from the recycling of polyurethane foam (PUR), epoxy resin, general purpose polystyrene (GPPS), and expanded polystyrene foam is not shown in Figure 30 since the recycling of those materials is not widespread due to structural changes that occur in these materials during the recycling process. However, these plastic fractions can potentially be used to generate energy through incineration.

Figure 29: Contribution of virgin material consumption for GHG emissions from the manufacturing of a 65L SureChill fridge

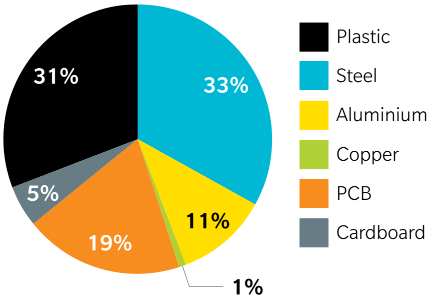
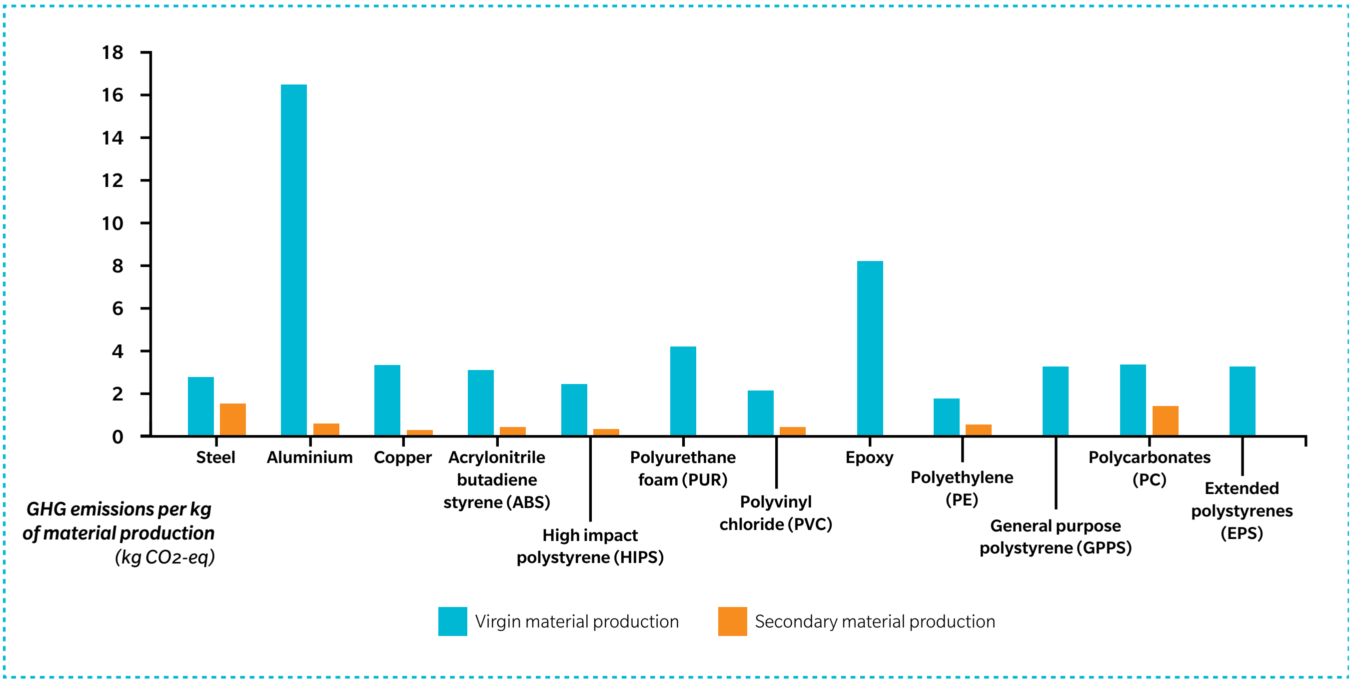


Figure 30: GHG emissions from the production of unit weight (1 kg) of materials from virgin processes and recovery from recycling



Note: the values used in this graph are from different literature sources, see Annex A (Table 15) for more details

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[70] Ecoinvent database (version 3.7)

[71] Van Yken. J., Boxall, N.J., Cheng, K.Y., Nikoloski, A.N., Moheimani, N.R. and Kaksonen, A.H. 2021. E-Waste Recycling and Resource Recovery: A Review on Technologies, Barriers and Enablers with a Focus on Oceania. Metals 2021, 11(8), 1313

[72] Materials that recuperate from end-of-life recycling can be used as secondary reserves to replace the virgin materials

GHG emissions in virgin material production and material recovery mainly arise from the use of fossil energy and grid electricity. Figure 30 indicates how much fossil fuel consumption-related emissions can be avoided from the material extraction processes if some of virgin material production was substituted with material recovery in recycling. The resource recovery rate of end-of-life refrigerators should be maximised at the level of the material recovery and smelting facilities. Emissions savings via resource recovery should be noted as one of the co-benefits from implementing appropriate recycling mechanisms. By avoiding dumping of end-of-life refrigerators at landfill sites, numerous other co-benefits, such as avoiding human toxicity arising from unsafe informal recycling processes, ecosystem toxicity and depletion of fossil resources, can be achieved. Quantification of these other co-benefits are outside the scope of this study.

2.4.9 Climate impact from using a SureChill refrigerator powered by different energy sources

The refrigeration model assessed in this study is an off-grid DC Solar Direct Drive 65L refrigerator. Given its long autonomy period with the built-in thermal storage, such a refrigerator can also be effectively used in weak-grid applications such that it derives its power from a utility grid source rather than a solar source. When neither solar PV nor grid electricity is available, fossil fuel back-up generators are the last resort. Nearly 9% of the electricity consumed in Sub-Saharan Africa and 2% in Asia is powered by fossil fuel back-up generators.[73] This scenario will compare the climate impact of using SureChill refrigerator powered by solar PV, Kenya grid or fossil fuel back-up generators during a 10-year lifespan with informal recycling as the end-of-life treatment method.

As the SureChill refrigerator runs on DC power, to use it with mains power or diesel back-up we would need an AC to DC adaptor. Given that the DC compressors are more expensive than their mass-produced AC counterparts, if the company was aiming for the AC market, an AC compressor would have been fitted instead of DC compressor and a converter. The authors have assumed the emission of an AC compressor is the same as a DC compressor for simplifying this analysis regarding different energy sources. The approximate electricity requirement for operating the SureChill fridge model would be 204Wh/day.[74] Based on this figure, the total energy consumption for the ten years of lifespan of the 65L fridge would be 744.6kWh.

GHG emissions factor for grid electricity production in Kenya is 0.603 kg CO$_2$-eq/kWh62. Based on these figures, total GHG emissions caused due to grid electricity consumption during the ten-year use phase of the fridge are 449 kg CO$_2$-eq. Small diesel back-up generators are the type of fossil fuel generators for this application. GHG emissions factors for small diesel back-up generator produced electricity is 0.807kg CO$_2$-eq/kWh[75] (see Annex A for details). Accordingly, total GHG emissions from running a small diesel back-up generator during the ten-year use phase of the fridge are 601 kg CO$_2$-eq. This calculation assumes that Kenya's grid emission factor and small diesel generator's emission factor will not change significantly over the next 10 years.

The total life cycle GHG emissions from an on-grid SureChill 65L fridge is 142 kg CO$_2$-eq, estimated by aggregating the emissions from different life cycle phases. It is assumed that the refrigerator will be informally recycled at end-of-life in keeping with Africa's low formal recycling capacity.

Figure 31: Comparison of SureChill 65L refrigerator model powered by different energy source

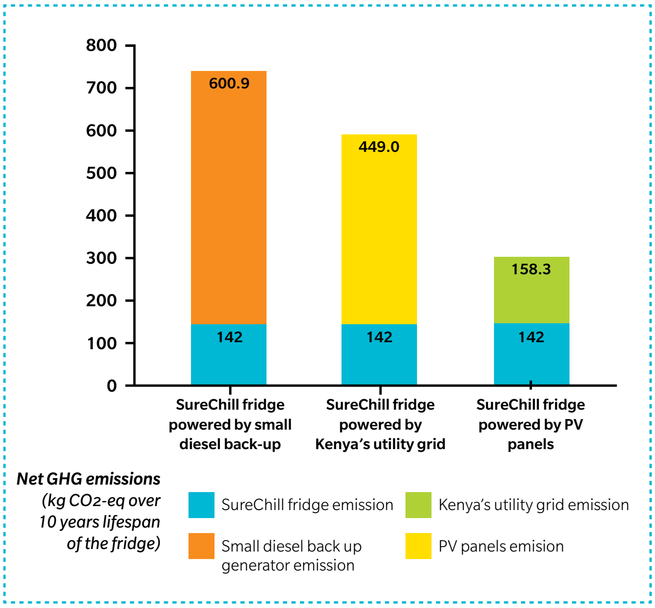

Figure 31 illustrates the impact of the different energy sources that are relevant to the overall emissions of the fridge. A comparative life cycle assessment of using it with solar PV vs. using it with a small diesel generator or utility grid revealed that running this fridge with solar PV will lead to a 60% or 49% GHG emissions reduction, respectively. This assessment demonstrates that refrigerators powered by solar PV could contribute to significant emissions savings compared to those powered by the grid or a diesel back-up generator. This is especially true for cases where the utility grid mix has a greater proportion of non-renewable sources of power.

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[73] International Finance Corporation. 2019. The Dirty Footprint of the Broken Grid: The Impacts of Fossil Fuel Back-up Generators in Developing Countries. International Finance Corporation. 2121 Pennsylvania Avenue, N.W. Washington, D.C. 20433: World Bank Group. https://www.ifc.org/wps/wcm/connect/industry_ext_content/ifc_external_corporate_site/financial+institutions/resources/dirty-footprint-of-broken-grid

[74] Personal communication with SureChill expert

[75] IFC, 2019. The Dirty Footprint of the Broken Grid. The Impacts of Fossil Fuel Back-up Generators in Developing Countries. Available in https://www.ifc.org/wps/wcm/connect/2cd3d83d-4f00-4d42-9bdc-4afdc2f5dbc7/20190919-Full-Report-The-Dirty-Footprint-of-the-Broken-Grid.pdf?MOD=AJPERES&CVID=mR9UpXC

2.4.10 Summary scenario table for the SureChill refrigerator

	VARIABLE ANALYSED IN EACH SCENARIO	**BRIEF DESCRIPTION OF ALTERNATE SCENARIO**	**CLIMATE IMPACT – 10 YEAR LIFESPAN (kg CO_2-eq)**					**% EMISSIONS CHANGE FROM CURRENT SCENARIO TO ALTERNATE SCENARIO**	**KEY TAKEAWAY**
			EMISSIONS FROM VARIABLE ANALYSED IN CURRENT SCENARIO	**EMISSIONS FROM VARIABLE ANALYSED IN ALTERNATE SCENARIO**	**TOTAL LIFE CYCLE EMISSIONS WITH CURRENT SCENARIO**	**TOTAL LIFE CYCLE EMISSIONS WITH ALTERNATE SCENARIO**	**NET CHANGE IN EMISSIONS**		
2.4.1	Refrigerant	Impact of using R134a instead of natural refrigerant (R600a)	0.1	107.9.0	300.5	408.3	107.8	**+36%**	Using R134a would increase the emissions of the fridge by 36% compared to the natural refrigerant used
2.4.2	Blowing agent	Impact of using HFC (HFC-245fa) instead of natural blowing agent (Cyclopentante)	16.8	501.4	300.5	785.2	484.7	**+161%**	Using HFC-245fa would increase the emissions of the fridge by 161% compared to the natural blowing agent used
2.4.3	Recycling PV	Impact of open dumping instead of recycling	-53.2	0.0	300.5	353.7	53.2	**+18%**	Any kind of recycling is better than no recycling. Our analysis finds small difference between informal and formal recycling as this is a pure GHG emissions analysis. If you were to include other aspects (e.g. black carbon, human health safety considerations) this would change
2.4.4	Recycling fridge	Impact of open dumping instead of recycling	-22.1	1.9	300.5	324.5	24.0	**+8%**	
2.4.6	Lifetime	Impact of extending lifespan to 20 years instead of 10	300.5	239.1	300.5	239.1	-61.4	**-20%**	Increasing the lifetime of the system reduces emissions per 10-year period. This is because as we are only replacing the parts of the system which require changing. For those components that can last a long time, you are maximising their lifetime
		Impact of extending lifespan to 30 years instead of 10	300.5	165.8	300.5	165.8	-134.7	**-45%**	
2.4.7	Batteries	Impact of using lead acid batteries instead of ice storage	0.0	233.5	239.1	472.6	233.5	**+98%**	Not using batteries saves significant emissions. Where possible use lithium-ion as this type produces fewer emissions
		Impact of using LFP batteries instead of ice storage	0.0	224.6	239.1	463.7	224.6	**+94%**	
		Impact of using NMC batteries instead of ice storage	0.0	241.5	239.1	480.6	241.5	**+101%**	
2.4.8	Non-virgin materials	Not for table since multiple scenarios exist. Refer to Section 2.4.8 for details.							
2.4.9	Different energy sources	Impact of using grid electricity instead of a solar system	158.3	449.0	300.5	591.2	290.7	**+97%**	The grid electricity factor is assumed to be Kenya grid electricity emission factor
		Impact of using diesel back-up generator instead of a solar system	158.3	600.9	300.5	743.1	442.6	**+147%**	

*For battery scenario analysis, the authors have used 20-year lifespan in the analysis and have scaled it down to 10-year lifetime for consistency in this table.

2.5 Brief summary of the LCA of the solar powered SureChill fridge

The concept of LCA was used as the basis for the carbon assessment and related climate impact from off-grid refrigeration technologies. The application of the LCA concept is beneficial to quantify the impacts from all the phases of the life cycle in a systematic approach. Life cycle GHG emissions for the PV power production unit (no battery included as SureChill fridge has built-in thermal storage) used in SureChill fridge is 373.3 kg CO_2-eq. 80% of these emissions are caused from manufacturing of PV panels, followed by the manufacturing of mounting system and cables, logistical movement, and end-of-life cycle recycling at the rate of 14%, 4%, 1%, and 1%, respectively. Material recovery from informal recycling helps save 56.7 kg CO_2-eq emissions. The resultant net life cycle GHG emissions from the PV power system used to power SureChill fridge amounts to 316.6 kg CO_2-eq over a 20 year lifespan. The estimated GHG emissions per unit of electricity production are 47g CO_2-eq/kWh over a 20 year lifespan. By extending the serviceable lifetime of the PV system to 30 years the emissions can be further reduced to 32 g CO_2-eq/kWh (a reduction of 32% compared to 20 years).

In addition, the climate impact from the SureChill 65L DC off-grid refrigeration model was assessed across different phases of the life cycle, namely raw material extraction, processing and manufacturing phase, transportation phase, in-use phase and end-of-life treatment phase. These calculations include the impact from PV power production and the manufacturing and use of the refrigerator. Considering all the emissions from different phases, the total life cycle GHG emissions from the 65L DC refrigerator would be 370.35 kg CO_2-eq which includes emissions from the PV power production required to operate the fridge for its 10 year lifespan. Resource recovery from informal recycling results in savings of emissions equivalent to 69.85 kg CO_2-eq. Therefore, net life cycle emissions amount to 300.50 kg CO_2-eq for a 65L DC fridge for a 10 year lifespan which includes the 50% emissions from PV power production from a 20 year lifespan PV system. With proper handling and maintenance, refrigerators' serviceable life could be extended to 20 years, even 30 years. That would contribute to a 20% and 45% emissions reduction respectively on an annual basis compared to emissions in fridge use over a 10-year lifespan.

As part of the research, a baseline scenario was developed to compare the effectiveness of the SureChill fridge to a less environmentally friendly technology with more commercially prevalent specifications. This baseline refrigerator is assumed to be a SureChill 65L DC domestic refrigerator powered by a PbA battery bank and uses the gases R134 as the refrigerant and HFC-245fa as the blowing agent. The estimated net life cycle emissions from the baseline fridge is 1,171.8 kg CO_2-eq, with the highest contribution from use of and leakage of blowing agent, HFC245fa, amounting to 37% of total life cycle emissions. Emissions from the PV power system including the PbA battery bank is responsible for 38% of total emissions. Manufacturing of the refrigerator accounts for a 12% of life cycle emission and logistical movement contributes 1%. 5% of life cycle GHG can be saved in the base case because of recovering resources from informal recycling at the end of the life cycle of the PV system and the refrigerator.

Emissions from baseline technology are 3.9 times higher than the emissions from the SureChill fridge. In other words, the SureChill 65L refrigerator model resulted in 74% lower life cycle emissions than the baseline case. This comparative assessment demonstrates how appropriate design for energy savings and choice of thermal storage, natural refrigerant and blowing agents could influence life cycle emissions.

The identification of emission hotspots across the fridge life cycle can help prioritise the interventions necessary for climate change mitigation. The comparative assessment between the SureChill and the baseline fridge revealed three crucial hotspots that contribute to the lion's share of life cycle emissions. These are the choice of refrigerant, blowing agent, and energy storage method. While emissions from use of PV panel resulted in 38% of total emissions in the baseline case, the authors do not consider this area for active intervention since use of PV panels provides significant savings from using alternative sources of power such as the Kenyan utility grid, see discussion in Section 2.4.9. As far as the choice of refrigerant goes, substituting R134a with natural refrigerants like R600a can reduce emissions by 99.9%. Similarly, use of natural blowing agents like cyclopentane can reduce emissions by 97% compared to use of HFC245fa as blowing agent.

Use of thermal storage instead of traditional battery storage significantly reduces emissions, with the thermal storage system in the SureChill case contributing to a 60% emissions reduction compared to the PbA battery storage system in the baseline case.

Implementing appropriate end-of-life disposal practices would contribute to significant emissions savings. Among the disposal options discussed, formal recycling with recovery of resources shows the highest mitigation potential. Although the emissions savings from informal recycling (where only metal fractions are recovered) show a similar emission saving result as formal recycling, the actual climate impact from informal recycling is expected to be much higher due to black carbon (BC) emissions from plastic burning. This study only considers impact from GHG and does not include BC emissions. We recommend that climate impact from this is included in future research.

Improving the serviceable life of the PV system and the refrigerator could considerably reduce GHG emissions. For instance, emissions reductions per unit electricity production (per kWh) for 20 years, years, and 30 years lifespans PV system are 49%, and 65% lower than the ten-year lifespan. Expanding the fridge's lifespan to 20 and 30 years reduces annual emissions by 20% and 45% compared to the 10 year lifespan fridge. In addition, extending refrigerators lifespans to 20 or 30 years could dramatically reduce the need for fossil energy/virgin resource consumption that would otherwise be required to manufacture new fridges to replace the old ones.

Comparative assessment of the climate impact of using the off-grid DC fridge in its native model and powered with small diesel generator, or utility grid revealed that running this fridge with solar PV in its native model will lead to 60% or 49% fewer

GHG emissions respectively. Furthermore, the raw material use during manufacturing analysis revealed that the highest GHG emissions are from steel, followed by plastics, PCB, aluminium, carboard (used for packaging) and copper. Virgin aluminum production process chain shows the highest emissions.
Thus, recycling every bit of aluminium would contribute to substantial emissions savings. Similarly, recycling all kinds of metals and some plastics would contribute to further reduction potential. Implementing an appropriate mechanism for formal recycling of end-of-life refrigerators would maximise the availability of secondary resources.

Analysis of GHG emissions from logistical movements revealed that only 1-2% of life cycle emissions occur from transportation, 2/3 of which are from international transport, and the remaining 1/3 from local transportation. Manufacturing items at the local level would lower the emissions from the logistical movements while creating other co-benefits for the society.

The findings of the study help demonstrate that use of technologies such as the SureChill refrigerator, can help minimise the carbon footprint of off-grid refrigeration. The quantification of mitigation benefits is expected to inform appropriate legislation and policies for developing a low carbon emission off- and weak-grid refrigeration sector.

Chapter 3:
Life cycle Emissions Assessment Cold Room - SelfChill

One of the key contributors to food crises in developing countries is the inability to preserve food surplus, and not low food production as is commonly perceived.[76]

Excess of fruits and vegetables produced during the rainy season go to waste due to the lack of appropriate preservation and storage, resulting in food loss rates of up to 50%.[77] Perishable produce requires cooling temperatures between 0°C and 15°C for safe storage and transport. In the absence of the right preservation technologies like cold storage, fruits and vegetables are highly susceptible to rapid quality degradation. Led by various country level national cooling action plans, many developing countries have started to strengthen their cold storage infrastructure. Implementing a green cold chain infrastructure can significantly enhance the mitigation impact by lowering the infrastructure's carbon footprint at the same time as eliminating the need for growing more food by reducing food wastage. To help inform a policy aimed at promoting a green off-grid cold rooms infrastructure, it is vital to do a life cycle emissions analysis of these technologies.

Chapter 3 and 4 aim to estimate GHG emissions over the life cycle of typical off-grid, solar-powered, walk-in cold rooms operational in rural Africa: SelfChill cold room in this chapter and ColdHubs in Chapter 4.

3.1 Life Cycle Assessment of Cold Room by Solar Cooling Engineering (SCE)

The SelfChill cold room approach was developed by Solar Cooling Engineering (SCE), a spinoff company from the University of Hohenheim, in collaboration with the German solar company Phaesun GmbH. SelfChill cold rooms are 100% solar-powered, use 100% natural refrigerants, and composed of modular cooling systems suitable to run with or without electrical batteries. SCE also provide technical support to local companies and entrepreneurs to manufacture or assemble their own solar-powered cold rooms, milk cooling systems and icemakers by facilitating access to key components.

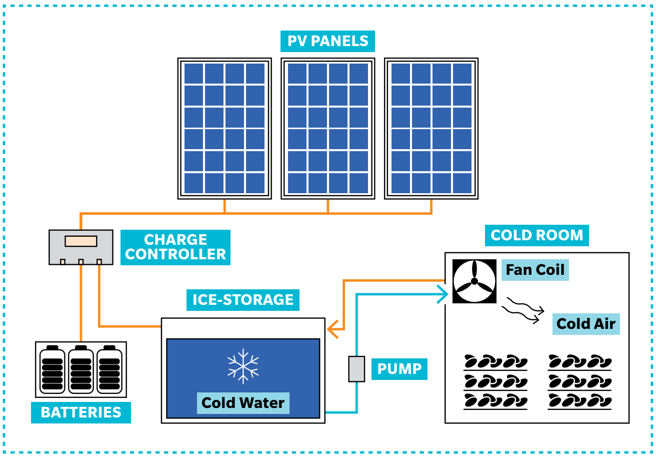
3.1.1 Solar Cooling Engineering (SCE) SelfChill Assembly Kit Cold Room 20m^3

The SelfChill 20m^3 cold room was selected as an appropriate candidate for the LCA assessment due to its thoughtful, environmentally friendly and modular design. The cold room is designed to function in any location in the absence of grid electricity and can remain cool for long periods of low solar radiation due to use of ice thermal storage. This type of cold room is particularly suitable for storing farm produce in off-grid locations as it is (a) 100% solar powered, (b) uses small scale compressors with 100% natural refrigerants like HC-600a or -HC290 with low global warming potentials, (c) is designed to operate with no or the most optimally sized electrical batteries and (d) is pay-as-you-go (PAYG) enabled, to help with end-user affordability.

The SelfChill 20m^3 cold room can cool and store agricultural products down to 6°C. The SelfChill concept utilises solar-powered cooling units integrated in a modular ice-storage (water chiller) system. During solar radiation hours, ice is generated by the cooling units and stored as an ice reservoir. This provides constant availability of cold water at around 2°C, which is circulated on demand by a water pump into the cold room. Here, a water-to-air heat exchanger (fan coil) generates cold air which maintains a constant set-point temperature. A schematic of the SelfChill cold room is shown in Figure 33, with actual components shown in Figure 32. The standard SelfChill unit can be directly connected to a 12V PV Panel or, where electrical batteries are used, to a 12V or 24V charge controller.

The SelfChill solar cooling unit is a hermetically sealed cooling device that works as a vapour-compression refrigeration machine. Six cooling units filled with refrigerant (HC-600a) are used in the standard model and consist of a compressor, condenser, evaporator plate, temperature sensors and control unit.[78] The copper tube between the evaporator plate and condensing unit is flexible to adapt to the size of the ice storage system. SelfChill electronics control the operation of the water chiller, and therefore the internal temperature, by varying the speed of each compressor depending on the solar radiation and battery state of charge.

Figure 32: SelfChill approach 20m^3 cold room



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[76] Wandra,R., Hussain,T., Soy,A., Mishra, S. and Yadav.R. 2014. Application and Effectiveness of Low Cost Solar Cabinet Dryer: Experimental Investigation. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE). PP 41-44 www.iosrjournals

[77] Nantambi, H. and Namazzi, S. 2019. Design and test of an affordable Cold Room powered by solar for improving storage quality and reducing wastage of horticulture produce. Ecolife Food. Available in http://www.postharvest.org/EcoLife_Cold_Room_Innovation.pdf

[78] University of Hohenheim, 2019. DIY Solar Cooling. Available in 2019-03-08-DIY-solar-cooling-Manual-University-of-Hohenheim.pdf (energypedia.info)

Figure 33: SelfChill system from left to right: a) SelfChill solar cooling unit, b) Ice-storage water chiller) c) SelfChill solar cold room

SelfChill system from left to right: a) SelfChill solar cooling unit, b) Ice-storage water chiller) c) SelfChill solar cold room

3.1.2 Methodology of life cycle carbon assessment of SelfChill cold room 20m^3

The life cycle of solar power production and the off-grid cold room is divided into different phases: production (including raw material extraction, parts production, and assembly), transportation, use, and end-of-life disposal. According to the information provided by SelfChill, the average lifetime of the cold room is 20 years and could extend to 30 years with careful handling and maintenance. The warranty period of solar PV system is 25 years and that can be extended up to 30 years with proper maintenance.[79] The battery system is replaced on average every 7 years. Emissions from transporting the PV panels and other components of the cold room were calculated from the manufacturing country to the project location in Kenya. Life cycle inputs (electricity, thermal energy, raw materials) and outputs (emissions, recovered resources) were gathered for each component in this cooling technology. The system boundary of the SelfChill approach 20m^3 cold room is shown in Figure 6.

Emissions estimation from the SelfChill cold room considers the entire life cycle for three different lifespans: 20, 25 and 30 years. The functional unit for the assessment was defined as kg of CO_2-eq emissions from the 20m^3 cold room across its entire lifespan. For the purpose of comparison with other cold room technologies, the common functional unit considered is 'kg CO_2-eq emissions per unit of cooling energy' as discussed in Section 1.7.

3.1.3 Life cycle inventory of PV power production system

A detailed questionnaire was prepared for the SelfChill 20m^3 cold room that considered the different life cycle phases. The questionnaire was shared with the SelfChill experts to gather primary data. To supplement the primary data and fill missing gaps, we used the Ecoinvent database (version 3.7) and published sources such as peer-reviewed papers as secondary data sources to extract the remaining data required for the assessment. A basic set of specifications of each component of the power system is described below.

Solar panels: six mono-crystalline panels, each with a capacity of 350 Wp, power the SelfChill 20m^3 cold room. A single panel's total mass is 24 kg with the frame. Solar PV panels are fitted with an anodized aluminium frame. The warranty period of PV panels is 25 years. The detailed specifications of the solar panels are summarised in Annex B-1.1.

Mounting structures and cable: an above the roof mounting system is used to support the panels. The total mass of the supporting structures amounts to 2 kg per panel, made from 100% aluminium. The total mass of the solar array cable is 3.96 kg, and the cable is 30% plastic and 70% copper. The expected lifetime is assumed to be 25 years – similar to the solar panels.

Charge controller: three maximum power point tracker (MPPT) charge controllers are used in the PV power production system to manage the charging and discharging of the battery bank. The capacity of each charge controller is 580W, and the expected lifetime is 20 years. The mass of each charge controller is 0.65 kg.

Battery bank: there are six absorbent glass mat (AGM) 120 Ah, 12V lead acid batteries that store excess energy and power the equipment when there is no solar radiation. The weight of each battery is 30.6 kg, and the maximum depth of discharge (MDOD) is 40%. An average lifetime of seven years was assumed for this project.

Detailed information on the LCI of each component is presented in Annex B-1.1.

3.1.4 Life Cycle Inventory (LCI) of the SelfChill cold room

GHG emissions from the cooling system, waste chiller and the cold room itself are estimated for the SelfChill 20m^3 cold room.

Cooling system: six cooling units are used in the standard SelfChill 20m^3 cold room. Each one weighs 10 kg and consists of a compressor, a condenser, evaporator plates, pipes and a fan. The refrigerant used in the cooling system is HC-600a which has very low global warming potential (4 kg CO_2-eq/kg). The amount of refrigerant required in each cooling system is 35 g with 210 g required for all six in order to avoid refrigerant leakage from the cooling system. In the use phase, capillary tubes have been fixed instead of expansion valves. However, it was assumed that 1% refrigerant would leak during the use phase due to unavoidable

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[79] This is based on an interview with an expert from SelfChill

accidental leakages and would need to be topped-up. The expected lifetime for the cooling system is 10 years.

Water chiller: The SelfChill cold room uses a water chiller (including ice-storage) to generate cold water which is pumped to a heat exchanger (fan coil) to introduce cold air into the cold room and maintain the set point temperature. The water chiller is constructed from a 500L polyethylene box and pellet. The box is covered with 100% closed-cell elastomeric foam insulation. The mass balance and material composition of the water chiller are presented in Annex B-1.2. The expected lifetime for the water chiller is 20 years.

Cold room: The dimensions of the SelfChill cold room are 3.00m × 3.00m × 2.16m, and the expected lifespan is 20 years. The cold room consists of PU foam panels, cables and a heat exchanger. The walls of the cold room are constructed from 18 panels totaling 596 kg with another 25 kg of panels used for the door. Each panel consists of a polyurethane foam core with a 1mm thick galvanized steel layer on each side to provide structural stability and protection for the foam. Each panel's dimensions are 1.9m × 0.9m × 80mm. The cables and heat exchanger have a lifespan of 10 years, therefore it would need two sets during the 20 year lifespan of cold room. The detailed specification of the cold room, including the components and their mass balance, is summarised in Annex B-1.2. The estimated masses of galvanized steel, polyurethane foam and aluminum used to construct the 20m^3 cold room weighs 510 kg, 117 kg and 10 kg, respectively.

3.1.5 Life cycle GHG emission estimations from SelfChill 20m^3 cold room

Life cycle GHG emissions from this case study include emissions from both PV power production and the cold room. Life cycle stages of PV power production in the SelfChill case study include production of raw materials, manufacture of components, transport to the operating site, use phase and end-of-life management/disposal. The life cycle emissions (kg of CO2-eq) are calculated as follows:

Net life cycle GHG emissions from PV power production =
GHG emissions from PV panel manufacturing +
GHG emissions from manufacturing mounting structures +
GHG emissions from manufacturing electric installations (cables and charge controllers) +
GHG emissions from the manufacturing of batteries +
GHG emissions from transportation +
GHG emissions from end-of-life management –
GHG emissions avoidance from resource recovery at end-of-life

The life cycle stages in the cold room include raw materials extraction, manufacturing the cooling system, water chiller and cold room, transport to the operating site, use phase and end-of-life management/disposal phase. The life cycle emissions (kg of CO2-eq) are calculated as follows:

Net life cycle GHG emissions from the cold room =
GHG emissions from manufacturing of cooling system +
GHG emissions from manufacturing of water chiller +
GHG emissions from manufacturing the cold room –
GHG emissions avoidance from resource recovery at end-of-life

The total GHG emissions for the SelfChill cold room can be estimated by combining the emissions from PV power production and the cooling system.

Net GHG emissions from SelfChill 20m^3 cold room =
Net life cycle emissions from PV power production +
Net life cycle emissions from the cold room

3.1.6 GHG emissions from the raw material extraction and manufacturing of components in PV power production

Manufacturing of 350 Wp x6 solar panels: The Ecoinvent database (version 3.7) is used to gather the energy and emissions data related to raw material extraction and manufacturing of the panels. A detailed estimation of this process is summarised in Annex B-1.1. The net GHG emissions per m^2 of monocrystalline panel production is 260.7 kg CO2-eq. Therefore, the GHG emissions from the six 350Wp panels used in this case study are 3035.1 kg CO2-eq.

Manufacturing of mounting structure: The SelfChill cold room currently uses a basic mounting system. In this study, we have used the Ecoinvent database 3.7 to find emissions related to a properly designed and commonly used mounting system installed on a roof. For this purpose, a PV panel mounting system for a flat-roof installation in Europe is considered. The GHG emissions from the supporting structures for six 1.940m^2 panels amounted to 494.6 kg CO2-eq. It should be noted that 95% of the mass is aluminium, and the aluminium production process would be the major contributor to GHG emissions. Detailed results are presented in Annex B-1.1.

Manufacturing of solar array cables: Solar array cable with a mass of 3.96 kg has been used to connect solar panels to the charge controller/battery bank. The cable is composed of 70% copper and 30% plastic. Ecoinvent LCI of cable production with similar material composition cable was used to estimate the GHG emissions. The estimated GHG emissions from the production of 3.96 kg of solar array cable are 26.4 kg CO2-eq. Detailed calculations are presented in Annex B-1.1.

Manufacturing of charge controller: There is no data available on the LCI of the remote controller or charge controller. Therefore, Ecoinvent LCI of the inverter (500W) was extrapolated to quantify the manufacturing emissions from the 580W charge controller as we expect them to have a similar material composition. Extrapolated data indicated that GHG emission from material extraction and manufacturing of a single 580W charge controller is 43.3 kg CO2-eq. Emissions from the manufacture of three charge controllers amounts to 129.9 kg CO2-eq.

Manufacturing of AGM lead acid battery bank: 120 Ah sized six AGM lead acid batteries are used to power a cold room in the night and on rainy days. The lifetime of these batteries is assumed to be seven years. GHG emissions from the manufacturing of lead acid batteries were quantified based on an LCA study done by Spanos et al.[47] and the detailed LCI is presented in Annex B-1.1. The estimated GHG emissions from raw material extraction required to produce PbA battery is 1.22 kg CO_2-eq/kg. The energy consumption for manufacturing of the PbA battery would lead to 0.68 kg CO_2-eq/kg emissions. In total, estimated GHG emissions from the manufacture of 1 kg of PbA battery amounts to 1.90 kg CO_2-eq. The average mass of the PbA battery is 30.6 kg. Emissions from manufacturing one battery is 58.25 kg CO_2-eq, and from the PbA battery bank with six batteries is 349.49 kg CO_2-eq. Batteries need to be replaced three times within 20 years lifespan of the project and total GHG emissions from manufacturing of batteries would be 1048.48 kg CO_2-eq.

Total GHG emissions from manufacturing of items required to produce PV power for 20 years lifespan cold room is 4734.5 kg CO_2-eq, see Table 14.

Table 14: GHG emissions from material extraction and manufacturing of PV system

ITEMS	AMOUNT	GHG EMISSIONS (kg CO_2-eq)
PV panels	350Wp ×6	3035.1
Mounting structures	2kg	494.6
Solar array cable	3.96kg	26.4
Charge controller	580 W ×3	129.9
PbA battery bank	6 batteries ×3 replacement	1048.5
TOTAL GHG EMISSIONS		**4734.5**

3.1.7 GHG emissions from the raw material extraction and manufacturing of components in the SelfChill 20m³ cold room

Manufacturing of the cooling units: there are six cooling units used in the SelfChill cold room. The mass balance and material composition of the cooling systems used in 20m³ cold rooms are presented in Annex B-1.2. The estimated GHG emissions from the manufacture of each component is shown in Table 15. Total emissions from a cooling system are 64.68 kg CO_2-eq (see Table 15). The manufacturing of the six cooling units used in the cold room would emit 388.07 kg CO_2-eq. Emissions for the refrigerant used in the cooling units are accounted for in the use-phase.

Table 15: GHG emissions from material extraction and manufacturing of cooling systems

THE MAJOR COMPONENT OF THE COOLING SYSTEM	APPROXIMATE MASS (kg)	ESTIMATED GHG EMISSIONS (kg CO_2-eq)
Compressor	6.00	25.16
Evaporator plate	1.00	16.51
Condenser	1.00	16.51
Pipes	1.00	3.35
Fan – 24V - 120mm × 120mm - 5W	0.20	3.15
TOTAL MASS	**9.20**	**64.68**
Number of the cooling unit used in the cold room		6
GHG emissions from 6 cooling units – kg CO2-eq		388.07

Note: The above table provides estimates for 6 cooling units. Assuming a replacement period of 10 years, for a 20 year cold room span, we would double the emission estimates.

Manufacturing of the water chiller: the GHG emissions from various water chiller components were assessed using the mass balance and the material composition of the different parts. The GHG emissions from extracting the raw materials required to produce different components of the water chiller are 176.29 kg CO_2-eq. The GHG emissions from fossil fuel consumption for manufacturing and injection molding of the elements of the water chiller is 73.84 kg CO_2-eq. Altogether, the total GHG emissions from raw material extraction and manufacturing of water chiller is 244.16 kg CO_2-eq.

Manufacturing of the cold room cell: climate impact from individual components used in the cold room are assessed using the material composition of the cold room cell, door, cable, heat exchanger etc.[80] GHG emissions from the use of steel and polyurethane foam for the cold room cell amounts to 1,415 and 494 kg CO_2-eq, respectively. The total climate impact from the materials extraction and construction of the cold room cell, cables and heat exchanger is 2290.76 kg CO_2-eq (see Table 16), in which 83% of the emissions result from the cold room cell and door, and the remaining emissions from the heat exchanger (16%) and cables (1%). Emissions from manufacturing of the blowing agent used in the polyurethane foam is included with manufacturing emissions of PU foam

Table 16: GHG emissions from material extraction and manufacturing of cold room

ITEM IN THE COLD ROOM	MATERIALS MASS (kg)	CLIMATE IMPACT FROM MATERIAL EXTRACTION AND MANUFACTURING OF COLD ROOM (kg CO_2-eq)
Cold cell	596	1831.86
Door	25	76.84
Cables ×2	2×2	26.66
Heat exchanger ×2	16×2	355.40
TOTAL CLIMATE IMPACT		**2290.76**

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[80] The cold room cell is defined as the wall structure constructed from the polyurethane panels with galvanized steel facing material

3.1.8 GHG emissions from transportation

The GHG emissions from transportation of all the components used in the cold room are estimated based on the mode of transportation and distance from the manufacturing location to the project location in Kenya. The exact location of the manufacturing companies of each item is not known and therefore, transportation distance was estimated from the manufacturing country's capital city to the project location in Nairobi, Kenya. The EcotransIT World tool, a publicly available online calculator is used to estimate transport emissions.[17] Total emissions estimation from logistics of materials for PV power production and the cold room is shown in Table 17. Total GHG emissions from the logistical movement of items needed for PV power production and manufacturing the cold room is 206.65 kg CO_2-eq for the 20-year cold room lifespan. If the cold room lifespan is extended to 25 years or 30 years, GHG emissions from logistics would increase to 224.62 kg CO_2-eq and 242.32 kg CO_2-eq, respectively. In these extended lifetime cases, additional emissions are incurred for procuring replacement parts such as battery units, items in the water chillers and compressors. Material logistics contributes an estimated 2.0% of life cycle emissions for the SelfChill cold room over a 20-year life period. Transport emissions depend on transportation mode type, fuel used, fuel consumption efficiency, transportation routes, etc. In the SelfChill case study, sea transport by ships caused the highest emissions compared to ground transport by trucks. Although emissions from material logistics are not significant compared to other phases of the life cycle, it is worth identifying potential pathways of reducing emissions from transportation. Manufacturing these items locally in Kenya would lower the emissions from the logistical activities while creating other co-benefits for the Kenyan economy.

Table 17: GHG emissions from the logistical movement of parts required for the PV system and the cold room

ITEM	MANUFACTURING COUNTRY	TOTAL MASS OF COMPONENTS REQUIRED FOR A 20 YEAR LIFESPAN (kg)	TOTAL TRANSPORTATION DISTANCE (km)	GHG EMISSIONS (kg CO_2-eq / kg)	TOTAL GHG EMISSIONS FROM EACH COMPONENT (kg CO_2-eq)
PV panel	Italy	144	8,424.37km	0.110	15.840
Mounting structures and cables	Germany	5.96	12,933.53km	0.146	0.870
Charge controller	India	1.95	6,074.14km	0.139	0.271
Batteries	China	183.6×3a	13,220.87km	0.141	77.663
Construction materials for the cold room	Germany	637	12,933.53km	0.146	93.002
Water chiller (ice storage)	Germany	80.2	12,933.53km	0.146	11.709
Refrigeration system	-	-	-	-	-
Variable speed compressor	China	6 x 2a	13,220.87km	0.141	1.692
Other items of cooling system + heat exchanger	Germany	19.2×2a	12,933.53km	0.146	5.606
TOTAL GHG EMISSIONS (kg CO_2-eq)					**206.654**

(a: Number of times replacement is required within a 20 year lifespan)

3.1.9 GHG emissions from the use phase of the cold room

GHG emissions from the use phase of a cold room are mainly caused due to emissions of any leakage of the refrigerant and blowing agent.

There are hardly any emissions in the use phase emerging from energy consumption. Because this system was explicitly designed for off-grid applications, in this study, all of the PV power production emissions were allocated to the manufacturing phase and end-of-life phase. This is a logical assumption as all emissions for this off-grid system are embedded.

There is direct climate impact from any leakage of gases such as refrigerants and blowing agents during the use phase. SelfChill cold room uses HC-600a (Iso-Butane- GWP -3) as the refrigerant and HC-601(N-pentane) (GWP-5) as the blowing agent, both with very low global warming potentials. This system is hermetically sealed so should not leak any refrigerant. However, in around one in a hundred systems, there is a catastrophic leakage of refrigerant where it all leaks out. Therefore, an average leakage rate of 1% has been assumed amounting to 0.0042 kg of refrigerant, which contributes to GHG emissions of 0.013 kgCO_2-eq.

Any leakage in blowing agent from the polyurethane panels during use phase also has a climate impact. The estimated mass of the polyurethane foam in the panels used in the cold room is 117.48 kg (11.5 kg by mass of the foam is comprised of blowing agent). Approximately 5% of blowing agent is assumed to be emitted in the first year, followed by a leakage at the rate of 0.5% per year.[81] Based on these figures, the total blowing agent leakage within a 20-year lifespan is 1.569 kg. The global warming potential of the blowing agent HC-601(N-pentane) is 5 kg CO_2-eq/kg. Therefore, total GHG emissions from the use phase of the SelfChill cold room would amount to 7.859 kg CO_2-eq.

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[81] EPA, 2015. Determination of comparative HCFC and HFC emission profiles for the foam and refrigeration sectors until 2015. Available in https://www.epa.gov/sites/production/files/2015-08/documents/foamemissionprofiles_part2.pdf

3.1.10 GHG emissions from end-of-life management/disposal

Informal recycling is assumed to be the current approach of end-of-life disposal practice in Kenya. ShelfChill 20m^3 cold room has been designed for 20 years lifespan. Therefore, it was assumed that after 20 years, both the PV power production system and the cold room would need replacing. With proper maintenance, there is a possibility of extending the lifespan of both the PV system and the cold room. Therefore, two extended lifetime scenarios (25 years and 30 years lifespans) have also been assessed as part of various scenario analyses. This part of the assessment summarises emissions from the end of the life of the PV system and the cold room after a 20 year lifespan under an informal recycling mechanism.

GHG emissions from the informal recycling of PV power production system: in this scenario, valuable materials such as steel, aluminum, copper and lead from the PV panels, supporting structures and solar array cables, and lead acid batteries, are assumed to be extracted by the informal recyclers. Emissions caused by plastic burning to extract the copper from copper wire and lead from PbA batteries have been accounted for under recycling emissions. The extracted valuable materials would be sold to the local agents in the area. Those materials are then sent to the smelting facilities to recover the materials. Material recovered from the end-of-life can be used as a secondary resource. Therefore, avoided emissions from an equivalent amount of material production through virgin production process chain has been credited. As a result, net emission values show a negative magnitude for PV panels, mounting systems and cables, indicating that informal recycling would contribute to GHG savings (see Table 18).

Charge controllers are small items (0.65 kg mass) consisting predominantly of plastic and a circuit board of low value. Therefore, emissions from recycling controllers are considered to be zero since informal recyclers do not recycle less valuable items in isolation (see Table 18).

Recycling lead acid batteries is a common practice in informal recycling as lead is a precious metal. In the lead acid battery manufacturing process, 70% of the lead used for the batteries is recycled, whereas 30% is made from new raw materials.[47] Thus, only 30% of recovered lead at the end of the life cycle is credited for avoiding the virgin lead production. Therefore, in the case of PbA batteries, emissions from informal recycling of PbA batteries show a slightly lower GHG savings potential through resource recovery. Recovering the maximum amount of lead from end-of-life batteries would contribute to significant virgin resource savings.

Net GHG emissions from an end-of-life PV power production system, was estimated by aggregating the net emissions from informal recycling of the individual components and amounts to -458.412 kg CO_2-eq.

GHG emissions from informal recycling of end-of-life 20m^3 SelfChill cold room: GHG emissions and avoidance potential from the informal recycling of items in the 20m^3 cold room were assessed and these values are presented in Table 19. There are six cooling units in the cold room, and the lifespan is ten years. Therefore, two sets of cooling units are needed within a 20 year lifespans. Informal recyclers would extract valuable metals like steel and aluminium from the compressor, evaporator plate and condenser. Net GHG emissions from end-of-life cooling units amount to -556.30 kg CO_2-eq. The resulting negative value indicates GHG savings potential.

A significant proportion of the mass of the water chiller is plastic, which does not have a big monetary value. Informal recyclers are only expected to collect the steel fraction from the supporting structure of the water chiller. Therefore, net GHG emissions from the recycling of the waste chiller indicates a relatively low value amounting to -9.79 kg CO_2-eq.

The cold room consists of polyurethane panels, cables and a heat exchanger. Informal collectors would extract the steel portions from the insulation panels, copper from cables and steel and aluminium parts from the heat exchanger. Estimated emissions savings from the end-of-life recycling of panels, cables and heat exchangers are -514.96, -5.87 and -274.83 kg CO_2-eq, respectively.

It is expected that the refrigerant and the blowing agent will leak into the atmosphere during the dismantling of the cold room at the end of its life. The estimated climate impact from the release of refrigerant and blowing agents amounts to 1.26 kg CO_2 -eq. and 49.72 kg CO_2-eq. Their GHG emission values are relatively low as a result of using natural refrigerant and blowing agents in the SelfChill cold room.

Net GHG emissions are estimated by aggregating all the possible emissions savings shown in Table 19. These amount to a total of 1310.775 kg CO_2-eq emissions that can be saved via resource recovery and avoided primary production for a 20m^3 cold room.

Table 18: Net GHG emissions from informal recycling of PV power production system

ITEMS	**NUMBER OF COMPONENTS REQUIRED FOR A PV SYSTEM WITH A 20 YEAR LIFESPAN**	**MATERIALS COLLECTED BY THE INFORMAL RECYCLERS**	**A) GHG EMISSIONS FROM RECYCLING** (kg CO_2-eq)	**B) EMISSIONS AVOIDANCE POTENTIAL FROM RESOURCE RECOVERY** (kg CO_2-eq)	**C) NET GHG EMISSIONS** (kg CO_2-eq) (C)=(A)+(B)
PV panels	350Wp ×6	Aluminium frame	5.488	-154.082	-148.594
Mounting structures	1.9403m^2 ×6	Metal (aluminium structures)	23.059	-323.723	-300.665
Solar array cable	3.96 kg	Copper cable	3.674	-9.589	-5.915
Charge controller	580 W ×3	No value in informal recycling	0.000	0.000	0.000
PbA battery bank	6 batteries ×3 replacement	Lead component	229.479	-232.717	-3.238
NET GHG EMISSIONS					**-458.412**

Table 19: Net GHG emissions from informal recycling of 20m^3 cold room

ITEMS	NUMBER OF COMPONENTS REQUIRED DURING A 20 YEAR LIFESPAN	TYPE OF MATERIAL RECYCLED BY INFORMAL COLLECTORS	GHG EMISSIONS FROM RECYCLING (kg CO2-eq)	EMISSIONS AVOIDANCE POTENTIAL FROM RESOURCE RECOVERY (kg CO2-eq)	NET GHG EMISSIONS (kg CO2-eq)
6 cooling units	6 Compressor ×2*	Aluminium and steel from the compressor; Aluminium from evaporator plates and condenser	113.760	-670.061	-556.301
	6 Evaporator plates ×2				
	6 Condenser ×2				
	6 pipes ×2				
Water chiller	PE box, PE cover, PE pellets	Aluminium from supporting structure	11.705	-21.497	-9.792
	Thermal insulation foam				
	Supporting structure				
Cold room	1.9m ×0.9m-18 panels	Steel from panels	615.534	-1130.490	-514.956
	25kg door				
	Cable ×2	Copper from cables	3.814	-9.686	-5.872
	Heat exchanger ×2	Steel and aluminium from the heat exchanger	26.809	-301.643	-274.834
	Refrigerant	Emission of refrigerant	1.26		1.26
	Blowing agent	Emissions of blow	49.721		49.721
TOTAL NET EMISSIONS					**-1310.775**

* Multiplication by 2 indicates two set is required within a 20 year lifespans

Total GHG emissions/savings potential from end-of-life disposal

The total GHG emissions/savings potential from the end-of-life disposal phase was estimated by aggregating the GHG emissions from the end-of-life PV power production and the cold room under informal recycling. The estimated net GHG emissions from the end-of-life management SelfChill cold room are -1769.187 kg CO2-eq (see Figure 34). The resulting net negative value indicates that the informal recycling process contributes significantly to GHG savings via resource recovery.

3.1.11 Net life cycle GHG emissions from SelfChill 20m^3 cold room (PV power production + cold room)

Using the results from Chapter 3.1.10, net life cycle emissions from individual items used in the PV power production system and SelfChill 20m^3 cold room across their life stages are presented in Figure 35. The highest emissions are associated with use of PV panels followed by the cold room structure itself and lead acid battery bank. It should be noted that if the SelfChill cold room is compared to a more common cold room technology that is not as carbon friendly, the emission hotspots will be concentrated differently. For example, the emissions related to the use of fluorinated gases and use of larger sized battery banks would be much larger. These scenarios are discussed in Chapter 3.2.11.

Figure 34: Net GHG emissions avoidance potential from resource recovery at end-of-life after accounting for emissions in informal recycling for both PV system and cold room

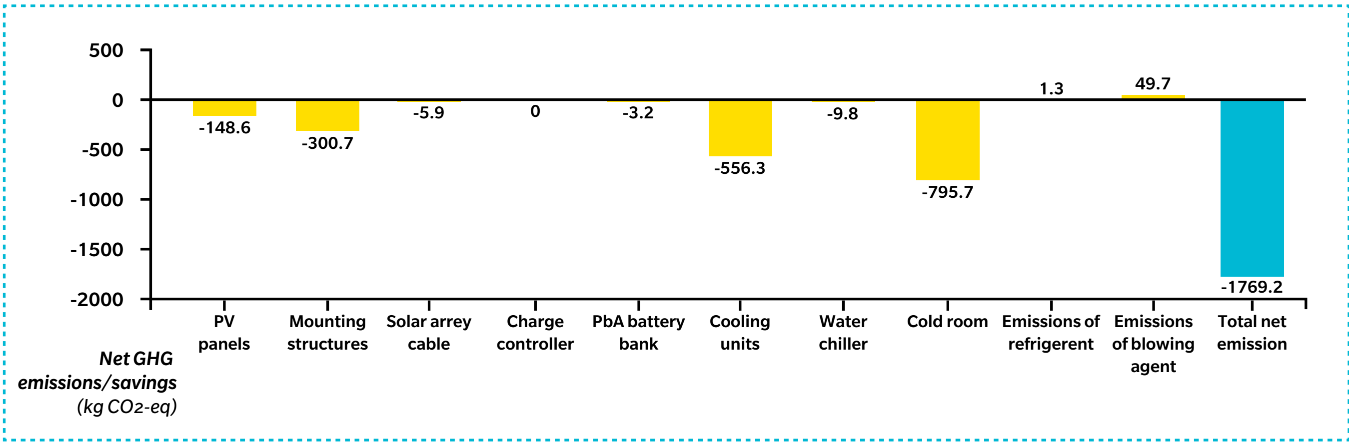
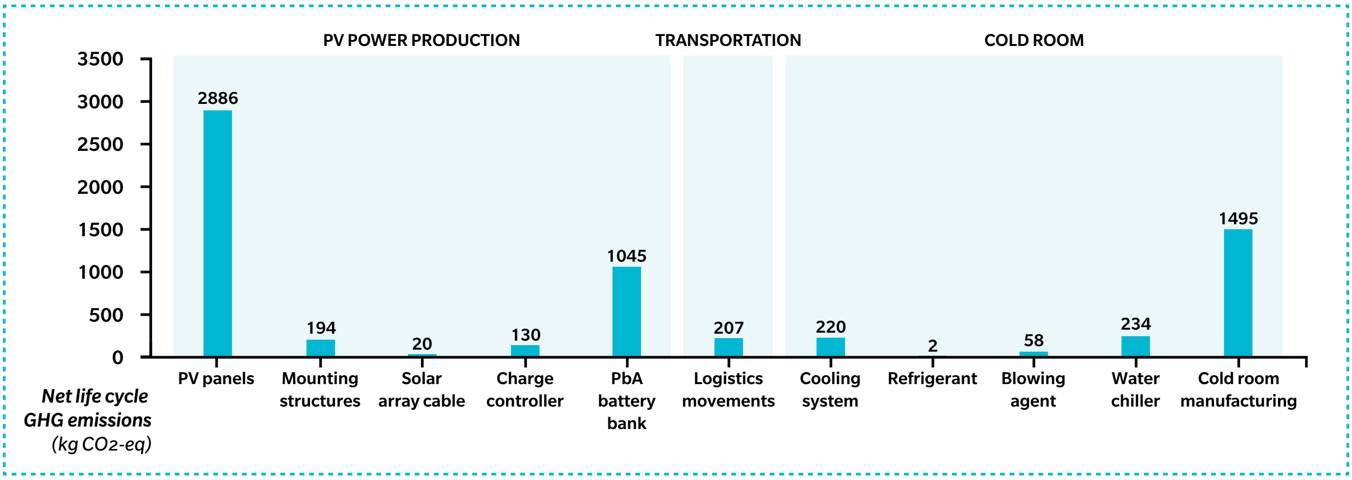


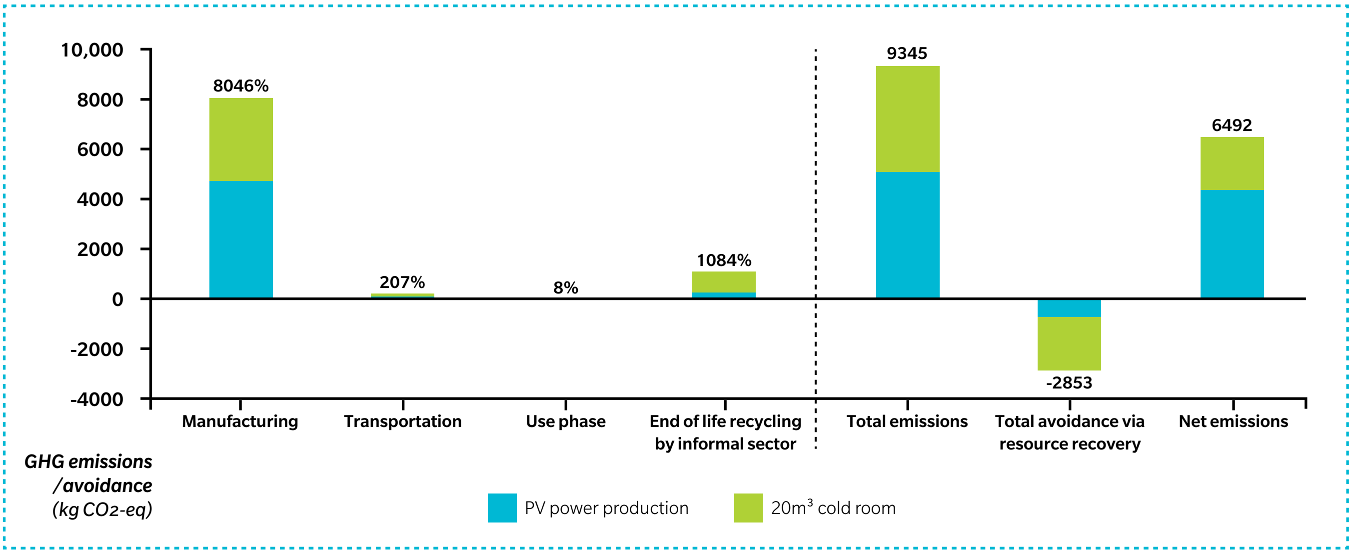
Figure 35: Life cycle GHG emissions across individual components for the 20m^3 SelfChill cold room assuming a 20-year lifespan



Net life cycle GHG emissions are estimated by aggregating the emissions from different life cycle phases, see Figure 36. The raw material extraction, processing, and manufacturing of the PV system and cold room results in emissions of 8,046 kg CO2-eq, represent 86.1% of life cycle GHG emissions without resource recovery. 4734 kg CO2-eq of these emissions are related to material extraction and manufacturing emissions from the PV system, and the remaining 3312 kg CO2-eq is associated with the cold room. GHG emissions from transportation contributed 207 kg CO2-eq (2.2% of life cycle emissions without resource recovery) and emissions from the 20-year use phase of the cold room (caused by leakage of the blowing agent) contributed only 0.1% of life cycle GHG emissions. The remaining 11.6% of GHG emissions (1,084 kg CO2-eq) result from informal recycling activities at the end-of-life. Considering all these emissions, the total life cycle emissions without resource recovery of the SelfChill cold room would be 9,345 kg CO2-eq. As a result of resource recovery from end-of-life cycle recycling by informal recyclers, there is a possibility for the avoidance of emissions up to -2,853 kg CO2-eq. Therefore, the overall net life cycle GHG emissions are estimated at 6,492 kg CO2-eq for a 20-year lifespan (see Figure 36).

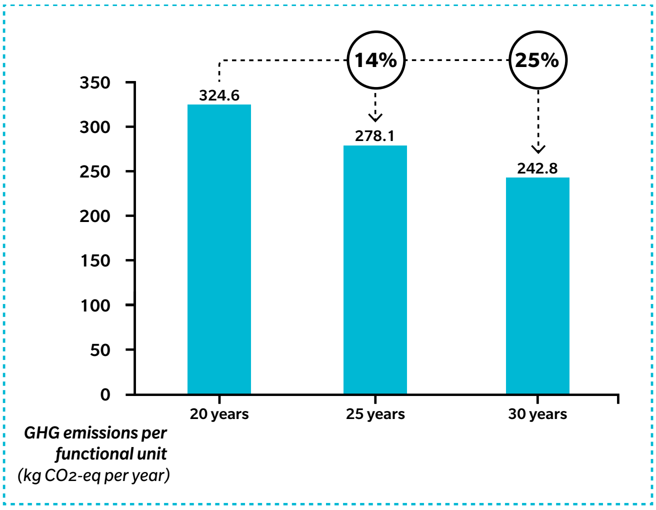
The PV system and SelfChill 20m^3 cold room could be used for more than 20 years with careful management. We have also estimated emissions over a 25-year and a 30-year lifespan using the approach highlighted in the sections above. For the 25-year lifespan, the number of batteries after factoring in replacements will increase from 18 to 21, and to 24 for a 30-year lifespan. Other components such as cooling systems and water chillers would require replacement as well. The estimated net life cycle emissions over 25-year and 30-year lifespans of the SelfChill cold room are 6,953 kg CO2-eq and 7,284 kg CO2-eq, respectively. It should be noted that more items need to be replaced (e.g. charge controller, water chiller) at the end of a 20 year lifespan and only a few items need to be replaced at the end of the 25 year lifespan. Therefore, a bigger difference of net emission values can be noticed between 20-25 years, compared to the 25-30 year lifespan. Emissions with respect to different life cycle phases of 25- and 30-year lifespans are presented in Annex B-1.3. In conclusion, life cycle emissions from the SelfChill 20m^3 cold room are estimated to be between 6,492 and 7,284 kg CO2-eq for a lifespan between 20-30 years.

Figure 36: Total GHG emissions from 20m^3 SelfChill cold room over a 20-year lifespan



Cold rooms have an especially powerful climate positive effect by reducing agricultural produce wastage. For a complete analysis of life cycle emissions, the authors also take into account the avoided emissions from reduced food waste in Chapter 5.2. As the lifespan of the cold room increases, the total number of tons of food stored would increase proportionally. To relate the amount of food stored in the cold room to its emission, we have used the functional unit of 'emissions from storing one tonne of food in the cold room under a specific setpoint temperature'. It should be noted that these emissions are specific to SelfChill's technology and cannot be used to compare to another cold room, unless all the assumptions about the cooling load were the same (e.g. set point temperature, amount of food added, climate region). SelfChill cold room is new to the market and therefore there is no historic data on the amount of food stored. We have therefore used SelfChill's designed cooling capacity of 500 kg per day across the entire year giving an annual storage capacity of 182.5 tons per year and 3650 tonnes over 20 years. The estimated life cycle GHG emissions from annually stored food is 1.80 kg CO_2-eq. These results are presented in Figure 37 alongside the results from the 25 year and 30 year lifespans. The results show that extending the PV system and cold room lifetime to 25 and 30 years would result in a 14% and 25% reduction in emissions per year when compared a 20-year lifespan. Furthermore, extending cold room lifespans to 25-30 years have additional mitigation benefits by dramatically reducing emissions and fossil energy/resource consumption that would otherwise be required to replace a system earlier. Other socio-economic benefits are possible through an increase in system lifetime such as increased affordability, but these are outside the scope of this report.

Figure 37: Comparison of GHG emissions per functional unit (kg CO_2-eq/year) under different lifespans



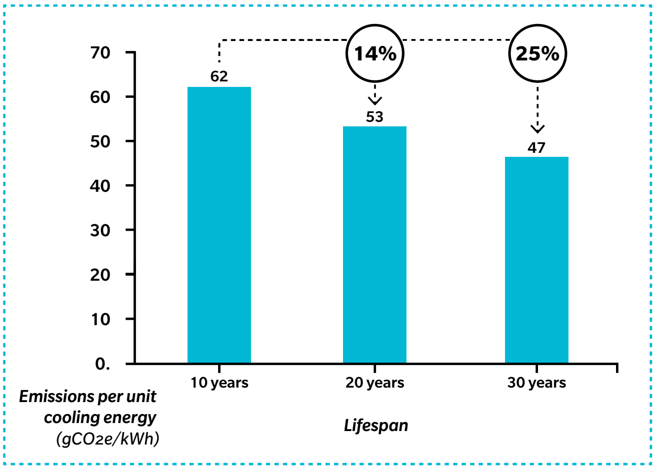
3.1.12 GHG emissions per unit of cooling energy

The general method for calculating the GHG emissions per cooling energy unit can be found in Section 1.7. For the SelfChill cold room, the cooling energy is calculated using a monthly thermal model, provided by SelfChill, which calculates thermal losses, infiltration losses and food cooling energy required using the following assumptions:

- Cold room dimensions and insulation levels as detailed in inventory
- Coefficient of performance of cooling unit provided by SelfChill
- Climate conditions for Kisumu, Kenya
- Internal set point temperature of 10°C
- One air change per day for infiltration losses
- 500 kg of food to be cooled per day
- Initial food temperature of 25°C

The cooling energy required was calculated to be 5217 kWh per year. Using the total emissions (6,492 kg CO_2-eq) over a 20-year lifespan, this gives 62 g CO_2-eq/kWh. Figure 38 shows the emissions comparison for the various lifespans of the system. Increasing the system lifetime to 30 years can reduce emissions per kWh cooling energy by 25%.

Figure 38: GHG emissions per unit cooling energy for the SelfChill cold room



3.2 Scenario analysis of the SelfChill 20m^3 cold room

There are various factors related to off-grid cold room technologies that could significantly affect life cycle GHG emissions. Therefore, conducting a sensitivity analysis is essential for predicting the true climate impact with different manufacturing/management and end-of-life disposal options of the SelfChill cold rooms.

3.2.1 Choice of refrigerant and related climate impact

The refrigerants used in the cold room are gradually being replaced by newer, more environment-friendly alternatives due to the adverse effects of older refrigerants on the ozone layer and climate change. The use of HC-600a is increasing due to its low environmental impact and excellent thermodynamic performance, and is now the refrigerant gas of choice in domestic and small commercial refrigerators and cold rooms. It is non-toxic with zero ozone depletion potential (ODP) and very low GWP; its GWP value is 3. Many manufacturers continue to use the HFC gases like HFC-134a, HFC404A, widely used refrigerants in industrial chiller units, with a very high GWP (HFC134a -1430; HFC404A - 3992).[82] The SelfChill cold room uses natural refrigerant, HC-600a. This section details a comparative assessment of climate impact from use of HC-600a compared to HFC-134a and HFC404A.

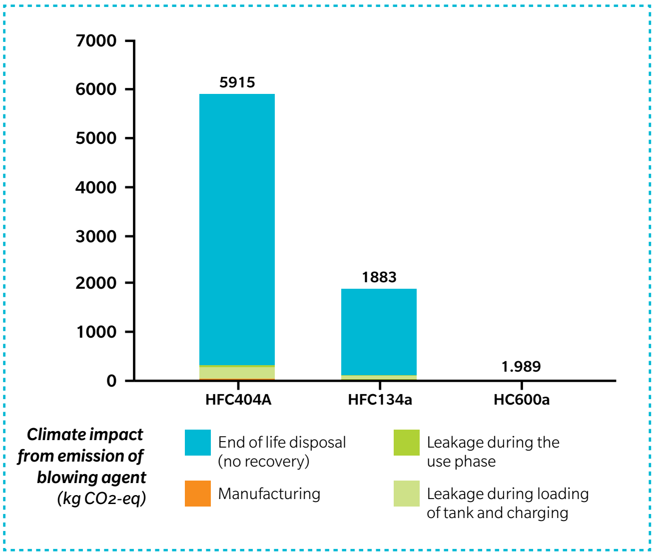
Global warming-related refrigerant emissions occur when refrigerant gases leak into the atmosphere. These leakages could occur during the filling or re-filling of gases in cooling units or during the disposal phase of the end-of-life cooling system (dismantling or recycling). The SelfChill cooling system used capillary tubes instead of expansion valves, which provides a leak-proof system. However, there are times where catastrophic leakage occurs (e.g. from damage to the system), which is estimate to occur in around 1% of systems in the wider market. Therefore, we have assumed an average leak rate of 1% for the SelfChill cold room's refrigerant.

In general, the amount of charge mass required for natural refrigerants like HC-600a is relatively lower compared to charge mass required for HFC gases for the same amount of cooling. Qureshi et al (2012) stated that for a particular cooling system, the required HC-600a amount is 66% lower than HFC-134a,[83] and amount of HFC134a required is 11.9% lower than HFC404A[84] respectively. The HFC-134a refrigerant amount required for 20m^3 cold room is estimated based on the result obtained from the study by Qureshi et al (2012) while HFC404A refrigerant amount required was estimated based on information presented in Embraco,(2020)84. The SelfChill cold room has six cooling units with a 10-year lifespan each. Each cooling unit uses 35g of HC-600a refrigerant. Therefore, 12 cooling units would require 420g of refrigerant charge within a 20-year period. For the same amount of cooling, the estimated refrigerant charge for HFC-134a and HFC404A amount to 1235g and 1402g respectively. With the average leakage rate of 1%, this amounts to 4.2g of HC600a or 12.35g of HFC134a or 14.02g of HFC404A.

At the end of the life cycle, with improper handling of informal recyclers, it can be assumed that the cooling system would be broken, and therefore, the refrigerant would leak into the atmosphere without any possible recovery. As there is no enforcement of any regulation to avoid leakages, the easiest way is to let the gas go, especially in the absence of any viable economic incentives to the informal recyclers.[85]

Life cycle GHG emissions from the use of HC-600a, HFC-134a and HFC404A amount to 1.989, 1883 and 5915[86] kgCO_2-eq, respectively. See Figure 39. Natural refrigerants such as HC-600a over HFC-134a or HFC404A in the cold room helps reduce emissions by 99.9% for a single 20m^3 cold room during 20 years.

Figure 39: Potential GHG emissions from the most prominent types of refrigerants used for cold rooms (comparison assessment of the use of natural refrigerant vs HFCs)



3.2.2 Choice of blowing agent and related climate impact

In the case of rigid foam insulation in cold rooms and refrigerators, a key contributor to emissions is the choice of blowing agent used to formulate the panels. From the year 2000 onwards, some of the foam market shifted away from the use of HCFC gases and adopted the use of HFC based blowing agents.[87] Industry evaluations have shown that HFC-245fa produces foams with the highest insulation value across any HCFC-141b alternative-blowing agent in the construction market.[88] HFC gases do not have a negative impact on the ozone layer but have a high impact on global warming potential. This section discusses the results of a comparative assessment of the climate impact from the use N-Pentane (HC-601), a type of natural refrigerant used in the panel of the SelfChill cold room and HFC-245fa. HC-601 has a very nominal GWP value of 5 and is used as the blowing agent in polyurethane (PU) foam used in SelfChill cold rooms. HFC-245fa with a GWP value of 1030 is used as a prominent blowing agent in the off-grid market.[89]

An estimation of the amount of blowing agent required for manufacturing PU foams for a 20m^3 cold room and its climate impacts is described in Annex B-1.4. Emissions from manufacturing blowing agents are not included in this part of the analysis to avoid double counting with PU foam production emissions. In the absence of proper recovery methods of blowing agents from PU foams at the end of the cold room life cycle, the gases are expected to leak into the atmosphere and contribute to climate impact. Estimated total GHG emissions to produce polyurethane foam using HC-601 (11.51 kg) and

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[82] Cooling post, 2021. Refrigerant choice in HVAC chillers. Available in https://www.coolingpost.com/blog-posts/refrigerant-choice-in-hvac-chillers/

[83] Qureshi, M.A. and Bhatt, S. 2012. Comparative Analysis of Cop Using R134a & R600a Refrigerant in Domestic Refrigerator at Steady State Condition, International Journal of Science and Research (IJSR), ISSN (Online): 2319-7064

[84] Embroco, 2020.Guide for use of HCs refrigerant R600a and R290. Available in https://www.embraco.com/wp-content/uploads/2020/01/e1web-a5-refrigerant-guide-book-en.pdf

[85] Personal communication with e-waste recyclers in Africa

[86] There is no available data on manufacturing emissions of HFC404A and authors assumed that manufacturing emissions is similar to HFC134a. However, according to the analysis, manufacturing emissions of refrigerant is not significant, and it is less than 1% life cycle emissions of HFCs refrigerants

[87] UNEP, 2016. Fact Sheet 16, Insulation Foam. Available in https://ozone.unep.org/sites/ozone/files/Meeting_Documents/HFCs/FS_13_Insulating_Foam_Oct_2015.pdf

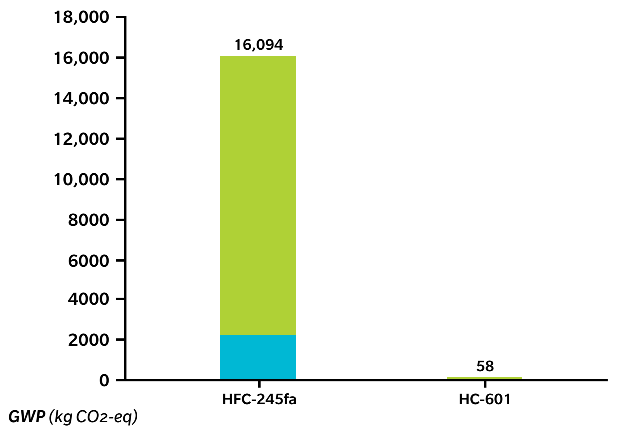
[88] Bogdan, M., Williams, D. and Verbiest,P. 2001. HFC245fa Spray Polyurethane Foam Systems Co-Blown with Water: A Quality, Cost Effective, Safe Substitute for HCFC141b. Journal of Cellular Plastics 37(1):58-7

[89] Vachon. C. and Gendron, R. Evaluation of HFC-245fa as an Alternative Blowing Agent for Extruded Polystyrene. Cellular Polymers 22(5):295-313

HFC-245fa (15.62 kg) as blowing agents required for $20m^3$ cold room manufacturing are 57.57 kg CO_2-eq and 16,094 kg CO_2-eq, respectively, see Figure 40. 5% of blowing agent would leak from the PU panels used in the construction field in the first year and then 0.5% will be leaked annually.[81] At present, there is no viable recovery method of blowing agents from end-of-life PU foams. These results help highlight the significance of the choice of blowing agent for manufacturing panels for the cold room. The choice of using HC-601 based foam results in 99.6% or 16,037 kg CO_2-eq of emissions reduction that would otherwise occur from the use of HFC-245fa as a blowing agent for a single $20m^3$ cold room. This creates a compelling case for phasing the use of HFC based blowing agents and replacing them with natural blowing agents, like HC-601 or cyclopentane (HC-601-c) to help improve PU foams' overall environmental performance.

In the case of HFC based blowing agents, approximately 13.6% are expected to leak during the cold room's 20-year lifespan. The net climate impact of HFC based blowing agents is highly sensitive to the end-of-life management. PU panels that are blown with HFC gases may be incinerated (minimum emissions) or shredded and sent to a landfill (maximum emissions). Incinerating PU form would release CO_2 during the combustion process. However, incinerating foam blown with HFCs significantly reduces leakage of these gases in the atmosphere therefore minimising emissions.

Figure 40: GHG emissions from use of different blowing agents in the production of insulation forms required for the SelfChill $20m^3$ cold room



3.2.3 Choice of end-of-life management method for solar power production and cold room units and related climate impact

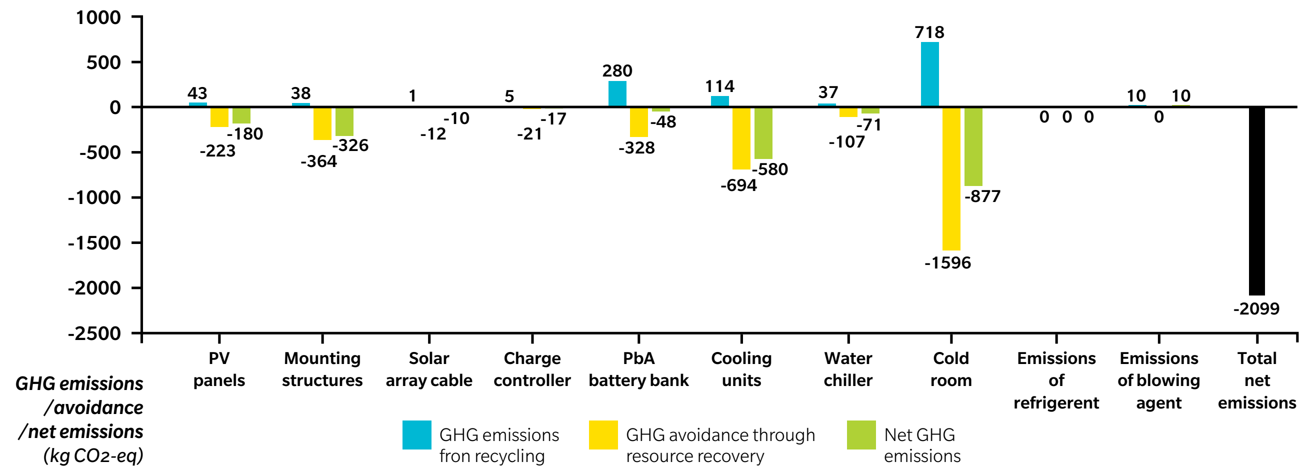
Three main disposal methods are considered in this study for end of the life cycle management: open dumping without any informal or formal recycling, informal recycling, and formal recycling. As explained in the previous chapter, most developing countries have a high reliance on informal recycling methods. Informal recyclers recover only the valuable materials from end-of-life PV systems and cold rooms.

Open dumping without any recycling scenario: Much of the waste from the PV system is stored on site or ends up in a landfill. Given such storing or dumping does not lead to any decomposition process, there are no emissions. Transportation of end-of-life waste to a landfill or nearby site, would cause a small amount of emissions. The open dumping option shows relatively low GHG emissions as the refrigerant and the blowing agent would escape into the atmosphere at the end of the life itself. Although various other harmful impacts would be caused by open dumping like contamination of heavy metals from PCB with ground waste, GHG emission under this scenario is considered low.

Informal recycling: the detailed assessment of the impact of informal recycling is presented in the previous session under the end-of-life disposal phase. Total net GHG emissions estimated by accumulating net emissions from all the items amounted to -1769.19 kg CO_2-eq (see Figure 34). The resulted net negative value indicated that informal recycling activities contributed to saving 1769.19 kg CO_2-eq via recycling activities.

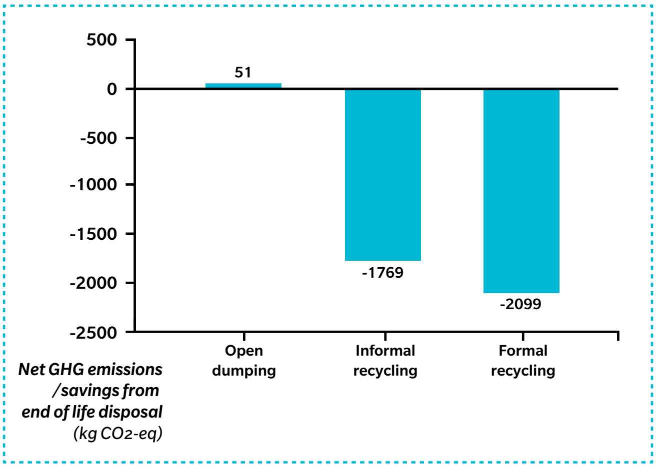
Formal recycling, a potential future scenario: a detailed assessment was carried out for the formal recycling of end-of-life PV power production and cold rooms at the end of the 20-year lifespans. GHG emissions from the recycling avoided emissions through resource recovery, and net emissions are presented in Figure 36. Aggregated net climate impact from end-of-life formal recycling of all the items used in the SelfChill cold room amount to -2,098.98 kg CO_2-eq, and indicate significant GHG saving potentials.

Figure 41: GHG emissions, avoidance and net emissions from end-of-life formal recycling



Comparison assessment of end-of-life management scenarios of the PV system and cold room: Net climate impact from the three main end-of-life disposal options were assessed and presented in Figure 42. Materials recovered from end-of-life PV systems and cold rooms can be used as secondary reserves to replace virgin materials. That means that substantial amounts of energy and virgin resources can be saved while minimising the GHG emissions related to virgin resource extraction.

Figure 42: Net life cycle GHG emissions from end-of-life disposal options of the PV systems and the 20m^3 SelfChill cold room



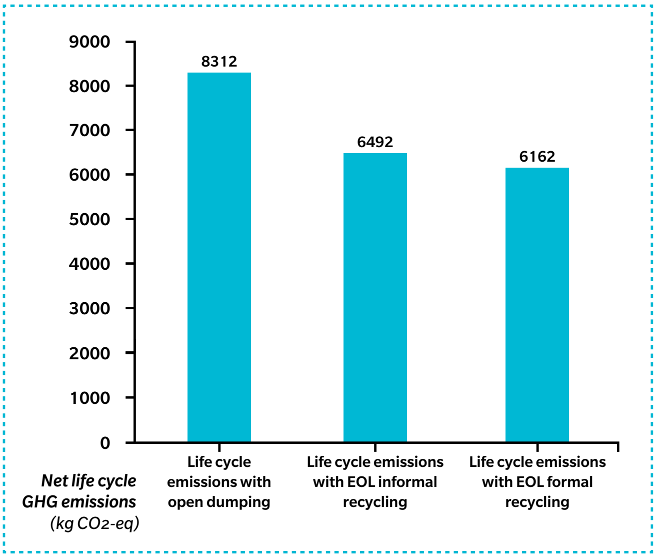
The analysis results show that both informal and formal recycling processes have the potential for significant emissions avoidance due to resource recovery. Informal and formal recycling options show net negative GHG emissions of -1769 kg CO2-eq and -2,099 kg CO2-eq. While the difference in emissions savings between the two scenarios seems low, there are numerous adverse health and the environmental impacts in informal recycling, including black carbon emissions, contamination of soil and water bodies, that this study does not account for. Moving towards formalising recycling including mechanisation and adoption of safer recycling techniques, would help maximise socio-economic and environmental benefits.

3.2.4 Net life cycle GHG emissions from the SelfChill case study with different end-of-life treatment options

As previously mentioned, net GHG emissions from PV power production systems and cold rooms vary with end-of-life management plans. The emissions savings potential from open dumping without any form of recycling is zero, resulting in the highest life cycle emissions. Net life cycle emissions with informal recycling as the end-of-life disposal option has been presented in Chapter 3.2.3. The estimates for net life cycle emissions for the SelfChill cold room are 8,311, 6,492 and 6,162 kg CO2-eq for open dumping without any recycling, informal recycling and formal recycling, respectively (see Figure 43).

This analysis reveals that improvements in the recycling rate has considerable potential to reduce life cycle GHG emissions. Implementing informal and formal recycling mechanisms can help reduce life cycle emissions by 22% and 26%, respectively, compared to no treatment option at the end-of-life cycle.

Figure 43: Life cycle emissions from the SelfChill case study relating to the different end-of-life treatment options after 20 years lifespans



3.2.5 Emission reduction potential by increasing the serviceable life of the cold room

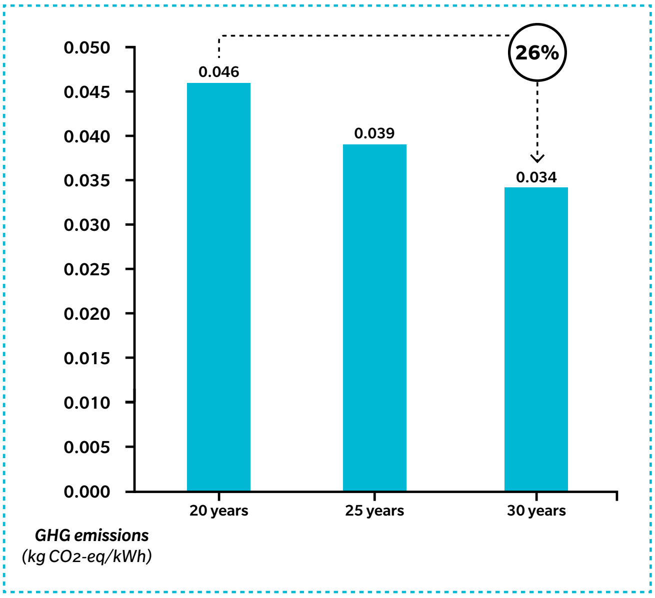
Improving a product's usable life would delay the need for replacement, lead to savings in material resources and avoid emissions related to new production. It is recommended that products and parts become more durable, repairable, and reusable.

Estimation of GHG emissions per unit of electricity production under different lifespans of PV systems would provide tangible information to support the decision-making process related to the off-grid power production approach. For this analysis, emissions per unit (kWh) of electricity production under three possible lifespan scenarios were analysed. In the first scenario, the lifetime of the SelfChill cold room was assumed to be 20 years. It was assumed that both the PV system and the cold room would be discarded after 20 years of serviceable life. Total power production from six PV panels was estimated, assuming at least 6.5 hours of typical peak sunlight would be received every day. Further, it was assumed that 0.5% of the PV panel is degraded each year until the end of the lifespan. Considering these factors, the estimated electricity production from six monocrystalline 350Wp PV panels is estimated to be 95,051 kWh for a 20-year lifespan. Considering the total life cycle emissions from the PV system over 20 years, the projected GHG emissions per kWh electricity production is 46g CO2-eq/kWh under an informal recycling practice at the end of the life cycle.

As a general solar industry rule of thumb, solar panels last about 20-30 years[59], and the warranty period is around 25 years. The more recent generation of panels are expected to last up to 30-40 years[60]. Therefore, emission potentials per kWh electricity production from 20 years, 25 years and 30 years lifespans of PV panels were estimated to assess a more realistic situation. The estimated emissions from 20, 25, and 30 years of the lifetime of six panels are 46 g CO2-eq/kWh, 39 g CO2-eq/kWh and 34 g CO2-eq/kWh, respectively, with the assumption of informal recycling of the panels at the end of the life cycle, see Figure 44.

If the lifespan is extended further with proper maintenance, emissions per unit of electricity production can be reduced further. These results were compared with a critical meta-survey on the LCA assessment of solar power production,[61] in which the 'best' sample of 41 articles has been evaluated. As per this study, the average life cycle greenhouse gas emissions for solar PV panels are estimated as 49.9 g CO_2-eq/kWh. Emissions from PV power production in the SelfChill case is within the same range as in this study. In addition, emissions from solar powers across the three lifespan scenarios is very low compared to the per unit emissions generated from use of the Kenyan utility grid (603 g CO_2-eq/kWh).[62]

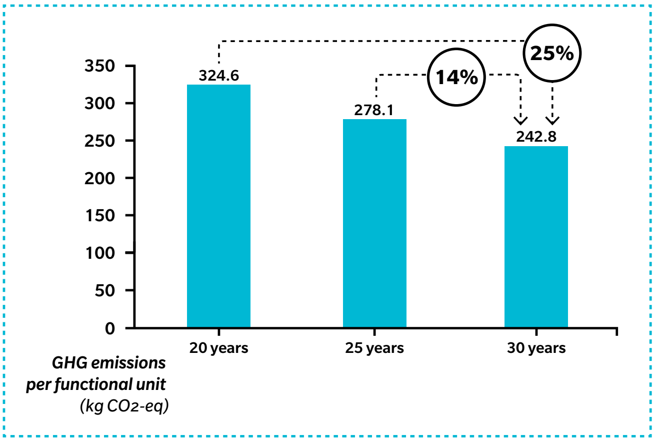
Figure 44: Life cycle GHG emissions per kWh electricity production from different PV system lifespans under informal recycling for the SelfChill cold room



Emissions reduction can be achieved by improving the serviceable life of the PV system. For instance, emissions reduction potential from a PV system with a 30-year lifespan can reduce 26% of life cycle emissions compared to the 20 year lifespan system with informal recycling at end-of-life (see Figure 44).

Further, emissions reduction potential by expanding the serviceable life of the SelfChill 20m^3 cold room (both the PV system and cold room) was assessed considering all the phases of the life cycles. Net emissions per functional unit were estimated to compare the climate impact from different lifespans with different end-of-life disposal options to enable a meaningful comparison. The functional unit for the comparison is emissions, defined as 'net emissions of the SelfChill cold room per year' in the cold room under the specific setpoint temperature. For example, emissions from the 20 year lifespan SelfChill cold room is 324.6 kg CO_2-eq per year under an informal recycling at end-of-life disposal.

Figure 45: Life cycle emissions per functional unit (kg CO_2-eq/year): lifespans vs different end-of-life disposal methods



As shown in Figure 45, expanding the lifespans of the PV system and cold room with proper management would contribute to maximum savings. Expanding the lifespans of the PV system and the SelfChill 20m^3 cold room to 30 years could contribute to a 25% reduction in emissions compared to a 20 year lifespan with informal recycling as the end-of-life disposal. Further extending SelfChill cold room lifespans until 30 years could dramatically reduce fossil energy/virgin resource consumption that would otherwise require manufacturing new PV systems and cold rooms to replace the old ones.

3.2.6 Comparative assessment of GHG emissions from the lead acid battery, lithium-ion and hybrid battery

The use of a battery bank as power storage is becoming an increasingly popular addition to off-grid cooling systems / cold rooms for use in poor weather. Lead acid batteries are the most popular type in the off-grid market. They have cost-effective battery chemistry, are available in large quantities, have very few supply issues and come in a variety of off the shelf pack sizes. A detailed assessment of climate impact from lead acid batteries used in the SelfChill cold room is presented in the previous chapter.

In most cases, lithium-ion battery technology is superior to lead acid due to its reliability and efficiency, among other attributes including a faster charging rate. However, the implementation of a lithium-ion battery bank would be a costly option due to the high capital expenditure associated with the manufacturing of lithium-ion batteries.

SelfChill is looking forward to developing a hybrid battery system to improve the batteries' overall performance. The hybrid battery bank is a fully scalable solution to enhance performance in solar, or any applications with storage needs. The hybrid system can be used with new or existing 12 V lead acid battery systems. The system is easy to install by simply connecting the lithium extension battery next to the lead acid batteries.[90] Capacity can

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[90] BOS, 2021. Lithium Extension Battery. Available in https://www.bos-ag.com/products/le300/

be increased by stacking multiple lithium batteries in parallel until it matches the system energy storage requirement.

In pure lead acid systems, batteries often fail within a few years, as batteries get damaged by continuous operation at a low state of charge. Pure lithium systems perform way better and have longer lifetimes, but are expensive and complicated to install. A hybrid smart battery system can make a real impact on the storage system with its unique features. The lithium-ion battery takes most of the charging cycles in a hybrid system, while the lead acid battery provides inexpensive backup capacity. The lead acid battery is charged with higher priority, while the lithium battery takes all surplus energy. This process helps to increase the lead acid battery lifetime by 10-15 years.[90]

The following scenario is a comparative assessment of the climate impact from a pure lead acid battery system, pure lithium-ion battery system and a hybrid system. According to the power requirement of the 20m^3 SelfChill cold room, the specifications of the required pure lead acid battery bank, lithium-ion battery bank and hybrid battery bank (lead acid + lithium ferro phosphate (LFP) battery) is summarised below (see Table 20). The Phaesun Sun Store AGM batteries catalogue is used to estimate the lead acid battery's energy density and battery mass. The energy density and mass of the lithium-ion batteries were derived based on the information available in the literature.[63,90]

At present SelfChill is importing lead acid batteries from China using different modes of transportation including sea transport and ground transport. Emissions from logistics were estimated using EcoTransIT World model.[17]

Estimation of net emissions from lead acid battery: GHG emissions from pure AGM sealed lead acid battery banks were estimated using available emission factors in published literature. The life cycle inventory of PbA batteries was obtained from Spanos et al.[47] to estimate emissions from manufacturing and recycling. Informal recycling is assumed to be the end-of-life treatment option. Mining and smelting for lead production have significant environmental impacts. There is a possibility of recovering 80-90% of lead from batteries, which will reduce the environmental impact associated with lead batteries. Thanks to the recovery of lead and other metals (e.g. copper) and some plastics, informal recycling has been credited for avoiding emissions that would otherwise occur through conventional production. As mentioned in the previous chapters, only 30% of recovered lead was credited for avoidance of virgin production to calculate the potential GHG savings. Net GHG emissions from the battery banks required within 20 years of the cold room lifespans are 1,460 kg CO_2-eq under the existing disposal practice of informal recycling at the end of the life cycle. 97% of net life cycle emissions are emitted from raw material extraction and manufacturing of the batteries, and the remaining is due to transportation (7%) and end-of-life disposal (9%).

Table 20: Specifications of lead acid, lithium-ion and the hybrid battery bank

SPECIFICATIONS	UNITS	LEAD ACID BATTERY BANK	LITHIUM-ION BATTERY BANK (LFP)	HYBRID BATTERY BANK	
				LEAD ACID	LFP
Capacity	Ah	120	70	80	30
Voltage	V	12	12	12	12
Number batteries in the bank	Number	6	6	6	6
The capacity of the battery	Wh	1440	840	960	328
Bank capacity	Wh	8640	5040	5760	1968
Lifetime	Years	5	10	15	15
Energy density	Wh/kg	48.3	88	45.7	96.5
Mass of the battery	kg	29.84	9.55	21	3.73
Number of battery replacement required within 20 years lifespan	Times	4	2	2	2

Estimation of emissions from pure lithium-ion battery bank: emissions from the manufacturing of lithium-ion were taken from the study done by Bettez et al.[63] Recycling for lithium-ion batteries is not mature. Most lithium-ion batteries that get recycled undergo a high-temperature melting-and-extraction or smelting, which are highly energy-intensive processes. The recycling plants are also costly to build and operate and require sophisticated equipment to treat the smelting process's harmful emissions. Despite the high costs, these plants do not recover all valuable battery materials. For these reasons, less than 5% of lithium-ion batteries are recycled today.[91] There is no large-scale informal recycling practice in Kenya for lithium-ion batteries yet. End-of-life batteries are aggregated and sent to India, China or Europe for recycling. There are several challenges associated with transporting end-of-life batteries overseas due to tight regulations associated with shipping lithium batteries. A mixture of lithium, manganese, cobalt and nickel are available in different ratios that are the most valuable and most difficult to recover in the recycling process. Therefore, recycling and recovering iron, copper, aluminium, and PCB should be considered under the formal recycling of lithium-ion batteries. Net emissions from the lithium-ion battery banks within a 20-year lifespan SelfChill cold room are 1,505 kg CO_2-eq under the existing disposal practice of informal recycling at the end of the life cycle. 99% of net life cycle emissions is emitted from raw material extraction and manufacturing of the batteries, and the remaining 1% is due to transportation. GHG emissions

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[91] CEN, 2021. It's time to get serious about recycling lithium-ion batteries (acs.org). https://cen.acs.org/materials/energy-storage/time-serious-recycling-lithium/97/i28

from end-of-life recycling of lithium-ion batteries are assumed to be zero as there is no appropriate recycling mechanism at the informal level.

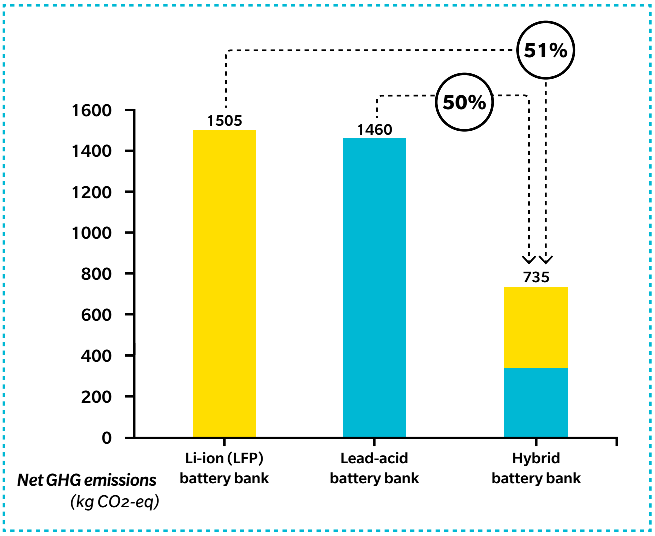
Estimations of net emissions from hybrid battery banks: life cycle emissions from lead acid and lithium-ion batteries in the hybrid system were assessed considering all the life cycle phases.

In contrast to lead acid batteries, lithium-ion batteries are not valued by the informal sector for recycling due to the complexity involved in extracting valuable metals. Therefore, it was assumed that lithium-ion batteries would be transported and recycled elsewhere under the formal recycling mechanism in the future. Net emissions from lithium-ion batteries within 20 year lifespans under informal recycling were compared with the pure lead acid battery system.

Net emissions from a hybrid battery bank that is equivalent in function to the AGM lead acid batteries being used in the 20m^3 SelfChill cold room within 20-year lifespans were assessed. In the hybrid system, life cycle emissions from lead acid and LFP batteries are presented in Figure 46 under the different life cycle phases. Net emissions from the lead acid batteries used in the hybrid system amount to 343kg CO2-eq for a cold room with a 20-year lifespan. Similarly, net emissions from the lithium batteries used in the hybrid system are 392 kg CO2-eq. Based on these results, total emissions from the hybrid battery bank is 735 kg CO2-eq (see Figure 46). Lead acid batteries cause 47% of life cycle emissions from hybrid battery banks, and the remaining 53% is due to the use of lithium-ion batteries in the hybrid system.

Comparisons of net emissions from pure lead acid vs hybrid battery system: net emissions from pure lithium-ion, lead acid and hybrid battery banks that would provide an equivalent function were compared. As shown in Figure 46, net emissions from the pure lithium-ion, lead acid and hybrid battery banks amount to 1,505 kg CO2-eq, 1,460 kg CO2-eq and 735 kg CO2-eq, respectively. Shifting to a hybrid battery bank would reduce net emissions by 51% and 50% that would otherwise occur due to the use of pure lithium-ion and lead acid battery banks. The results revealed that a hybrid system would contribute to significant emissions reduction in addition to the major benefits of better performance and a longer lifespan.

Figure 46: Net life cycle emissions from pure lead acid vs hybrid battery banks

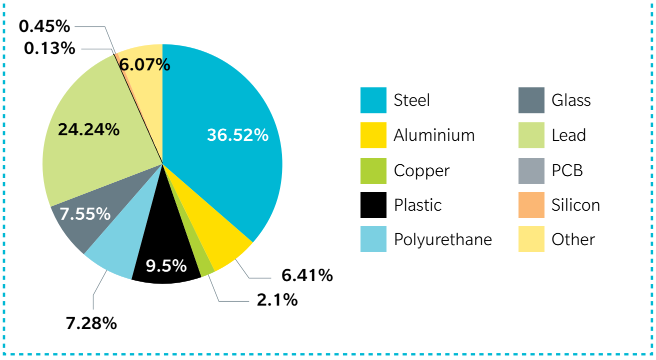


3.2.7 Potential emissions savings from substituting virgin material use with recovered materials at the coldroom's end-of-life

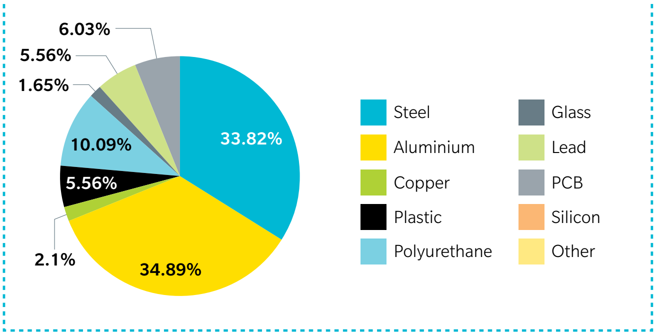
Mining and extracting abiotic resources such as precious metals and fossil-based plastics used to manufacture PV systems and the cold room would contribute to significant emissions. According to the mass balance of the raw materials used in the PV system and the cold room of the SelfChill case study, 36.52% of the mass consists of steel. The remaining mass is split between different type of materials such as lead (24.24%), plastics (9.5%), glass (7.55%), polyurethane (7.28%), aluminium (6.41%), copper (1.66%), silicon (0.45%), paper (0.19%), PCB (0.13%) and others (6.07%) (see Figure 47a). Significant emissions would be emitted from the virgin extraction of these metals and plastic. Items used in the SelfChill cold room may include both virgin and recycled raw materials. However, except in lead acid batteries (only 30% of lead is virgin) there is not enough adequate information available to estimate the proportion of virgin and recycled materials used in each item. Therefore, it was assumed that items in the SelfChill case study are made from virgin raw materials (except the battery bank) and estimated the related climate impact to show the significance of utilising only virgin resources for the manufacturing of a similar cold room, The contribution in emissions from production of different types of virgin materials is presented in Figure 47b which considers the number of replacements of items required within the 20 year lifespan of the cold room. The highest levels of emissions are caused by aluminium, followed by steel, polyurethane, materials in PCB, plastics, lead, copper and glass.

Figure 47: (a) Mass balance of raw material consumption (b) GHG emissions from raw material production of SelfChill 20m^3 cold room (Contribution from both PV system and cold room) for the items used within 20 years lifespans

(a) Material consumption for manufacturing SCE PV power produciton and Selfchill cold room



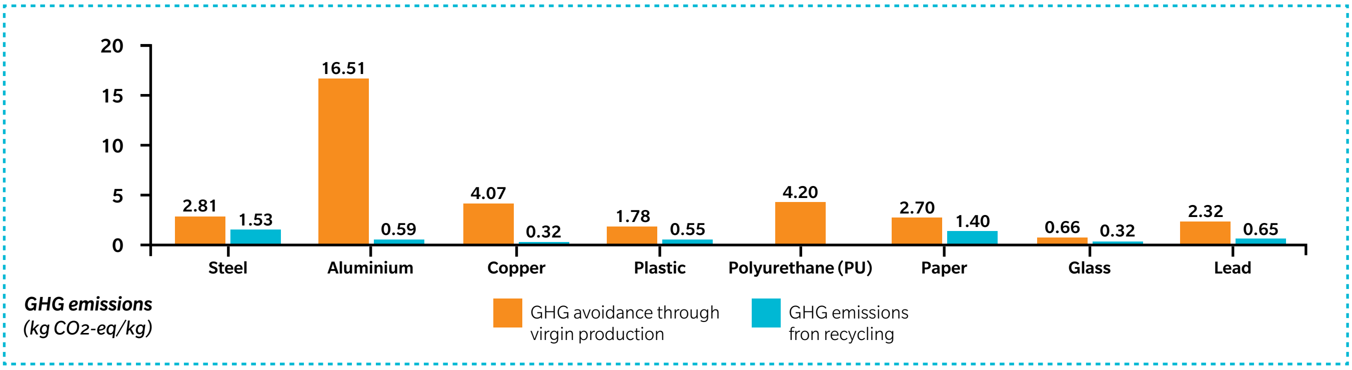
(b) GHGs emissions from virgin materials production for SCE PV power produciton and Shelfchill cold room



At present, Waste Electrical and Electronic Equipment (WEEE) has been identified as a secondary source of resources. Thus, materials retrieved from end-of-life PV systems and cold rooms would contribute as secondary reserves and to replace virgin fossil fuel, metal consumption and related abiotic resource depletion. GHG emissions from the virgin production per kg mass and production of an equivalent amount from the recycling of end-of-life PV system and cold room are presented in Figure 42. This figure indicates material specific emissions hotspots. The virgin aluminium production process has the highest GHG emissions.

Recycling all types of metals and some plastics would contribute to significant emissions savings. Implementing an appropriate mechanism for formal recycling of end-of-life of WEEE would maximise the recovered resources that can also be considered secondary reserves. Emissions from polyurethane recycling have not been shown in Figure 48 since recycling those materials is not widespread due to structural changes that occur in the material during the recycling process. However, these plastic factions can be used to generate energy through incineration. Emissions mainly arise due to fossil energy/grid electricity consumption in virgin material production. Figure 48 indicates how much net fossil fuel consumption related to emissions can be avoided by implementing an appropriate recycling mechanism. The recycling rate or resource recovery rate should be maximized at the factory level to further improve the emissions mitigation potential and minimise use of virgin ores.

Figure 48: GHG emissions from the production of unit mass (1 kg) of materials from the virgin process and recycling



3.2.8 Analysis GHG emissions impact from using different energy sources

The SelfChill cold room is a Solar Direct Drive technology, so it would be useful to demonstrate the climate impact of the SelfChill cold room using different energy sources. This chapter will compare the climate impact of using a SelfChill cold room powered by solar PV, Kenya grid electricity or fossil fuel back-up generators during a 20-year lifespan with informal recycling method.

Similar to the methodology in Chapter 2.4.9, the authors have assumed that the emissions from an AC compressor is the same as a DC compressor, for the purpose of simplifying this analysis regarding different energy sources. The approximate cooling energy requirement for operating the SelfChill cold room would be 2694 kWh/year with 10C cold room set point temperature and 500 kg food/day loading condition. Based on this figure, the total energy consumption for the 20-year of lifespan of the 20m^3 SelfChill cold room would be 53,885 kWh. The net GHG emission of a PV power production system is 4371 kg CO_2-eq with a 20-year lifespan.

The GHG emissions factor for grid electricity production in Kenya is 0.603 kg CO_2-eq/kWh.[62] Based on these figures, total GHG emissions caused due to grid electricity consumption during the 20-year use phase of the cold room is 32,493 kg CO_2-eq. The cold room can also be run by small diesel back-up generators. GHG emissions factors from small diesel back-up generators is 0.807 kg CO_2-eq/kWh. Accordingly, total GHG emissions from running a small diesel back-up generator during the 20-year use phase of the cold room are 43,485 kg CO_2-eq. This calculation assumes that Kenya's grid emission factor and small diesel generator's emission factor will not change significantly over the next 20 years.

Total life cycle GHG emissions from the 20m^3 SelfChill cold room is 2,121 kg CO_2-eq. This was estimated by aggregating the emissions from different life cycle phases. It is assumed that the cold room will be informally recycled at end-of-life in keeping with Africa's low formal recycling capacity.

Figure 49: Comparison of 20m^3 SelfChill coldroom powered by different energy sources

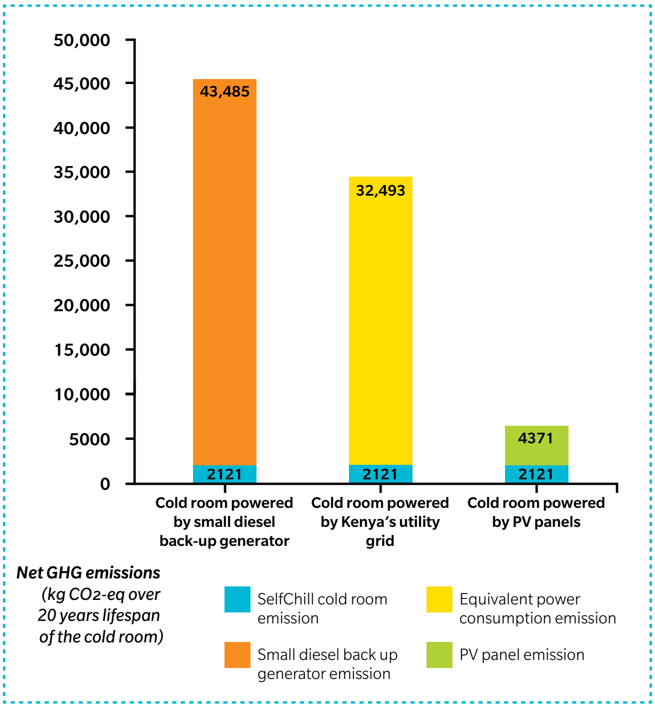


Figure 49 illustrates the impact of different energy sources relevant to overall emission of the SelfChill cold room. Comparative life cycle assessment of using the SelfChill cold room with solar PVs. using it with small diesel generator or utility grid revealed that running this cold room with solar PV will lead to 86% or 81% less GHG emissions reduction respectively. This assessment discovered that a cold room powered by solar PV could contribute to significant emissions savings compared to one powered by grid or diesel back-up generators. This is especially true for cases where the utility grid mix has a greater proportion of non-renewable sources of power.

3.2.9 Analysis for assessing insulation thickness on emissions

Thermal insulation is the most efficient way of maintaining cold room temperatures. The optimum insulation thickness is based on several factors such as the cost of insulation panels and the cost of PV panels and battery bank. Polyurethane panels used in SelfChill cold rooms are made of polyurethane insulation layers that are 78 mm in thickness and protected using 1 mm thick galvanized steel sheets on either side. Thus, the total thickness of the PU panels used in the cold room is 80 mm.

Increasing the thickness of PU panels would reduce the energy required to maintain the setpoint temperature of the cold room and thereby reduce the sizing of the PV panels and the batteries. SelfChill have developed a design tool for a cold room which has been used to estimate the PV panel and battery capacities for different thicknesses of insulation.

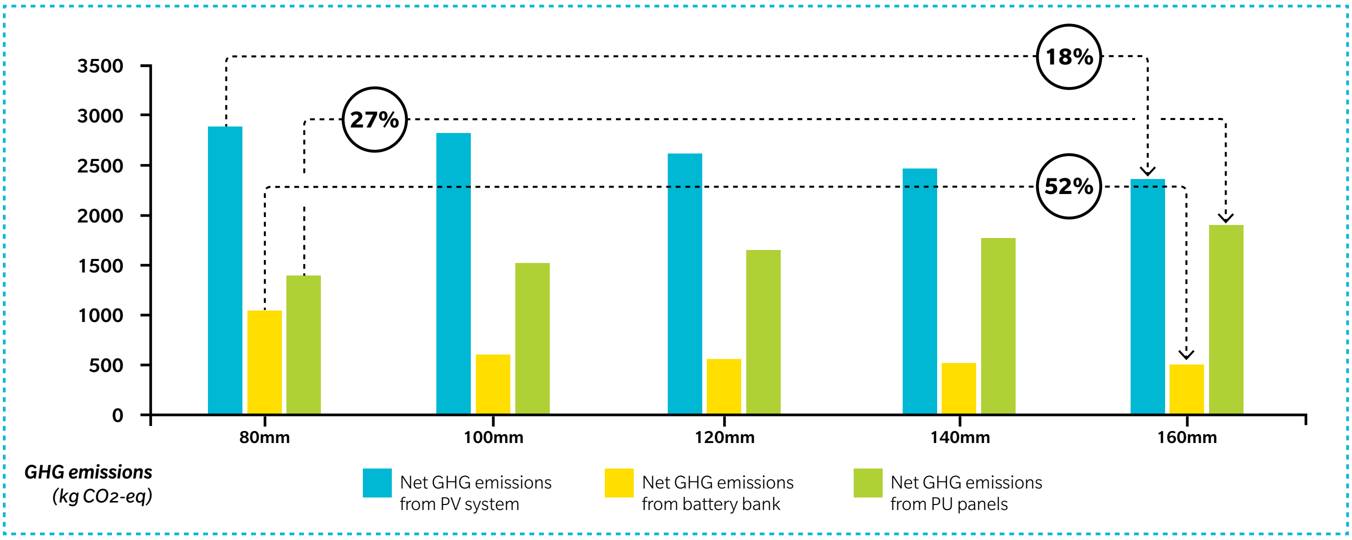
As shown in Table 21, when the thickness of the PU panels is increased, the size of the PV panels and PbA batteries can be reduced due to the reduced thermal energy losses from the cold room. The sizing of the PV array and battery bank was estimated using the SelfChill design tool for four additional thicknesses of the PU panels: 100mm, 120mm, 140mm and 160mm. Net GHG emissions caused due to manufacturing and end-of-life management of various PV panels, PbA batteries, and the corresponding thickness of PU panels is estimated. Figure 43 summarises the estimated emissions from the different sizing of PV panels, batteries, and PU panels corresponding to the various thickness of PU panels.

Table 21: PV panel and lead acid battery sizing for 20 years lifespans cold room with respect to different thicknesses of the PU panel

DETAILS	UNIT	SCENARIO				
		CURRENT	I	II	III	IV
Insulation thickness	mm	80	100	120	140	160
PV panel requirement	Wp	2100	2054	1904	1797	1717
PbA battery requirement ×3 sets of batteries within 20 years lifespans	Ah	2160	1251	1155	1089	1038

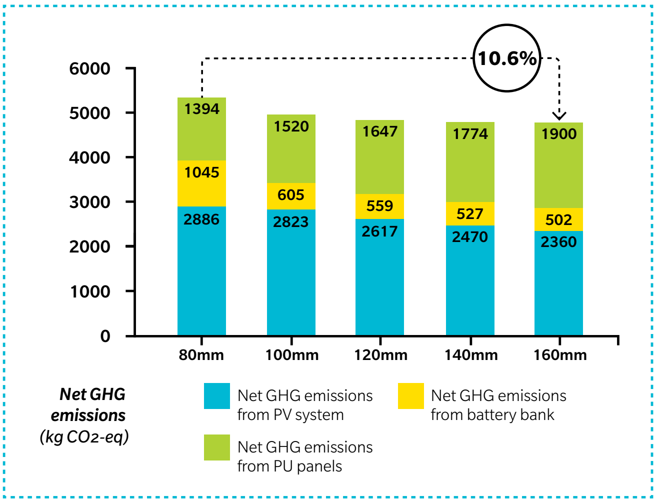
The GHG emissions from PV power production can be reduced gradually by increasing the thickness of the insulation. If the insulation thickness increases to 160mm, emissions from PV panel manufacturing and end-of-life management can be reduced by 18%, compared to PU panels which are 60 mm thick. Net emissions from the battery bank can be reduced gradually as the panel thickness is increased. For instance, increasing the PU panel thickness to 160mm would reduce the emissions related to the battery bank by 52% compared to panels with 80mm thickness. In contrast, increasing the PU panel thickness would increase the mass of polyurethane panels, which would increase the emissions from polyurethane panel manufacturing and disposal. Although the thickness of the polyurethane panel is increased, the galvanized steel layer thickness is assumed to be the same for all the panels (1 mm thickness coat on both sides). Therefore, emissions from steel manufacturing and disposal is considered the same for all PU panel thicknesses. As the mass of polyurethane panel increases with increasing thickness, net emissions related to polyurethane panel production increase by 27% as compared to the emissions from polyurethane panels from the existing cold room, see Figure 50.

Figure 50: Net emissions mitigation potential from different PU panel thicknesses, battery bank and the polyurethane panels



Total emissions with respect to the PV panel, battery bank and the associated polyurethane panel requirement is summarised in Figure 51. Net emissions from these three components under the 80 mm thickness polyurethane panels cold room is 5,325 kg CO_2-eq. Implementing a cold room with 100 mm, 120 mm, 140 mm and 160mm panels would reduce emissions of the above three components by 7.1%, 9.4%, 10.4% and 10.6%, respectively. It should be noted that as the insulation thickness increases, emissions reduce significantly from decreased use in PV panels and battery banks. It is worth mentioning that, if the PU panel used in the cold room is blown with HFC blowing agent instead of a natural blowing agent, climate impact could be very high with increasing the panel thickness.

Figure 51: Net GHG emissions PV panels, battery bank and polyurethane panels relative to the panel thickness



3.2.10 Effect of PV panel efficiency on GHG emissions

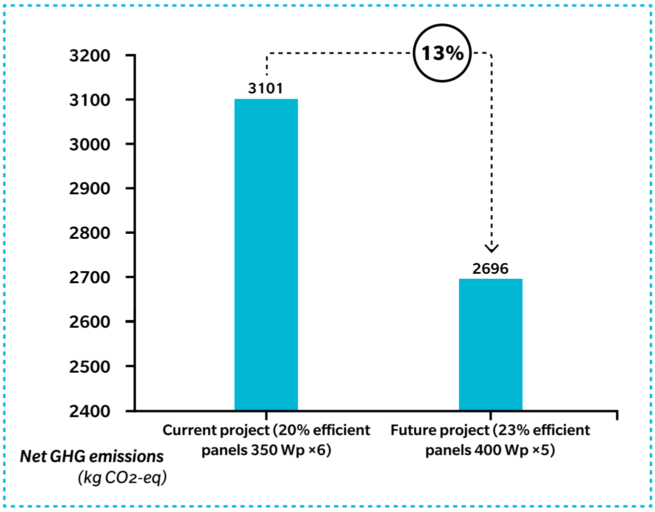
The majority of photovoltaic panels used for solar projects today are between 15% and 20% efficient. Recently developed high-quality solar panels are optimised multi-junction cells which are used to capture different frequencies of light. This technology can exceed 22% efficiency, and efficiency levels of 23% also possible.[50] Efficiency is the key factor in maximising electricity production from the PV system and minimising the number of panels used to provide an equivalent function. In a SelfChill cold room, 350Wp x 6 monocrystalline panels have been used to supply the 6100Wp power demand in the cold room. Monocrystalline panels used in SelfChill cold rooms are more efficient in general than their polycrystalline counterparts.

Shifting to more efficient panels would be one possible way to reduce the emissions from the existing PV systems. For example, the cell efficiency of the current panel used in the SelfChill case is 20% while the most efficient solar panels available in the market today have a cell efficiency of approximately 23%. It is also possible that a 400 Wp panel can be produced with the same dimension (1956 mm × 992 mm × 40 mm) as the current 350 Wp SelfChill panel by increasing the cell efficiency to 23%. Thus, the number of panels required to power the same cold room can be reduced to five instead of 350Wp ×6 panels at the current efficiency level. Reducing the number of PV panels means reducing the material and energy used to manufacture and dispose of the extra panel, thus reducing emissions.

According to the analysis, total emissions from manufacturing and end-of-life disposal of 350 Wp ×6 PV panels, mounting system and cable would be 3,101 kg CO_2-eq. An equivalent function could be provided by using the 23% efficient 400Wp ×5 panels, that would result in emissions of 2,696 kg CO_2-eq. This analysis hence shows that shifting to more efficient panels in the SelfChill cold room can result in a 13% emission reduction (see Figure 52).

However, it should be noted that more efficient solar panels tend to cost more than their less efficient counterparts. It would be beneficial to analyse the upfront cost difference and justify the potential cost and emissions savings that could generate more electricity over the lifespan of the PV system.

Figure 52: Emissions mitigation potential by selecting more efficient PV panel to power the SelfChill cold room



3.2.11 Scenario analysis summary table for the SelfChill cold room

	VARIABLE ANALYSED IN EACH SCENARIO	**BRIEF DESCRIPTION OF ALTERNATE SCENARIO**	**CLIMATE IMPACT – 20 YEAR LIFESPAN (kgCO$_2$-eq)**					**% EMISSIONS CHANGE FROM CURRENT SCENARIO TO ALTERNATE SCENARIO**	**KEY TAKEAWAY**
			EMISSIONS FROM VARIABLE ANALYSED IN CURRENT SCENARIO	**EMISSIONS FROM VARIABLE ANALYSED IN ALTERNATE SCENARIO**	**TOTAL LIFE CYCLE EMISSIONS WITH CURRENT SCENARIO**	**TOTAL LIFE CYCLE EMISSIONS WITH ALTERNATE SCENARIO**	**NET CHANGE IN EMISSIONS**		
3.2.1	Refrigerant	Impact of using HFC-134a instead of natural refrigerant (HC-600a)	1.99	1882.67	6491.57	8372.24	1880.67	**+29%**	Using HFC-134a would increase the emissions of the fridge compared to the natural refrigerant used
Interpretation example – Total life cycle emissions from SelfChill cold room for a 20 year lifespan assuming informal recycling at end-of-life are 6491.26. If the use of natural refrigerant HC-600a is switched to fluorinated gas HFC-134a, total life cycle emissions of the cold room will increase by 29%									
3.2.2	Blowing agent	Impact of using HFC (HFC-245fa) instead of natural blowing agent (HC-601)	57.56	16,094	6491.57	22,528.01	16,036.44	**+247%**	Using HFC-245fa would increase the emissions of the fridge by 247% compared to the natural blowing agent used
3.2.3	Recycling fridge and PV	Impact of open dumping instead of informal recycling	-1769	51	6491.57	8311.57	1820	**+28%**	Any kind of recycling is better than no recycling. Our analysis finds small difference between informal and formal recycling as this is a pure GHG emissions analysis. However, a consideration for the type of recycling to be adopted should consider broader environmental and social impacts such as black carbon emissions, human health safety considerations, etc.
3.2.5	Lifetime	Impact of extending lifespan to 25 years instead of 20	6491.57	5562.41	6491.57	5562.41	-929.16	**-14%**	For comparison purpose, we choose to demonstrate average emissions for 20 years, when the lifetime increases to 25 or 30 years. Increasing the lifetime of the system reduces emissions per 20-year period. This is because as we are only replacing the parts of the system which require changing. For those components that can last longer, we are maximising their lifetime.
		Impact of extending lifespan to 30 years instead of 20	6491.57	4832.20	6491.57	4832.20	-1659.37	**-26%**	
3.2.6	Batteries	Impact of using lithium-ion batteries instead of lead acid	1460	1505	6491.57	6536.57	45	**+0.7%**	Lead acid and lithium-ion do both produce significant emissions but lead acid has slightly smaller emissions due to the high percentage of recycled lead used in manufacturing stage. It is possible to reduce emission further by using a hybrid battery system.
		Impact of using hybrid (Li + PbA) battery instead of lead acid	1460	735	6491.57	5766.57	-725	**-11%**	
3.2.7	Non-virgin materials	Not for table since multiple scenarios exist. Refer to Section 3.2.7 for details.							
3.2.8	Different energy sources	Impact of using grid electricity instead of a solar system	4370.70	32,492.53	6491.57	34,613.40	28,121.83	**+433%**	The grid electricity factor is assumed to be the Kenya grid electricity emission factor.
		Impact of using diesel back-up generator instead of a solar system	4370.70	43,485.03	6491.57	45,605.90	39,114.33	**+603%**	
3.2.9	Insulation thickness	Impact of increasing PU panel thickness from 80 mm to 160 mm	5325	4763	6491.57	5929.57	-562	**-9%**	Increasing the insulation thickness increases the emission related to PU panels, but the decrease of emissions related to PV system and battery bank outweighs this due to a smaller power production system needed. Emissions also go down because the SelfChill cold room uses a natural blowing agent. If a fluorinated gas is used, the result may be reversed.
3.2.10	PV panel efficiency	Impact of increasing PV panel efficiency from 20% to 23%	3101	2696	6491.57	6086.57	-405	**-6%**	Increasing PV efficiency decreases the overall emissions due to a smaller number of PV panels needed.

3.3 Summary and conclusions for the SelfChill cold room

SelfChill 20m^3 cold room has been designed for a 20 year lifespan and the average food storage capacity is 0.5 tonne/day. Emissions from the PV system and the SelfChill cold room was assessed from a life cycle perspective. Estimated values of GHG emissions per functional unit can be valuable information in the design decision-making process. The life cycle emissions (including the emissions from raw material extraction, manufacturing, and transportation) in PV power production in the SelfChill case are 4,829 kg CO_2-eq from the 20 years lifespans PV system with informal recycling as the end of the disposal method. The majority (63%) of these emissions are caused from manufacturing of PV panels, followed by the battery bank, mounting system, charge controller, cables and logistical movement, at the rate of 22%, 10%, 3%, 1% and 1%, respectively. Materials recovery by the informal sector from the end-of-life waste would save 458 kg CO_2-eq emissions. By accounting for possible emissions savings, the resulting net life cycle emissions from the PV system amounts to 4,371 kg CO_2-eq within a 20 year lifespan. The estimated emissions per unit of electricity production is 46 g CO_2-eq/kWh. PV systems can however last 25 to 30 years with proper maintenance. The estimated emissions from PV system with 25 and 30 years of serviceable life amount to 39 g CO_2-eq kWh and 34g CO_2-eq/kWh respectively.

For the SelfChill 20m^3 cold room (including cell with heat exchanger, cooling system, water chiller, refrigerant, blowing agent), 78% of life cycle emissions arise from raw material extraction, processing, and manufacturing of components for the cold room such as cooling units, water chillers, and the cold cell. Emissions from transportation phases contribute to only 2.6% of life cycle emissions. During the 20 years of the use phase, emissions from refrigerant due to accidental leaks and emissions of blowing agent leakage from polyurethane panels contributed to 0.2% of life cycle emissions. The remaining 19.3% emissions are caused due to the energy consumption required in smelting process of informal recycling at the end-of-life. Considering all these emissions, total life cycle emissions from a 20m^3 SelfChill cold room would be 4,254 kg CO_2-eq. As a result of resource recovery from end-of-life cycle recycling by informal recyclers, there is possibility for avoidance/savings of emissions up to 2,133 kg CO_2-eq from the items used in the cold room, which have been credited back in calculations. 65% of materials used in this cold room are highly valuable metals (e.g. steel, aluminium, copper). Our analysis assumes the materials were recycled informally and resulted in higher emissions savings via resource recovery. Therefore, the net life cycle emissions after adjusting for savings / avoidance potential, amounted to 2,121kg CO_2-eq for the 20m^3 cold room over a 20 year of lifespan. With proper handling and maintenance, the cold room’s serviceable life can be extended to 25 to 30 years.

Summary discussion of various scenario analyses: The comparative assessment of different scenarios revealed crucial emission hotspots or biggest contributors based on the share of GHG emissions. As far as the refrigerant choice is concerned, a natural refrigerant like HC-600a can lower 99.9% emissions that may be emitted by the HFC refrigerant HFC-134a. Furthermore, analysis results proved that avoiding use of HFCs as a blowing agent is crucial in GHG mitigation. The use of natural blowing agents like HC-601(N-Pentane) has the potential of reducing 99.6% of emissions that could be caused by the blowing agent, HFC-245fa. Implementing appropriate end-of-life disposal practices would also contribute to GHG savings.

Implementing a formal recycling mechanism would avoid 26% life cycle emissions aggregated net impact from PV system and the cold room compared to disposing at dumpsites without any informal or formal recycling. Emissions savings from informal recycling show significant emissions reduction potential. While the difference in GHG emissions between informal and formal recycling is small, the actual climate impact from informal recycling is relatively high due to use of fossil fuels in burning for extraction and associated black carbon emissions that have not been accounted for in this study.

Improvement of serviceable life of the PV system and the cold room could considerably reduce GHG emissions. An extended warranty period and appropriately enforced maintenance procedures of the PV system would be important aspects for better durability and enhanced serviceable life. Further, expanding the lifespans of both the PV system and the SelfChill cold room with proper management and appropriate disposal methods at the end of the life cycle would contribute to maximum emissions savings.

Power storage is an integral part of the PV power production system. Both, an enhancement of battery efficiency and emissions mitigation could be achieved by implementing a hybrid battery system comprising of lead acid and lithium batteries. According to the analysis results for the SelfChill cold room, shifting to a hybrid battery bank would reduce net emissions by 51.2% and 49.7% as compared to lithium-ion battery and pure lead acid banks respectively.

Raw material analysis revealed that implementing an appropriate mechanism for formal recycling of end-of-life PV systems and the cold room would maximize secondary reserves and prevent the mining of virgin ores.

Analysis of emissions from logistical movement of parts shows that only 2% of life cycle emissions occur from transportation. Local manufacturing and assembling could lower emissions from logistical movements while creating other co-benefits to the society.

Selection of appropriate thickness of insulation panel would be the most efficient way to maintain cold room temperatures. Emissions from PV panels and battery bank manufacturing would reduce by increasing the panel's thickness. However, increasing the panel thickness would increase the mass of polyurethane panels, which would increase emissions from polyurethane panel manufacturing and disposal. Accumulated emissions related to the sizing of PV panel, battery bank and the polyurethane panel with different thicknesses would be an indicator in decision-making. Doubling the thickness (160mm) of panels would reduce the emissions related to PV panels, battery bank and polyurethane panels only by 10.6% compared to the existing sizing. The emission reduction potential due to increasing the panel thickness would further reduce, if it was calculated relative to the life cycle GHG emissions of SelfChill cold room.

The efficiency of the PV panels is a critical factor in maximising electricity production and minimizing the number of panels used, thereby reducing emissions related to the PV panels manufacturing and disposal. The analysis revealed that if the SelfChill cold room is powered using 23% efficient 400 Wp ×5 panels instead of 20% efficient 350 Wp ×6 panels used in the existing system, GHG emissions could be reduced by 13%. However, it should be noted that more efficient solar panels tend to cost more than their less efficient counterparts. It would be beneficial to analyse the trade-off between upfront cost and emission mitigation potential in using PV panels with higher efficiency.

All in all, LCA-based results in this study would provide some tangible information for manufacturing and implementing of solar-powered cold rooms in the off and weak grid areas.
The development of off-grid cold rooms would contribute not only to reducing post-harvest losses but also make a significant contribution to national/global GHG mitigation targets. Authors of the report hope that the findings of this study, based on ongoing management practices from the SelfChill cold room model, will be beneficial for strengthening and implementing appropriate pro-climate policies in developing off and weak grid cooling technologies. In addition, the results would provide a systematic approach for sound material recycling and resource recovery at the end of the life cycle after the maximum serviceable life.

Chapter 4: Life cycle assessment of a cold room – ColdHubs

The second cold room in this study is developed by ColdHubs Ltd. based in Nigeria.

The second cold room in this study is developed by ColdHubs Ltd., based in Nigeria. Their cooling systems operate on a personalised pay-as-you-store or Cooling as a Service (CaaS) model and serves smallholder farmers, retailers and wholesalers of horticultural produce. Their aims are to eliminate food spoilage at key points within the food supply chain by deploying and operating robust off-grid cold storage.

4.1 Life cycle carbon footprint assessment of ColdHubs cold room

This 20m^3 cold room was selected for a life cycle assessment from the Efficiency for Access grantee portfolio of the LEIA programme.

The ColdHubs cold room, also branded as 'ColdHubs', is a plug-and-play assembled walk-in cold room powered using solar energy to provide off-grid storage for perishable food products. These cold rooms are deployed in farm clusters, produce aggregation centres and outdoor markets, and are principally designed to operate in rural areas to address the problem of post-harvest losses. These cold rooms store and preserve fresh fruit and vegetables, extending their shelf life from two days to more than 21 days. As an example, by renting out cold storage space on a per crate daily basis, ColdHubs helped save 20,400 tonnes of food from spoilage in 2019 alone.[92]

ColdHubs operates a simple pay-as-you-store model and helps increase income of farmers and retailers by improving access to cooling and eliminating associated food waste. This is achieved by allowing service users to rent storage space priced daily per crate, at a price they can afford, and on a scale appropriate for each of their needs. The cold storage process at ColdHubs starts once the fruits, vegetables and other perishable food arrive from the farms at the farm cluster's aggregation centres or outdoor food market. The hub operators transfer the food from baskets or bags into the clean returnable plastic crates. The crates are stackable, and each ColdHub can store up to 150 of these crates. Farmers and retailers pay 100 Nigerian naira (the equivalent of US$0.50) to store one 20 kg returnable plastic crate per day inside the cold room. Hubs are operated by a female hub operator, who monitors the loading and unloading of crates, collects the fees, and builds relationships in farm clusters and markets.

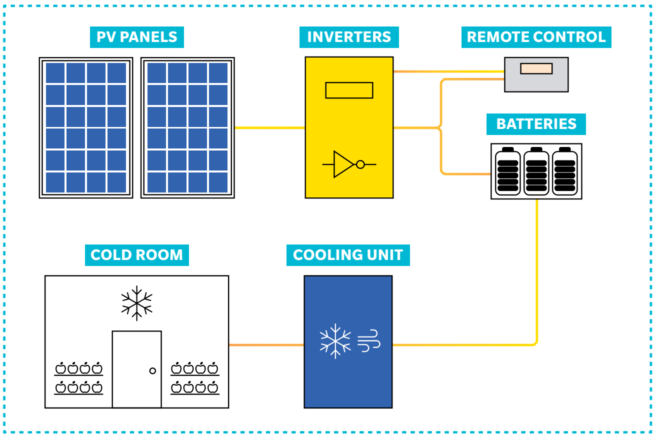
4.1.1 Specification of ColdHubs Cooling as Service (CaaS) Model- 20m^3 cold room

ColdHubs' cold room comprises of 150mm (6") thick insulated cold room panels with a floor made of stainless steel. The dimensions of the cold room are (L × W × H) 10 ft × 10 ft × 7 ft, and the approximate cooling volume is 20m^3. This cold room is sufficient to store three tonnes of perishable food arranged in 150 units of 20 kg plastic crates stacked on the floor.

This cold room is powered by a 6.12 kW rooftop-mounted solar array connected to a set of deep-cycle, long-lasting batteries. The power generated is sufficient to run the hubs in all weather conditions. There is a refrigeration unit designed for off-grid use which operates 24/7. The temperature is kept at around 5°C(41°F). The cooling unit is filled with a natural refrigerant (R290a) that is ready to use. A schematic of the ColdHubs cold room is shown in Figure 53.

There is a ColdHubs Advanced Remote Monitoring System (CARMS) in place to manage the breakdowns and downtime in cold rooms. This system helps monitor the conditions of the cold rooms, such as the number of door openings, battery state of charge, ambient temperature, cold room temperature, solar irradiation, etc. Recently, this system has been upgraded by incorporating video cameras that take and store pictures in the cloud, enabling the loading and offloading of the food to be monitored remotely.

Figure 53: Schematic diagram of ColdHubs' 20m^3 cold room



4.1.2 Methodology for the life cycle carbon assessment (LCA) of ColdHub's 20m^3 cold room

The standard LCA methodology presented in Chapter 1 was used to assess the climate impact from ColdHubs' cold room. The life cycle is divided into a production phase (including raw material extraction, parts production, and assembly), transportation, use, and end-of-life disposal (see Figure 6). Based on the information provided by ColdHubs, the average lifetime used in this study is 20 years and the PV system is expected to last for 25-30 years. However, with careful handling and maintenance, the service life of the PV system and the cold room could be extended to 30 years. The geographic boundaries for calculating emissions from the logistical movement of the components for the cold room are spread across Nigeria, Germany and Italy to the project location in Nigeria. Life cycle inputs (electricity, thermal energy and raw materials) and outputs (emissions and recovered resources) were estimated for each item used in this cooling technology. The system boundary of the ColdHubs' 20m^3 cold room is presented in Figure 6. The functional unit was defined as kg CO2-eq emissions per kWh of cooling energy required. Such a functional unit would help enable a comparison with other cold rooms in the region.

4.1.3 Life cycle inventory of PV power production system

A customised questionnaire was prepared for the 20m^3 ColdHubs cold room to gather primary data across its different life cycle phases and shared with the ColdHubs' design experts.

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[92] CaaS, 2019. CaaS in Nigeria. https://www.caas-initiative.org/casestudies/caas-in-nigeria/

In addition, the Ecoinvent databases (version 3.7), published literature and unstructured interviews with formal e-waste recyclers were used as secondary data sources to extract valuable data required for the assessment. Priority is given to using primary data over secondary data where it was available, since primary data has greater accuracy. An inventory analysis was done for the solar power production system including components such as panels, mounting structures, cables, mounting structures, charge controller and the battery bank.

Solar panels: 18 solar panels, each with a capacity of 340 Wp, are used to power the ColdHubs' 20m^3 cold room. Total power production capacity of PV power system 6120Wp. A single panel's mass is 22.5 kg with the frame. Solar PV panels are fitted with an anodized aluminium frame. The warranty period of PV panels is 25 years. The detailed specifications of the solar panels are summarised in Annex B-2.1.

Mounting structures and cable: the panels are installed on the roof of the cold room with the support of a mounting system. The supporting structures used to install the PV panels amount to 350 kg, and are made from galvanized angle iron. The total mass of the solar array cable is 12 kg, and the cable is made with 40% plastic and 60% copper.

Inverters: two inverters are used in the PV power production system to manage the power going into the battery bank from the solar array. The capacity of inverters are 5kW and 6kW, with an expected lifetime of 20 years. The mass of the inverters are 15 kg and 25 kg. In general, the lifespans of the PV system (panel, mounting system and cable) can be used for more than 20 years, however the inverters need to be replaced at the end of 20 years.

Remote controller: there is a remote controller with a capacity of 15W. The mass of the remote controller is 0.4 kg and the warranty period is 20 years. However, usually, there is an inverter inside the charge controller. In the case of ColdHubs, the inverters are connected separately. Therefore, the remote controller only has an outer cover and a printed circuit board (PCB). It is assumed that the smart box has similar material composition as the charge controller. This composition is extrapolated to determine the composition for a remote controller weighing 0.4 kg as for the purposes of conducting the LCI of the smart box.

Battery bank: There are 24 valve-regulated lead-acid (VRLA) 990Ah, 2V batteries that are used to store the excess power to be used at night-time and on rainy days. The mass of each battery is 61.3 kg, and the maximum depth of discharge (MDOD) is 80%. The lifetime of the VRLA batteries is assumed to be seven years. However, with proper maintenance these batteries might be used for more than seven years.

Power box: The power box is fabricated by ColdHubs to house all the electrical components (battery bank, inverter, wires and cables). The power box is made from 100% steel, and its mass is 150 kg. One power box has been included in each ColdHubs cold room.

Wire and cables: the Cold Hubs PV power system uses different gauge cables and wires to connect devices. Gauges and the mass of each type of cable and wire are summarised in a table Annex B-2.1. The total mass of the cables and wires is 11.5 kg and 1.5 kg, respectively. According to the Ecoinvent database, the two types are 66% and 80% copper by mass, and the remaining 34% and 20% plastic. In addition, there is a 5 kg wire trunk made with HDPE used for storing the wires and cables. Detailed specifications of the cables and wires and related emissions are presented in Annex B-2.1.

4.1.4 Life cycle inventory (LCI) of ColdHubs 20m^3 cold room

Life cycle inventory of the cooling system and the cold room was done to quantify the emissions related to the ColdHubs 20m^3 cold room.

Cooling system: a readily available cooling unit is used on the ColdHubs cold room with a total mass of 52 kg, and a lifespan of 15 years. 140 g of the natural refrigerant R290 (propane) is used which has a low global warming potential (3 kg CO_2-eq/kg) and zero ozone depleting potential. The amount of refrigerant required in a cooling system at a time is 140 g. It was assumed that the system requires a top up of 20% of the original refrigerant mass annually to compensate for any possible leakages and maintain the same refrigerant level in the cooling system. ColdHubs take extra care in handling the refrigerant and make it a priority to ensure that the hubs are not installed in areas where there is any fire or open flame nearby.

Life cycle inventory data of the manufacturing of the specific cooling system is not available. Therefore, inventory data was taken from Cascini et al, a study on a refrigeration unit designed for medium refrigerating temperature.[93] The main parts of the refrigerating system include a hermetic reciprocating compressor, a copper-aluminium finned evaporator, an aluminium micro-channel condenser, two fans powered by electric motors, an electronic control unit, copper piping, valves, and a steel/plastic support frame. The derived material composition of the cooling unit is 79.7% steel, 9.8% copper, 6.2% aluminium, 3.7% plastic 3.7% and 0.6% other materials.

Cold room: the dimensions of the cold room body is 10ft × 10ft × 8ft. The wall and roof are made of 18 polyurethane foam panels lined with 0.7 mm steel on each face. The dimensions of a single panel are 1.982 m × 1.005 m × 120 mm and each panel weighs 35 kg. Another 50 kg polyurethane panel is used for the door. It was assumed that the polyurethane used in the panels is blown with a blowing agent, made with 90% natural refrigerant – pentane and 10% HFCs. Aluminium chaka plates have been used for the floor weighing 25 kg and 150 crates made from HDPE that are used to store the food.

The detailed specification of the cold room, including the components and mass balance, are summarised in Annex B-2.2. The material composition of polyurethane foam was analysed

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[93] Cascini A., Gamberi, M., Moraa, C., Rosano, M. and Bortolinia, M.2016 Comparative Carbon Footprint Assessment of commercial walk-in refrigeration systems under different use configurations Journal of Cleaner Production 112 (2016) 3,998-401

considering the thickness (0.7 mm) and density (7850 kg/m^3) of galvanized steel layer. The estimated total galvanized steel and polyurethane foam used to construct the 20m^3 cold room amounts to 529 kg and 316 kg, respectively.

4.1.5 Life cycle GHG emission estimations from the ColdHubs 20m^3 cold room

The emissions from the manufacture of the PV power production system and cold room are calculated by aggregating emissions over the life cycle of every component. The mathematical formula used for estimating life cycle GHG emissions from PV power production and cold rooms is presented in Chapter 3.1.5.

4.1.6 GHG emissions from the manufacturing of components in PV power production

Emissions from the raw material extraction and manufacturing of 340 Wp ×18 solar panels: 18 polycrystalline solar panels power the ColdHubs 20m^3 cold room. The Ecoinvent database (version 3.7) was used to gather the energy and emissions data related to the raw material extraction and manufacture of the PV panels. As described in Ecoinvent, activities included in LCI are the production of the cell-matrix, cutting of foils and washing of glass, production of laminate, isolation, production of the aluminium frame of the panel and disposal after end of the use. A detailed estimation of emissions is summarised in Annex B-2.1. Net emissions per m^2 of monocrystalline panel production is 199.1 kg CO2-eq. Estimated emissions from eighteen 340Wp panels used in this case study are 6,955.84 kg CO2-eq.

Emissions from raw material extraction and manufacturing of mounting structure: ColdHubs uses 350 kg of galvanized angle steel as mounting structures. GHG emissions from production of per kg of hot-dip galvanized steel is 2.81 kg CO2-eq.[94] Based on this figure, estimated emissions from the mounting system are 983.5 kg CO2-eq. The amount of zinc used for galvanisation is assumed to be very small. Detailed results are presented in Annex B-2.1.

GHG emissions from raw material extraction and manufacturing of solar array cables: Solar array cables, with a mass of 12 kg, are used to connect solar panels to the charge controller/battery bank. The cable is made with copper 60% and plastic 40%. Ecoinvent LCI for production of cables with similar material composition was used to estimate emissions from cables used in ColdHubs. The estimated emissions from the production of 12 kg of solar array cable are 79.98 kg CO2-eq. Detailed calculations are presented in Annex B-2.1.

GHG emissions from raw material extraction and manufacturing of inverters: There is no LCI for the exact capacity of the two inverters used in PV power production in ColdHubs. Tschümperlin et al.[95] published LCI for a 2.5kW inverter. This result was extrapolated to estimate the LCI for the 5kW and 6 kW inverters used in ColdHubs. Extrapolation was done using a non-linear mass versus power relationship as reported in scientific literature. The estimated GHG emissions from manufacturing 5kW and 6kW inverters are 479.46 kg CO2-eq and 799.11 kg CO2-eq. Detailed calculations are presented in Annex B-2.1.

GHG emissions from raw material extraction and manufacturing of remote controller: emissions data from a similar device was extrapolated to quantify the emissions from the remote controller since the smart box and remote controller have similar material composition. The estimated emissions from raw materials extraction and manufacturing of 0.4 kg remote controller is 16.23 kg CO2-eq.

GHG emissions from raw material extraction and manufacturing of AGM lead acid battery bank: 24 valve-regulated lead acid (VRLA) batteries are used to store power to use during the night and rainy days. The lifetime of these batteries is assumed to be seven years. Emissions from manufacturing of VRLA batteries were quantified based on an LCA study done by Spanos et al. It was assumed that 70% of the lead used for the batteries is retrieved from a recycling process, whereas 30% is made of virgin materials Detailed LCI of VRLA batteries is presented in Annex B-2.1. Estimated emissions from raw material extraction required to produce PbA battery is 1.22 kg CO2-eq/kg of the battery which includes emissions from material extraction of 30% virgin lead and producing 70% of recycled lead. Energy consumption for manufacturing of per kg of the PbA battery is expected to emit 0.68 kg CO2-eq of emissions. Therefore, total emissions from manufacturing per kg of PbA battery amounts to 1.90 kg CO2-eq. The average mass of the PbA battery is 61.3 kg, and a single ColdHubs uses 24 batteries to store power. Emissions from manufacturing one battery is 116.64 kg CO2-eq, and total emissions from PbA battery bank with 24 batteries is 2,799.42 kg CO2-eq.

4.1.7 GHG emissions from manufacturing of components in a 20m^3 ColdHubs cold room

GHG emissions from raw material extraction and manufacturing of cooling unit: The total mass of the cooling unit is 52 kg, and the lifespan is 15 years. Mass balance and material composition of the cooling systems used in a 20m^3 cold room are presented in Annex B-2.2. The derived emissions from materials extraction and manufacture of a cooling unit is 214.5 kg CO2-eq. During the 20 years of the cold room lifetime, the authors have decided to include 1/3 of the manufacturing emissions from the second cooling unit for the remaining 5 years, assuming the second cooling unit would be re-used for another 10 years. Therefore the emission from raw material extraction and manufacturing of cooling units during 20 years is 286 kg CO2-eq.

GHG emissions from raw material extraction and manufacturing of the cold room: Climate impact from individual components used in the cold room is assessed using the material composition of the cold room cell, door, floor, crates etc. As far as the cold room is concerned, the total galvanized steel and polyurethane (PU) foam used to construct 20m^3 cold room amounts to 528.5 kg and 316.5 kg. The climate impact from use steel and polyurethane foam to build the cold room is 1,485 and 1,330 kg CO2-eq.

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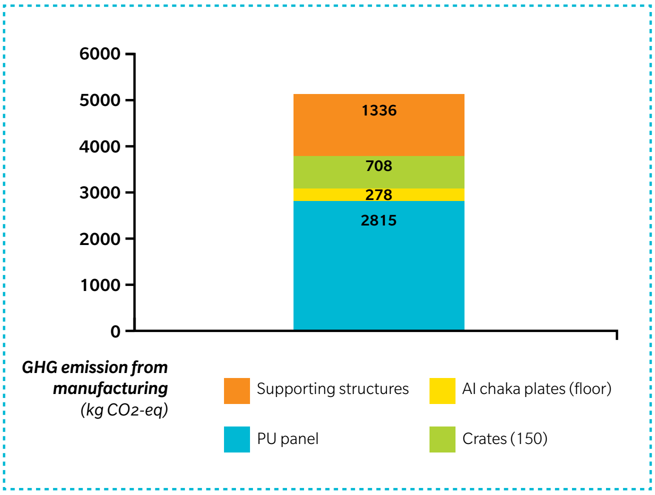
[94] World Steel Association, 2020. LCI of steel products. Available in LIFE CYCLE INVENTORY (LCI) REQUEST FORM | worldsteel

[95] Tschümperlin, L. Stolz, P. Franziska Wyss,F. and Frischknecht.R. 2016. Life cycle assessment of low power solar inverters (2.5 to 20 kW). Swiss Federal Office of Energy SFOE. Available in https://treeze.ch/

The total climate impact caused due to material extraction and construction of PU panels production is 2,815 kg CO_2-eq. GHG emissions from all the components used in the cold room is summarised in Figure 54. Total emissions from the manufacturing of 20m^3 cold room are 5,137 kg CO_2-eq. The manufacturing of PU panels including PU foam and galvanised steel lining causes 55% of the climate impact. Chaka plates for the floor, supporting structure and crates to store food contribute to 5%, 26% and 14% emissions, respectively.

Figure 54: GHG emissions from the material extraction and manufacturing of 20m^3 ColdHubs cold room

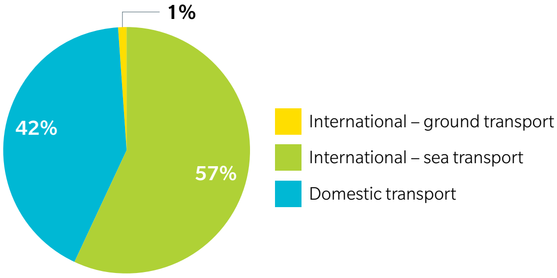


4.1.8 GHG emissions from transportation

GHG emissions from all the components used in the ColdHubs case study were estimated. Transportation distance was estimated from the manufacturing location of various items to the Owerri ColdHubs warehouse in Nigeria. Ecotrans IT World model is used to estimate emissions from logistical movements. Total emissions estimation from the logistical movement of items required for PV power production and the cold room is shown in below Table 22. Total emissions from the logistical movement of items needed for PV power production and manufacturing the cold room for 20 years lifespan is 646.70 kg CO_2-eq.

In the case of ColdHubs, most of the items are imported from Germany and Italy and transported to the ColdHubs warehouse in Owerri, Nigeria. Sea transport amounted to the highest emissions accounting for 57% of total emissions from transportation. International transport caused 58% emissions from logistical activities since further transportation overland is needed to reach the departure port in the manufacturing country. Some of the items are manufactured locally in Lagos, and 42% emissions arise from domestic transportation (see Figure 55). These results indicate that majority emissions are from international transport. Manufacturing items locally would lower transport emissions.

Figure 55: GHG emissions from international transport vs domestic transport



4.1.9 GHG emissions from the use phase of the cold room

GHG emissions from the use phase of any cold room would be mainly due to power consumption to operate the cold room and leakage (if any) of refrigerant in the cooling unit and blowing agent used in PU foams. GHG emissions from PV power production during the use phase are assumed to be negligible. As mentioned earlier, ColdHubs cold room uses the natural refrigerant, HC-290 which has a low global warming potential of 3 kg CO_2-eq/kg of refrigerant. As confirmed by ColdHubs design experts, at least 20% of refrigerant charged at the beginning (140 g) needs to be topped-up every year into the cooling unit. The total amount of leaked refrigerant over the 20 years of the use phase is 0.56 kg, which is expected to cause 1.68 kg CO_2-eq. emissions. It is worth noting that the Kigali amendment to the Montreal protocol, governing the usage of F-gases, is expected to have led to a reduction in refrigerant leak rates during use phases globally, due to increased monitoring and maintenance requirements. While this a low GWP refrigerant, anecdotal evidence suggests that this is a relatively high leak rate, perhaps something that can be improved as this technology is rolled out at scale.

Table 22: GHG emissions from the logistical movement of items required for PV system and cold room in ColdHubs

TOTAL GHG EMISSIONS	ITEMS	MANUFACTURING LOCATION	MATERIAL MASSES TRANSPORTED (20 YEARS LIFESPANS COLD ROOM)	GHG EMISSIONS (kg CO_2-eq)
PV power production	PV panels	Hamburg, Germany	340Wp × 18 = 405 kg	46.83
	Supporting structures	Lagos, Nigeria	350kg	15.05
	Solar array cable	Lagos, Nigeria	12kg	0.52
	Mass of invertors	Hamburg Germany	25 kg + 15 kg = 40 kg	4.63
	Mass of batteries	Hamburg Germany	61.3 kg × 72 batteries = 4414 kg*	510.39
	Power box	ColdHubs Nigeria	150 kg	17.35
	Cables and wires	Lagos, Nigeria	18 kg	2.08
Cold room	Cooling system	Sicily, Italy	52 kg	12.45
	Components in the cold room	Lagos, Nigeria	870 kg	37.41
Total GHG emissions				**646.70**

* Each set of battery has 24 batteries, and 3 sets of batteries are needed within a 20 year lifespans, so 72 batteries in total

ColdHubs uses polyurethane panels which are made locally by a company called Vitapur that use a blended blowing agent comprising of a natural blowing agent and HFC gas(es). Therefore, considering an expert's opinion on polyurethane panels manufacturing, it was assumed that 90% of the blend is a natural blowing agent like pentane, and the remaining 10% are HFC gases. The HFC blended system is a co-blown system in which HFC-365mfc, HFC-227ea, HFC-245fa are assumed to be included in equal proportions. The estimated climate impact due to the emissions of blowing agents during the use phase amounts to 460.97 CO2-eq. Total GHG emissions in the use phase are 462.65 kg CO2-eq due to refrigerant and blowing agent leakage.

4.1.10 GHG emissions from end-of-life management/disposal

It was assumed that informal recycling is the primary end-of-life disposal option at present in Nigeria. In general, informal activities in the WEEE recycling chain in Africa include collection, manual dismantling, open burning to recover metals and open dumping of residual fractions. Climate impact from ColdHubs 20m^3 cold room has been assessed over a 20 year lifespan. Therefore, it was assumed that after 20 years, both the PV power production system and the cold room need to be replaced. There is a possibility of expanding the PV system's lifespan and the cold room with proper maintenance. Therefore, this study also assesses extended lifetime scenarios (25 years and 30 years lifespans) under scenario analyses. This part of the assessment summarises the emission estimates from the end of the life PV system and the cold room management assuming a 20-year lifespan with informal recycling.

GHG emissions from informal recycling of PV power production system: the estimated emissions from informal recycling of different items used in the PV power production system are summarised in Table 23. The detailed methodology is the same as described in Chapter 3.1.10.

Recycling lead acid batteries is common practice in informal recycling as lead is a precious metal. In the lead acid battery manufacturing process, 70% of the lead used for the new batteries is retrieved from a recycling process, whereas 30% is made from new raw materials.[47] Thus, it was assumed only 30% of recovered lead would replace the virgin lead production, and therefore 30% of recovered lead is credited. Estimated emissions from informal recycling of PbA batteries indicate a potential for slight GHG savings through resource recovery which is amounted to -25.95 kg CO2-eq from 72 batteries used in 20 years lifespan (see Table 23).

The remote controller used in ColdHubs is a small item (0.4 kg mass) and mostly contains plastic and a wiring board. Therefore, it has not been included in recycling analysis since informal recyclers are not interested in recycling low value items.

Net GHG emissions from end-of-life solar power production system were estimated by aggregating net emissions from individual components, and this amounts to -1,214.98 kg CO2-eq. Due to the GHG savings potential from recycling of all the components used for PV power production, aggregated impacts show a net negative value indicating a GHG savings potential through resource recovery.

GHG emissions from informal recycling of end-of-life 20m^3 cold room: the recovered metal fraction from informal collectors is sold to local collection agents. It is assumed that these materials are eventually transported to smelting facilities. Most of the metals are assumed to be recycled within the country. Transportation emissions from the logistical movement of recyclables have not been calculated due to the unavailability of data about the location of the designated recycling facilities. Emissions and avoidance potential from informal recycling of items in the 20m^3 cold room are presented in Table 24. There is one monoblock cooling system in the cold room with a lifespan of 15 years. Therefore, emissions from production of 1/3 of the materials of the second cooling unit are considered for the remaining five years of a 20 year lifespan of the cold room. Net emissions from end-of-life cooling unit amounts to -122 kg CO2-eq resulting in emissions mitigation benefit.

The cold room consists of polyurethane panels, supporting structures, aluminum chaka plates on the floor etc. Informal collectors are expected to extract the steel fractions from panels, aluminum from chaka plates and the supporting structures. Aluminum chaka plates and aluminum rods have 46.86%[96] virgin aluminum. Recycling and recovery of aluminum from aluminum chaka plates and supporting structures have been credited back in calculations. Estimated emissions savings from recycling the materials from the end-of-life cold room are -1,426.89 kg CO2-eq.

Net emissions are estimated by aggregating emissions savings from cooling units and components of the cold room shown in Table 24. As a result of informal recycling of end-of-life items used in the 20m^3 cold room, 1,548.93 kg CO2-eq emissions can be saved via resource recovery.

Table 23: GHG emissions, avoidance and net emissions from informal recycling of PV power production system

TOTAL GHG EMISSIONS	ITEMS	TYPE OF MATERIAL RECOVERED BY THE INFORMAL COLLECTORS	GHG EMISSIONS FROM RECYCLING (kg CO2-eq) (A)	EMISSIONS AVOIDANCE VIA RESOURCE RECOVERY (kg CO2-eq) (B)	NET GHG EMISSIONS (kg CO2-eq) (C)=(A)+(B)
PV power production	PV panels	Aluminium frame	16.573	-448.025	-431.452
	Supporting structures	Metal (aluminium structures)	455.175	-835.975	-380.800
	Solar array cable	Copper cable	11.504	-29.058	-17.554
	Invertors	Copper, aluminium and steel	36.846	-225.431	-188.584
	Lead acid batteries	Lead component	1838.829	-1864.776	-25.947
	Power box	Steel	183.371	-336.779	-153.408
	Cables and wires	Copper	13.176	-30.407	-17.231
	Net emissions (kg CO2-eq)				**-1214.976**

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[96] Authors derived value based on the information in International aluminium organisation. Available in https://international-aluminium.org/statistics/primary-aluminium-production/

In addition, there are emissions from release of the refrigerant and the blowing agent into the atmosphere during the manual dismantling at the end-of-life of the cold room. Estimated climate impact from the release of refrigerant amounts to 0.56 kg CO_2-eq. There is no recovery of blowing agent from the end-of-life foam.

The foam used in a ColdHubs room is blown using a blended blowing agent (90% natural gas and 10% HFC blend) with the climate impact of 172.63 kg CO_2-eq/kg. There is no enforcement of regulation in place to avoid leakages in blowing agents from end-of-life. Total emissions due to the release of the blowing agent from the PU panel are 2,921 kg CO_2-eq.

Table 24: GHG emissions, avoidance and net emissions from informal recycling of items in the 20m^3 ColdHubs cold room

MAIN COMPONENT	ITEMS	TYPE OF MATERIAL RECOVERED BY THE INFORMAL COLLECTORS	GHG EMISSIONS FROM RECYCLING (kg CO_2-eq) (A)	EMISSIONS AVOIDANCE VIA RESOURCE RECOVERY (kg CO_2-eq) (B)	NET GHG EMISSIONS (kg CO_2-eq) (C)=(A)+(B)
Cold room	Cooling system	Steel, copper, aluminium	68.526	-190.560	-122.033
	Components in the cold room	Steel, aluminium	719.000	-2145.894	-1426.894
	Net emissions (kg CO_2-eq)				**-1548.927**

Total emissions/savings potential from end-of-life disposal

Total emissions/savings potential was estimated by accumulating emissions/saving potential from end-of-life PV power production and cold room under informal recycling, as well as leakage of the refrigerant and blowing agents during dismantling. The estimated net emissions from end-of-life management of all the items in ColdHubs amounts to 157.66 kg CO_2-eq (see Figure 56). Although informal recycling of all the items used in the PV system and cold room would contribute to savings (negative emissions values), substantial emissions caused from release of the blowing agent at the end of the life result in net positive emissions.

4.1.11 Net life cycle emissions from ColdHubs

Life cycle net emissions from PV power production: net life cycle emissions from PV power production amounts to 17,615 kg CO_2-eq (see Figure 57). The highest share of emissions occurs from raw material extraction and manufacturing phase. Total electricity production capacity within 20 years lifespan from PV system installed in ColdHubs case is 255,697 kWh, and estimated net emissions per unit electricity production would be 69 g CO_2-eq /kWh which is significantly lower than emissions from using electricity from the Nigerian grid (grid emission factor is 573 g CO_2-eq/kWh in Nigeria[62]) or running small diesel back-up generator (GHG emission factor is 807 g CO_2-eq/kWh[73]).

Figure 56: Net GHG emissions potential (emissions-avoidance through resource recovery) from informal recycling of various end-of-life items in a PV system and 20m^3 cold room

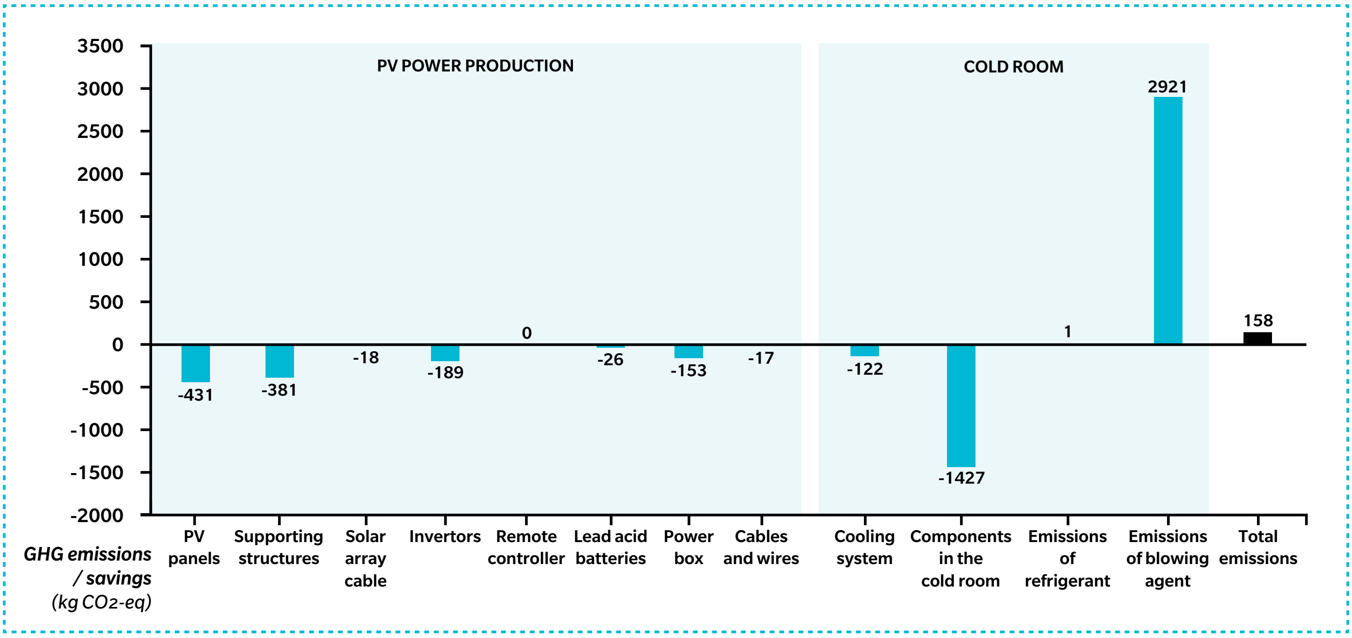
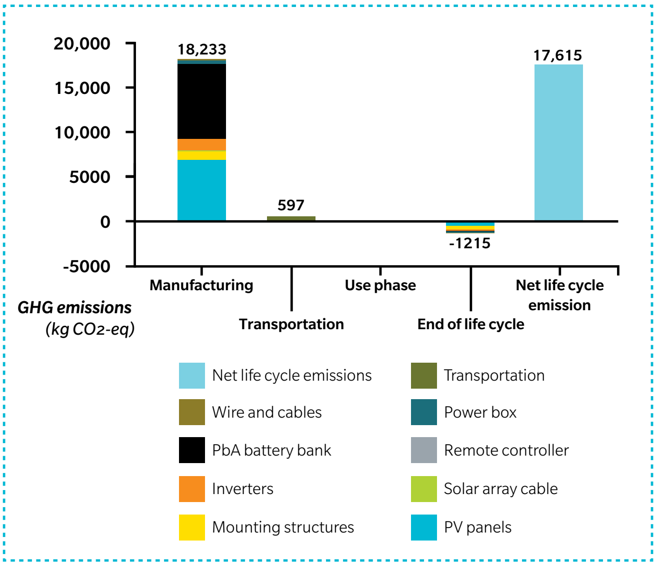
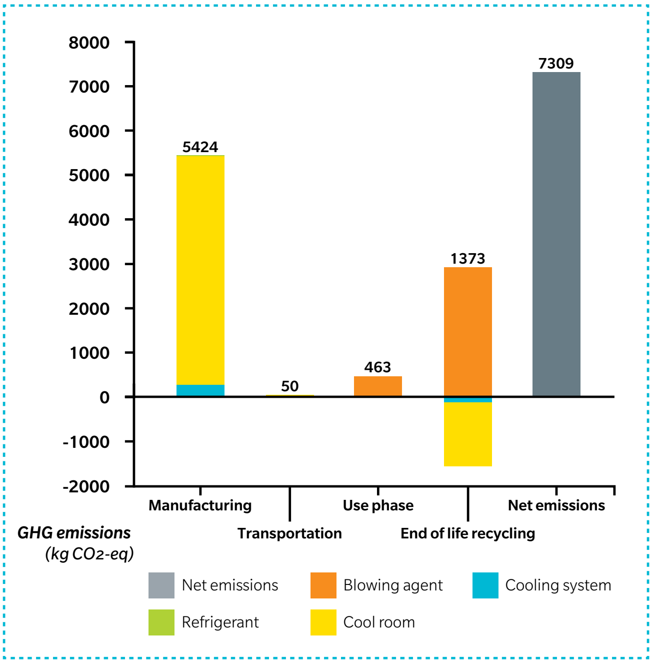


Figure 57: Net emissions from PV power production in ColdHubs



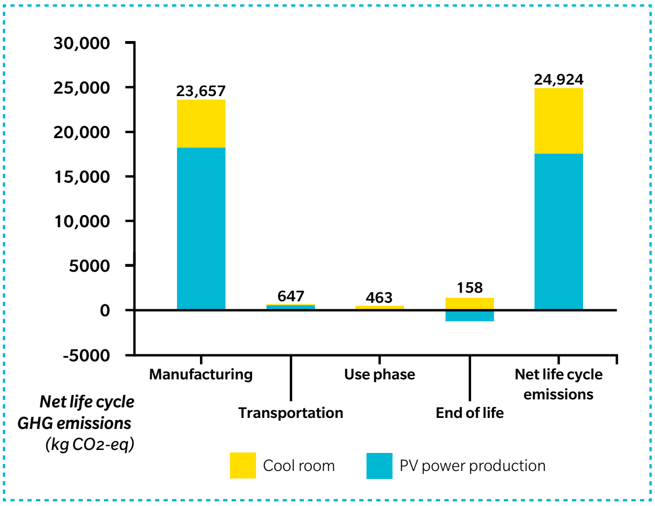
Life cycle net emissions from ColdHubs 20m^3 cold room: Life cycle net emissions from the cold room were estimated by aggregating emissions from the cooling unit and the cold room structure across all the life cycle phases. Raw materials extraction and manufacturing phase contributed to 5,424 kg of CO2-eq emissions, in which 95% emissions were attributed to the cold room, and the remaining 5% froto the cooling system. Emissions from the logistical movements are not significant and amount to 50 kg CO2-eq. Escaping refrigerant and blowing agents at the use and end-of-life phases would cause emissions of 463 kg CO2-eq and 2,922 kg CO2-eq of emissions, respectively. Resource recovery from informal recycling at the end of the life cycle shows the possibility of saving 1,549 kg CO2-eq of emissions. Estimated net life cycle emissions from the ColdHubs cold room amount to 7,309 kg CO2-eq (see Figure 58).

Figure 58: Net emissions from 20m^3 cold room in ColdHubs case



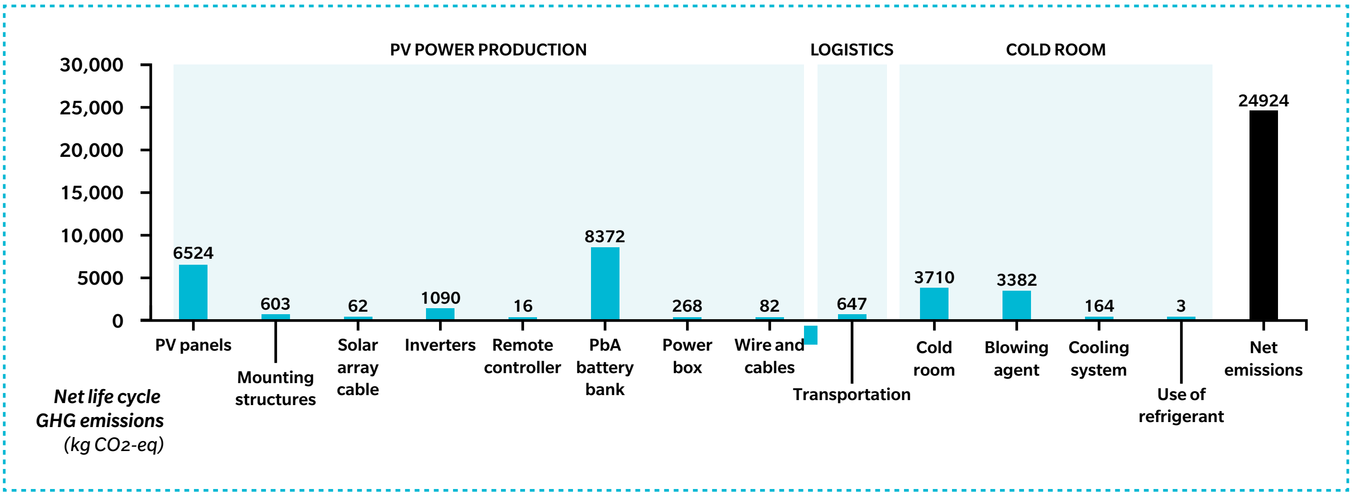
Net life cycle emissions from ColdHubs (both PV power production and cold room): Net emissions are estimated by aggregating net emissions from the PV system and the cold room. The raw material extraction, processing, and manufacturing of the PV system and the cold room resulted in considerable emissions of 24,924 kg CO2-eq. 77% of the manufacturing phase emissions are related to material extraction and manufacturing emissions from the PV system, and the remaining 23% is associated with the cold room (see Figure 59). Emissions from transportation of all the items contributed to 647 kg CO2-eq, only 2.6% of net life cycle emissions. During the 20 years of use phase of the cold room, emissions caused due to leakage of refrigerant and blowing agent contributed 1.9% of net life cycle GHG emissions. The remaining 0.6% of life cycle emissions are caused by informal recycling activities at the end-of-life. GHG savings via recovered resources have compensated the blowing agent emissions at the end-of-life cycle, which indicate relatively low emissions in the end-of-life phase.

Figure 59: Net life cycle GHG emissions from a 20-year lifespan from the ColdHubs cold room



The total net life cycle emissions from ColdHubs are 24,924 kg CO2-eq (see Figure 59). Furthermore, net life cycle emissions from individual items used in the ColdHubs case study were assessed to identify emission hotspots (see Figure 60). The highest emissions are related to the lead acid battery bank followed by PV panels, cold room and the blowing agent. It should be noted that the blowing agent features as one of the emission hotspots, even when 90% of the agent is propane.

Figure 60: Net life cycle emissions from individual components of ColdHubs case study



4.1.12 GHG emissions per unit of cooling energy

The general method for calculation of the GHG emissions per cooling energy unit can be found in Section 1.7. For the ColdHubs' cold room, the cooling energy is calculated using the same monthly thermal model as used in Section 3.1.12, which calculates thermal losses, infiltration losses and food cooling energy required using the following assumptions:

- Cold room dimensions and insulation levels as detailed in inventory
- Coefficient of performance of cooling unit extracted from datasheet for specific cooling unit used
- Climate conditions for Lagos, Nigeria
- Internal set point temperature of 10°C
- One air change per day for infiltration losses
- Multiple food cooling scenarios used (see below)
- Initial food temperature of 27°C

The ColdHubs 20m^3 cold room is operated in two different loading scenarios, which will be examined for this calculation:

- Three tonnes of produce are loaded into the cold room at the start of the week and is gradually emptied over the course of the week. In this scenario, the fridge works hard to cool down the food on the first day and then the subsequent days it just needs to account for thermal and infiltration losses. In some ways the fridge is oversized, although the size may be needed to cool the food on the first day.
- The maximum amount of food is loaded into the cold room per day in a high turnover scenario. In this scenario the fridge is often opened and closed and works very hard. We have calculated that the maximum amount of food that could be loaded into the fridge and cooled on a daily basis is 2.2 tonnes.

The cooling energy required was calculated to be 4029 and 16090 kWh per year for the three tonnes per week and optimum scenarios respectively. Using the total emissions (24,924 kg CO_2-eq) over a 20-year lifespan, this gives 309 and 77 g CO_2-eq/kWh for the two scenarios. Figure 61 shows the emissions per cooling energy unit for the three tonnes per week scenario and Figure 62 shows the same for the optimal loading. This highlights the benefits of utilising the cold room to the maximum level where possible, with a fourfold decrease in emissions per unit of energy cooled. It should be noted that these numbers may be a slight overestimation of the benefits as higher utilisation would also lead to an increase in maintenance and in turn, the need to replace components which would reduce the benefits. However, these increased emissions are not likely to be high enough to wipe out the benefits. Additionally, increasing the system lifetime to 30 years can reduce emissions per kWh and cooling energy by 22%.

Figure 61: Comparison of the emissions per cooling unit for ColdHubs' cold room with a three tonne per week loading scenario.

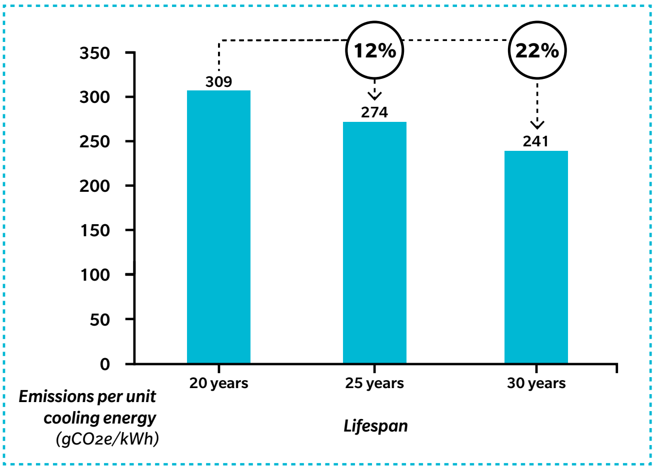
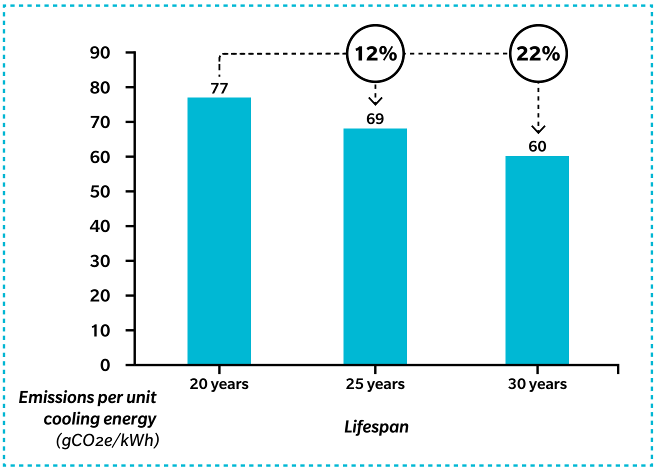


Figure 62: Comparison of the emissions per cooling unit for ColdHubs' cold room with an optimal loading scenario.



4.2 Scenario analysis for ColdHubs

As explained in Section 3.2, various factors such as choice of materials and component types, cold room design, disposal practice and so on, can impact life cycle emissions. This part of the analysis helps show how the emissions will vary if each of these factors is changed.

4.2.1 Analysis of the effect of the type of refrigerant on climate impact

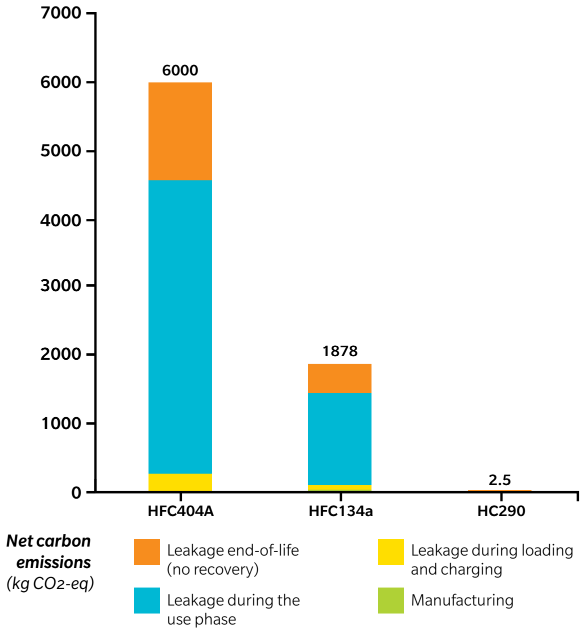
Details related to the type of refrigerant used in ColdHubs and its climate impact is described in Section 3.2.1. ColdHubs uses HC-290 (propane), a natural refrigerant, which has very low GWP (GWP-3). Like HC-600a (iso-butane), the use of HC-290 in cooling technologies is also increasing due to its low environmental impact and excellent thermodynamic performance. HC-290 is used as an alternative to R-404A and R-407 series refrigerants in new cooling systems. However, some manufacturers are still using the HFC gas, HFC-134a, which is a widely used refrigerant in industrial chiller units,[97] and R-404A in cold storage applications. Thus, a comparative assessment of climate impact from R-404A, HFC-134a and HC290 is described here.

Global warming-related to refrigerants occurs when refrigerant gases leak into the atmosphere. These leakages could occur during the filling or re-filling of gases in cooling units during the use phase or during the disposal phase at the cooling system's end-of-life (dismantling or recycling). Experts at ColdHubs confirmed that at least 20% of the refrigerant charged at the beginning needs to be topped-up every year during the use phase due to the possible leakages.

In general, the amount of charge of HC290 is relatively lower in mass compared to HFC gases. The required amount of HC-290 would be 40% lower than HFC-134a[98] and 48% lower than HFC404A. The original charge and the top-up amount of HFCs refrigerants were estimated using above mentioned ratios relative to the HC290. ColdHubs cold room has only one cooling unit, and lifespans are limited to 15 years. In the beginning, 140 g of HC-290 was charged as the refrigerant. After that, 28g (20%) of refrigerant is expected to be topped-up every year during the 15 years of use phase. After 15 years, the old cooling unit will be replaced with a new cooling unit. Thus, 1/3 of the climate impact caused due to the use of refrigerant in the second cooling unit is allocated to find the total emissions within a 20-year lifespan. Similarly, the required amount of HFC-134a and HFC404A refrigerants is estimated to provide the same function. At the end of the life cycle, any remaining refrigerant is expected to leak into the atmosphere at the time of recycling or dismantling.

Figure 63 summarises the climate impact caused by HC-290, HFC-134a and HFC404A refrigerants which are required to maintain equivalent functions in 20m^3 cold rooms for 20 years lifespan. Total climate impact due to the use of HC290, HFC-134a and HFC404A amount to 2.5,1,878 and 6000[99] kg CO2-eq, respectively. Thus, 99.9% of climate impact that could have been caused by HFC based refrigerants, is avoided, by using a natural refrigerant, even if the same leak rate is realised.

Figure 63: Potential emissions from the most prominent types of refrigerants used for cold rooms (comparison assessment of the use of natural refrigerant vs HFC based refrigerant)



4.2.2 Analysis of the effect of blowing agents on climate impact

General information related to the use of natural or HFC based blowing agents has been presented in the previous case study (see Section 3.2.2). Polyurethane panels used in the ColdHubs cold room are partially blown with HFCs. For the purposes of this analysis, it was assumed that 90% of the blowing agent blend is pentane, a natural blowing agent and the remaining 10% is an HFC blend. The HFC blended system is a co-blown system in which HFC-365mfc, HFC-227ea, HFC-245fa are blended in equal proportions.

HFC-245fa is the most prominent blowing agent in the off-grid market in Africa, with a very high GWP (GWP -1030). Therefore, a comparative assessment was performed to assess the climate impact from using foams with 100% natural blowing agent such as pentane, that has a GWP value of 5, natural gas and HFC blend used in ColdHubs case, that has a GWP value of 173 and using 100% HFC-245fa blowing agent that has a GWP value of 1030.

The amount of blowing agent required for manufacturing cold room PU foams and its climate impact is presented in Annex B-2.3. Emissions from the manufacturing of blowing agents are not included in this part of the analysis as it is accounted for in

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[97] Water Chiller, 2019. Common refrigerant used in the chillers. https://www.waterchillers.com/blog/post/types-of-refrigerant-used-in-chiller-plant

[98] Hydrocarbons, 2011. Available in http://hydrocarbons21.com/articles/2712/hydrocarbon_refrigeration_what_every_technician_should_know_part_1

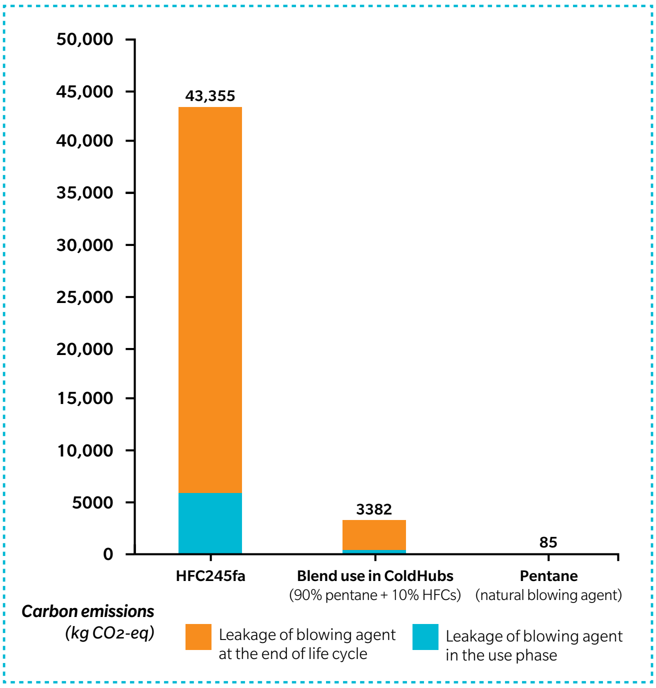
[99] There is no available data on manufacturing emissions of HFC404A and authors assumed that manufacturing emissions is similar to HFC134a. However, according to the analysis, manufacturing emissions of refrigerant is not significant, and it is less than 1% life cycle emissions of HFCs refrigerants

the PU foam production emissions. Approximately 6% of the blowing agent used in the foam insulation material is assumed to be released during the first year, and 0.5% /year thereafter.[55] Any remaining blowing agent in the panels would eventually be emitted into the atmosphere by the end-of-life of the cold room in the absence of an appropriate recovery system. Estimated emissions from the use of blowing agent required to produce polyurethane foam for a 20m^3 cold room using 100% pentane, 90% pentane + 10% HFCs blend and 100% HFC-245fa are 85 kg CO_2-eq, 3,382 kg CO_2-eq and 43,355 kg CO_2-eq, respectively, see Figure 64. These results help highlight the climate impact associated with the choice of blowing agent used in manufacturing panels for the cold room.

It should be noted that this estimation is sensitive to the assumptions undertaken in the analysis. The assumption of a 10% HFC blend is a conservative one, and if the proportion of the HFC blend in the blowing agent mix is greater, the estimated climate impact in the ColdHubs case would increase drastically depending on the change in proportions.

Most HFC gases remain in the panels at end-of-life. Polyurethane panels that are blown with HFCs may be incinerated in order to minimise the emissions, compared to being shredded and sent to a landfill which leads to the highest potential emissions. There would be a small amount of emissions from the energy required for the combustion process during incinerating PU foams, but the mitigation benefit from avoiding leaking these gases is far higher.

Figure 64: GHG emissions from the use of different blowing agents in the production of PU forms required for 20m^3 ColdHubs cold room



4.2.3 Impact of end-of-life disposal practice on emissions from solar power production and cold rooms

As mentioned in the previous chapters, this analysis considers three disposal methods for the scenario analysis: complete dumping (100%) without any recycling, informal recycling, and formal recycling. Please read session 3.2.3 for more information about these three disposal options with respect to the end-of-life treatment of cold rooms.

100% open dumping without any recycling scenario: the only emissions arising from open dumping of end-of-life items in ColdHubs cold room would be due to the escape of refrigerant and blowing agent into the atmosphere. ColdHubs uses a natural refrigerant (HC-290), which means that the climate impact from the emission of this is very low. For instance, the release of refrigerant under open dumping emits 0.56 kg CO_2-eq. Polyurethane panels used in ColdHubs cold room is blown with a blend (90% pentane +10% HFCs). The release of blowing agent at the disposal phase into the atmosphere in the absence of any recovery would cause 2,921 kg CO_2-eq emissions. Considering the climate impact caused due to both refrigerant and blowing agents, the total climate impact under open dumping is 2,922 kg CO_2-eq. In addition, various other harmful environmental impacts are caused by open dumping of end-of-life PV systems and cold rooms due to the leakage of heavy metals and other toxic material into the environment.

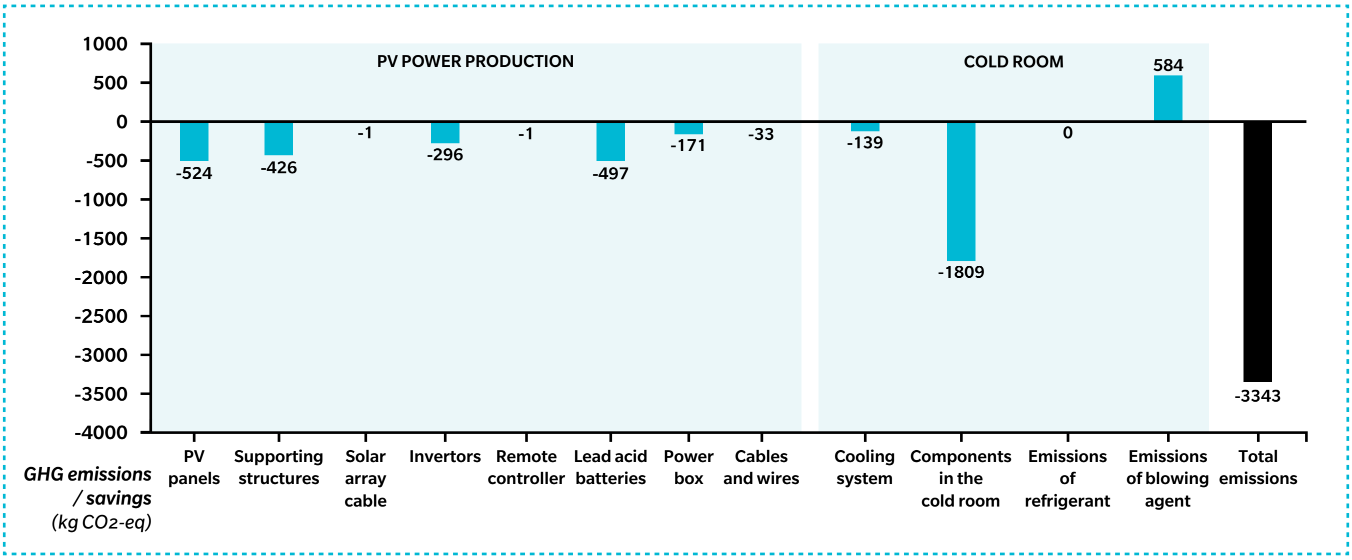
Informal recycling: in this scenario, part of the materials from the PV panels, supporting structures, solar array cables, lead acid batteries, cooling system, polyurethane panels in the cold room are collected by informal recyclers as they are interested in precious metals such as steel, aluminium, copper, lead etc. The detailed assessment of the impact of informal recycling is presented in Section 4.1.10 under end-of-life disposal phase.

Energy consumption (grid electricity and fossil fuel consumption) during informal recycling causes emissions. In addition, the release of blowing agent at end-of-life causes significant emissions. Resource recovered from valuable metals collected by informal recyclers would be useful to avoid virgin production of an equivalent amount of materials. The emissions saving potential from individual components used in the ColdHubs case study is presented in the previous section under end-of-life treatment analysis, (see Figure 65). Total net emissions estimated by accumulating net emissions from all the items amounted to 158 kg CO_2-eq. Although informal recycling of all the items would contribute to GHG savings, substantial GHG emissions would occur from blowing agent at the end of the life cycle, resulting in net GHG emission potential from end-of-life management.

Formal recycling: general information related to formal recycling has been presented in the previous sections. Implementing an appropriate formal recycling mechanism would support recovery of the maximum amount of valuable metals/materials from end-of-life PV systems and the cold rooms.

A formal recycling mechanism would include a proper collection mechanism of end-of-life items followed by appropriate dismantling and recycling. In this scenario, the refrigerant and the blowing agent are assumed to be recovered adequately, that would avoid release of harmful HFCs into the atmosphere. Most of the metal /material can be recycled through the formal recycling mechanism, and therefore, emissions savings potential would be higher than informal recycling. It was assumed that 20% of end-of-life blowing agents would escape into the atmosphere during the recovery process and the remaining 80% would recover under the formal recycling mechanism. A detailed assessment was carried out for estimating emissions under the formal recycling route of end-of-life items of PV power production and cold rooms at the end of 20 year lifespans, see Figure 65. Net climate impact from the formal end-of-life recycling of all the items is -3,343 kg CO2-eq.

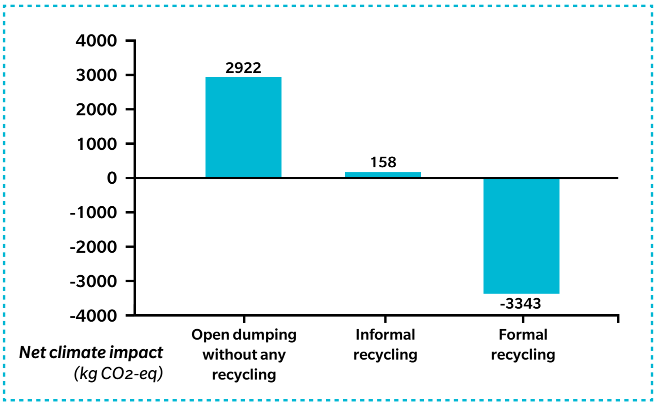
Figure 65: Net GHG emissions from formal end-of-life recycling of items used in ColdHubs cold room



Comparison of end-of-life management scenarios of the PV system and cold room: Net climate impact from end-of-life disposal options were assessed and presented in Figure 66. There are positive emissions associated with open dumping without any recycling as the refrigerant and the blowing agent is eventually expected to escape into the atmosphere.

Despite the emissions saving potential from all the items under informal recycling, net emissions from informal recycling are positive due to substantial emissions from the release of the blowing agent, which allows 10% HFCs into the atmosphere. It should be noted that burning plastic components to extract metal fractions in informal recycling emits significant amount of black carbon (BC), which is 1055–2020 times more potent than CO2 over a 100-year time horizon[56]. However, estimations of BC emissions are outside the scope of this study; the real climate impact from informal recycling is expected to be much higher if BC emissions are accounted. Formal recycling processes would contribute to the GHG savings potential, through resource recovery from all the items and recovery of 80% of the blowing agent at the end of the life cycle. Therefore, net GHG saving potential from formal recycling is considerably higher than informal recycling.

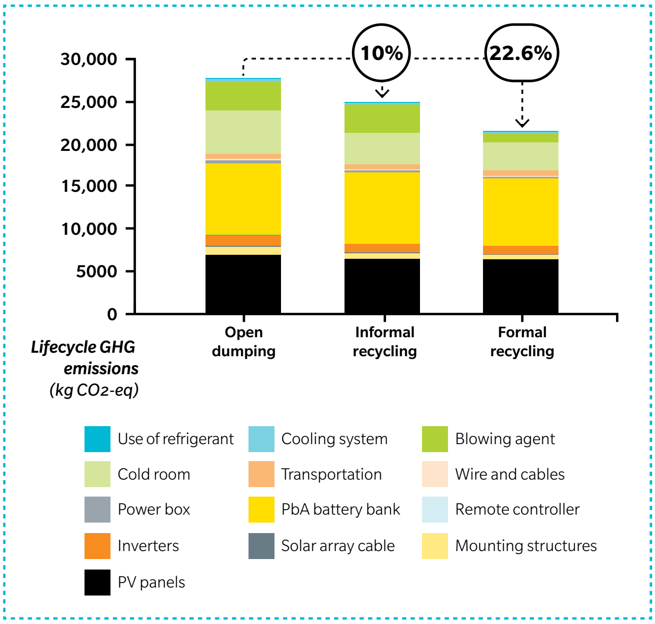
Figure 66: Net GHG emissions from end-of-life disposal method for ColdHubs



4.2.4 Net life cycle emissions from ColdHubs with different end-of-life treatment options

Net life cycle emissions from all the components used in both PV system and cold room after factoring in emissions from end-of-life management are 27,688, 24,924 and 21,423 kg CO2-eq for open dumping without any recycling, informal recycling and formal recycling, respectively (see Figure 67). This analysis helps understand that improvements in recycling rate and resource recovery rate has considerable potential to reduce life cycle emissions. For instance, implementing informal and formal recycling mechanisms can avoid life cycle emissions by 10.1% and 22.6% compared to open dumping practices, respectively.

Figure 67: Net life cycle emissions from ColdHubs across different end-of-life treatment options for a 20-year lifespan



4.2.5 Emissions reduction potential by increasing serviceable life

The default lifetime of PV system and the 20m^3 cold room is 20 years, but with careful management they could be utilised for more than 20 years. In these scenarios, it was assumed that all the items would be replaced once they reached the given lifespans. For example, 72 lead acid batteries (2V × 990 Ah) are required to store energy in a 20-year lifespan, which would increase to 84 and 96 if the lifespan expands from 25 years to 30 years. Similarly, the cooling system should be replaced every 15 years. Therefore, emissions were estimated considering replacing all the items when they reach the endorsed lifespans.

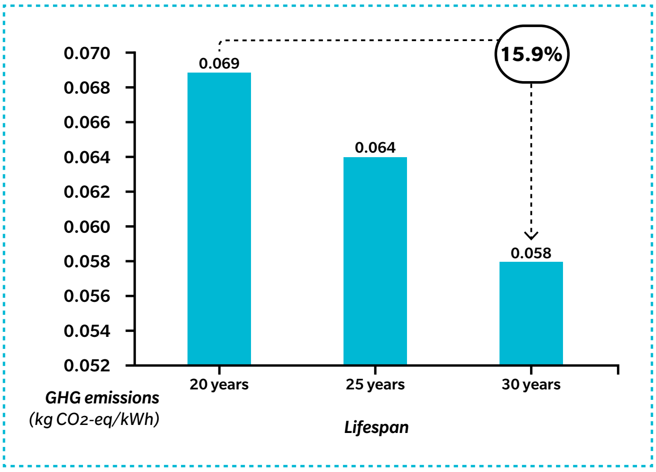
Emissions per unit (kWh) of electricity production were analysed for three different lifespans, 20, 25 and 30 years. Total power production capacity from 18 polycrystalline PV panels was estimated, assuming at least 6 hours of typical peak sunlight is received every day. Further, it was assumed that 0.5% of the PV panel is degraded each year till the end of the lifespan. With these assumptions, the estimated electricity production from ColdHubs PV system are 255,697 kWh for a 20 year lifespan. The estimated emissions per kWh electricity production in 20 years from the PV system are 69 g CO_2-eq/kWh with informal recycling at end-of-life.

As mentioned in the previous sections, with appropriate system maintenance, solar panels can last up to 30 years[59] and their typical warranty period is around 25 years. Emission estimates per kWh electricity production from 20 years, 25 years and 30 years lifespans of PV panels were estimated to help quantify the impact of extending serviceable life. The estimated emissions from 20, 25, and 30 years of the lifetime PV system would be 69g CO_2-eq/kWh, 64 g CO_2-eq/kWh and 58 g CO_2-eq/kWh, respectively, with informal recycling at end-of-life. If the lifespan is extended further with proper maintenance, emissions per unit of electricity production can be reduced further.

The assessment results were compared with a critical meta-survey on the LCA assessment of solar power production (including mounting structures, cabling and interconnection components, and inverter)[61] which concludes that the average life cycle greenhouse gas emissions for solar PV average to 49.9 g CO_2-eq/kWh. Emission factors of solar power production for the ColdHubs case are higher than the average value given in the meta-survey study. At the same time, ColdHubs emission factors are still substantially lower than the grid electricity mix (573 g CO_2-eq/kWh) in Nigeria.[62]

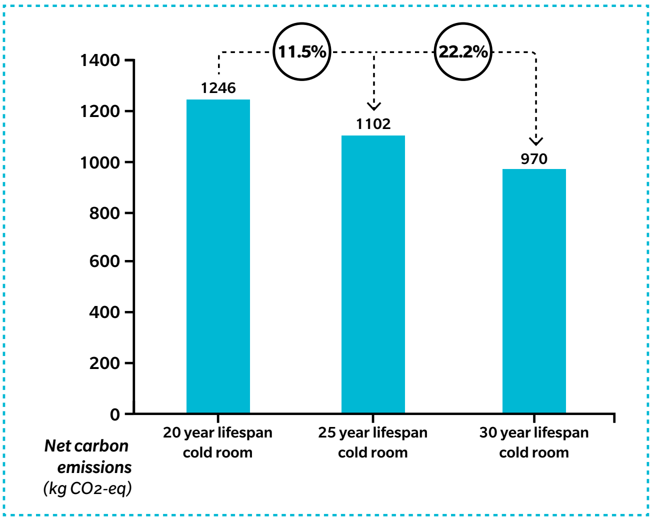
Further, emissions reduction potential per unit electricity production from 30 years lifespan PV system is 15.9% lower compared to the 20 years lifespan system with informal recycling at the end of the life cycle (see Figure 68).

Figure 68: Life cycle GHG emissions per kWh electricity production from different PV system lifespans with respect to current and future scenarios in ColdHubs case study



The life cycle net emissions from the ColdHubs 20m^3 cold room project are 24,924, 27,560 and 29,085 kg CO_2-eq for a 20-, 25- and 30-year lifespans respectively. Net emissions of cold room per year for different lifespans with informal recycling as the end-of-life disposal option are estimated and presented in Figure 69. Increasing the system serviceable life can be a key strategy for maximising emissions savings. For example, if the serviceable life of the ColdHubs system (both PV system and cold room) is expanded to 25 and 30 years respectively, 11.5% and 22.2% emissions can be avoided as compared to a 20 year lifespan with informal recycling at end-of-life. There would be additional climate benefits from reducing fossil energy/virgin resource consumption that would otherwise be required to manufacture new cold room systems to replace retired ones.

Figure 69: Life cycle net emissions per year: Lifespans vs disposal methods



4.2.6 Emissions from lead acid battery vs lithium-ion battery banks

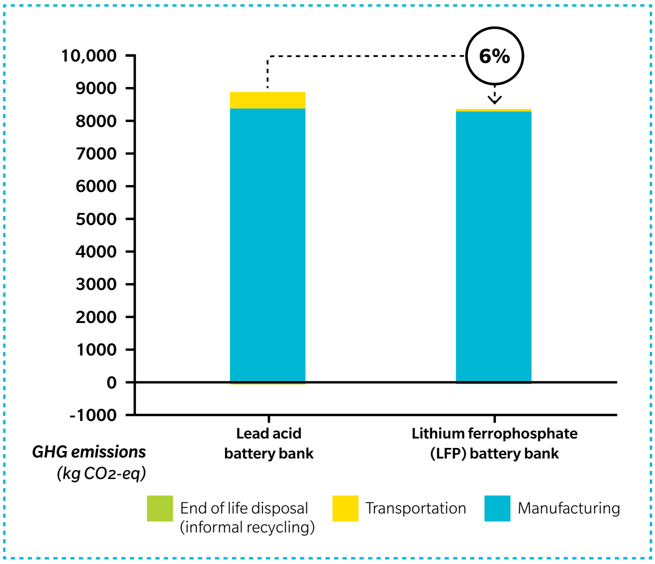
A description of the most popular types of batteries used in the off-grid market has been presented in Section 3.2.6. Lead Acid (PbA) batteries and lithium batteries such as lithium ferrophosphate (LFP) are popular batteries used in the off-grid solar markets. This section details the climate impact from an equivalent amount of lead acid and lithium-ion battery banks that would be required to power the 20m^3 ColdHubs cold room. This analysis assumes that materials are informally recycled at end-of-life. Specifications for lead acid and lithium-ion batteries required for PV power storage in ColdHubs cold room are summarised in Table 25.

Emissions from transportation of lithium-ion batteries were estimated, assuming that the batteries are manufactured in Germany, similar to the lead acid battery bank and transported to the project location in Nigeria. Emissions in informal recycling of lead acid battery banks were also accounted. As previously mentioned, the informal sector does not recycle lithium batteries due to the complexity in extracting valuable metals. Therefore, end-of-life emissions from informal recycling of LFP batteries is assumed to be negligible.

Total emissions potential from lead acid and lithium-ion batteries required to store power in the 20 year lifespan of a ColdHubs cold room were estimated. Net life cycle emissions (emissions from manufacturing, transportation and end of informal recycling) from the lead acid battery bank (72 batteries in 20 years lifespan) amounts to 8,883 kg CO_2-eq. The highest amount of emissions resulting from raw material extraction and manufacturing of the lead acid batteries amounted to 95% of life cycle emissions.

Similarly, net life cycle emissions from lithium-ion batteries required to provide an equivalent function within a 20 year lifespan amounts to 8,372 kg CO_2-eq. It should be noted that the approximate lifespans of lithium-ion batteries is 13.6 years.[100] Therefore, a 47% battery life of a second lithium-ion battery bank is required to supplement battery requirement for a 20-year lifespan of the cold room. 47% of net life cycle emissions from the battery bank are accounted for in the second set of the batteries, assuming that the remaining battery life of the second set will be utilised for some other purpose. The analysis results reveal that emissions from use of batteries can be reduced by 6% by shifting to lithium-ion batteries from lead acid batteries (see Figure 70). Furthermore, incorporating thermal storage to partially replace or completely replace chemical batteries would also significantly reduce emissions from the cold room.

Figure 70: Net life cycle emissions kg CO_2-eq from lead acid battery bank vs lithium-ion battery bank designed for 20m^3 ColdHubs cold room



4.2.7 Potential emission savings from substituting virgin material use with recovered materials at a cold room's EOL

Mining and extracting abiotic resources such as precious metals and fossil-based plastics used to manufacture PV systems and cold rooms contribute to significant emissions. According to the

Table 25: Specifications of lead acid and lithium-ion batteries required for PV power storage for 20 years ColdHubs cold room lifespan

DESCRIPTION	UNIT	LEAD ACID BATTERY BANK (EXISTING SYSTEM IN COLDHUBS)	LFP BATTERY BANK[a]
Battery voltage	V	2	48
Battery capacity	Ah	968	115
Battery capacity	Wh	1936	5521
Number of batteries in a battery bank	Number	24	7
Battery bank rated capacity	Wh	46,464	38,649
Assumed round trip efficiency	Percentage (%)	81	93
Assumed charging/discharging efficiency	Percentage (%)	90	96
Depth of discharge (DOD)	Percentage (%)	80	90
Usable capacity	Wh	37,171	34,784
Incorporating efficiency	Wh	33,454	33,393
Average lifetime of battery	Years	7	13.6
Number of replacements within 20 years	Number	3	2
Total number of batteries required	Number	72	14
Approximate mass of a battery	kg	61	62
Total mass of the batteries used within 20 years lifespans	kg	4414	868
Approximate energy density of battery	Wh/kh	32[b]	89[c]

[a] Values derived based on 47,63,68, [b] Energy density of lead acid battery[47], [c] Energy density of LFP and NCM[63]

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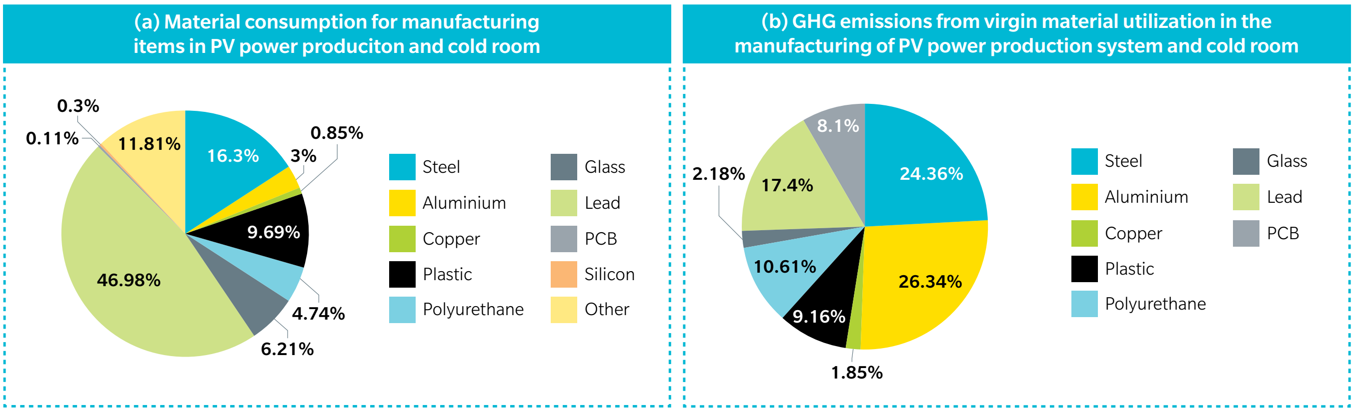
[100] IRENA, 2021. Available in https://www.irena.org//media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf

mass balance of the raw materials used in the ColdHubs case study, 46.98% of the mass consists of lead. ColdHubs uses 24 lead acid batteries. The mass of each battery is 61.3 kg, and 71% of the mass of the battery is lead in which 30% of lead accounted as virgin lead. Batteries need to be replaced at least two times in a 20-year cold room lifespan. Therefore, lead represents the highest share (46.9%) of material composition (see Figure 71a). Other prominent materials used are steel (16.3%), aluminium (3.0%), copper (0.85%), plastics (9.69%), polyurethane (4.74%), glass (6.21%), PCB (0.11%), silicon (0.3%) and other (11.81%), see Figure 71a.

Emissions contribution from production of different types of virgin materials used in the manufacturing phase is presented in Figure 71b. The highest emissions are caused by aluminium, followed by steel, lead, polyurethane, plastics, materials in PCB, copper and glass. It should be noted that although lead shows the highest percentage in material composition, GHG emissions from lead is not the highest. In the lead acid battery manufacturing process, 70% of the material used for the new batteries is retrieved from a recycling process, whereas 30% is made of new raw materials.[47] Thus, it was assumed that only 30% of lead used for battery manufacturing was from virgin resources; its corresponding volume of emissions is less than that from virgin steel and aluminium production.

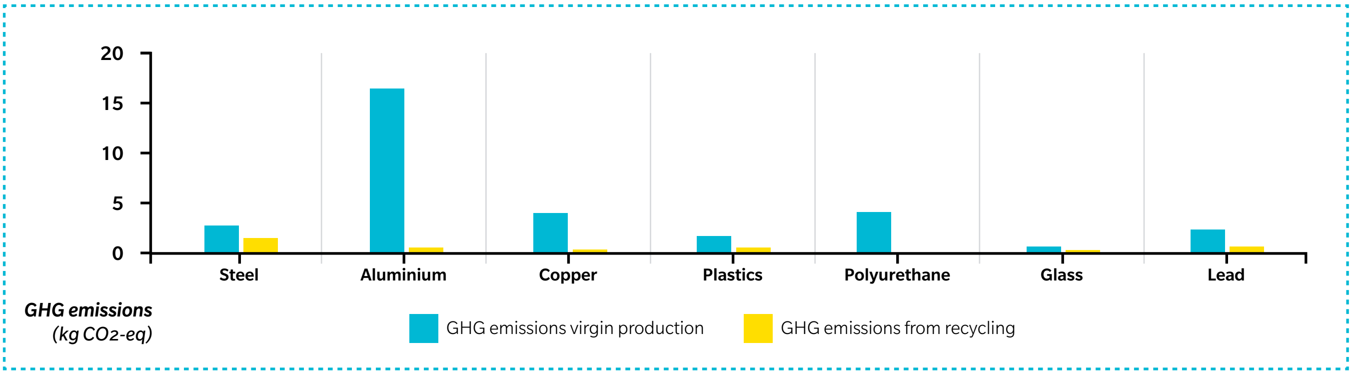
Recycling end-of-life PV systems and cold rooms could significantly reduce primary resource extraction. Recently Waste Electrical and Electronic Equipment (WEEE) has been identified as a secondary source of various metals as they contain many kinds of metals, including precious metals and less common metals. Besides, this allows the recovery of a considerable amount of less valuable materials like plastic. Materials retrieved from end-of-life PV systems and cold rooms would contribute as secondary reserves. Recovered resources can be an excellent solution to replace virgin fossil fuel and metal consumption and can help to reduce abiotic resource depletion. Emissions from virgin production per kg mass and production of an equivalent amount from the recycling of end-of-life PV system and cold room are presented in Figure 72. The highest level of emissions are associated with virgin aluminium production and recycling every bit of aluminium would contribute to significant emissions savings. The equivalent amount of material recovery from recycling all kinds of materials would emit lower levels of emissions than virgin production.

Figure 71: (a) Mass balance of raw material consumption (b) GHG emissions from virgin material production from all the items used in ColdHubs cold room (including the PV system) within a 20-year lifespan


(a) Material consumption for manufacturing items in PV power produciton and cold room

(b) GHG emissions from virgin material utilization in the manufacturing of PV power production system and cold room

Figure 72: GHG emissions/savings potential from the production of unit mass (1kg) of materials from virgin process and recycling



4.2.8 Analysis of the GHG emissions impact from using different energy sources

A ColdHubs cold room is also a Solar Direct Drive technology, so similar to Section 3.2.8, it would be useful to demonstrate the climate impact of ColdHubs cold room using different energy sources. This chapter will compare the climate impact of using the Coldhubs cold room powered by solar PV, Nigerian grid electricity or fossil fuel powered back-up generators during a 20-year lifespan with an informal recycling method.

Similar to the methodology in Sections 2.4.9 and 3.2.8, the authors have assumed the emission of an AC compressor is the same as a DC compressor for the purpose of simplifying this analysis regarding different energy sources. The approximate cooling energy requirement for operating the ColdHubs cold room would be 6,792 kWh/year with 10°C cold room set point temperature and 2.2 tonnes of food/day loading condition. Based on this figure, the total energy consumption for a 20 year lifespan of a 20m^3 ColdHubs cold room would be 135.8 MWh. The net GHG emission of PV power production system is 17,615 kg CO_2-eq with a 20-year lifespan.

GHG emissions factor for grid electricity production in Nigeria is 0.573 kg CO_2-eq/kWh.[62] With these figures, total GHG emissions from grid electricity consumption during the 20 year use phase of the cold room are 77,836 kg CO_2-eq. Small diesel back-up generators, which are appropriate in this application, produced electricity with GHG emission factor of 0.807 kg CO_2-eq/kWh. Therefore, the total GHG emissions from running small diesel back-up generators during the 20-year use phase of the cold room is 109,623 kg CO_2-eq. This calculation assumes that the Nigerian grid emission factor and the small diesel generator's emission factor will not change significantly over the next 20 years.

Total life cycle GHG emissions from the 20m^3 ColdHubs cold room is 7,308 kg CO_2-eq and was estimated by aggregating the emissions from different life cycle phases. It is assumed that the cold room will be informally recycled at end of life in keeping with Africa's low formal recycling capacity.

Figure 73: Comparison of 20m^3 ColdHubs coldroom powered by different energy source

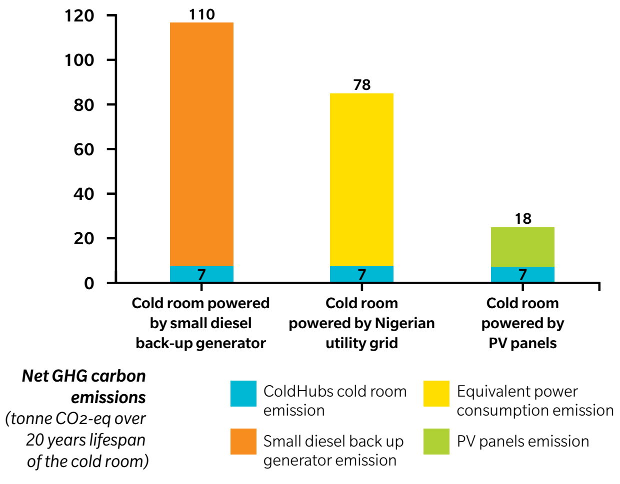


Figure 73 illustrates the impact of different energy sources on the overall emissions of the ColdHubs cold room. Comparative life cycle assessments of using the ColdHubs cold room with solar PV vs. using it with small diesel generator or utility grid revealed that running this cold room with solar PV will lead to a 78.7% or 70.7% GHG emissions reduction respectively. This assessment discovered that cold rooms powered by solar PV could contribute to significant emissions savings compared to those powered by grid or diesel back-up generators. This is especially true for cases where the utility grid mix has a greater proportion of non-renewable sources of power.

4.2.9 Impact of PV panel efficiency on GHG emissions

Most polycrystalline photovoltaic panels used for solar projects today are between 15% - 17% efficient.[101] Monocrystalline solar panels are more efficient than polycrystalline solar panels. Recently developed high-quality monocrystalline solar panels can exceed 22% efficiency and can be up to 23% efficient.[59] Efficiency is critical in maximising electricity production from the PV system and minimizing the number of panels used to provide equivalent function. In the ColdHubs cold room, 340 Wp ×18 polycrystalline panels with an efficiency of 17.52% have been used to supply the 6120Wp power demand in the cold room. These are 72 cells panels with the dimension of 1956 × 992 × 40 mm.

Shifting to more efficient panels would be one possible way to reduce emissions from the existing PV system. There are 380 Wp polycrystalline panels with 72 cells and 21.7% efficiency available in the market, with lower dimensions (1721 × 1016 × 30 mm) as compared to the existing panels. This high-efficiency rate means they produce more power per square foot and are therefore very space-efficient. The area of a 340Wp panel used in the ColdHubs cold room is 1.94m^2, while the area of 380Wp high efficiency (21.7%) panel is 1.75m^2. As the panel area reduces, it saves the amount of material and energy used and therefore reduces GHG emissions. If ColdHubs were to shift to these higher efficiency panels, the number of panels required to power the same cold room can reduce to 16 instead of 340Wp ×18 panels at the current efficiency level. Reducing the number of PV panels means reducing the material and energy used to manufacture and dispose of the extra two panels.

According to the analysis, the total emissions from the manufacturing and end-of-life disposal of 340 Wp ×18 PV panels, mounting system and cable would be 7,190 kg CO_2-eq. An equivalent function could be achieved by using 21.7% efficient 380 Wp ×16 panels, and it would result in the emissions of 5,759 kg CO_2-eq. Thus, a 20% emissions reduction can be made possible as compared to the emissions from existing PV panels used in the ColdHubs cold room (see Figure 74).

However, it should be noted that more efficient solar panels tend to cost more than their less efficient counterparts. It would therefore be beneficial to analyse the upfront cost difference and use that to judge the appropriate trade-off between cost and emissions savings.

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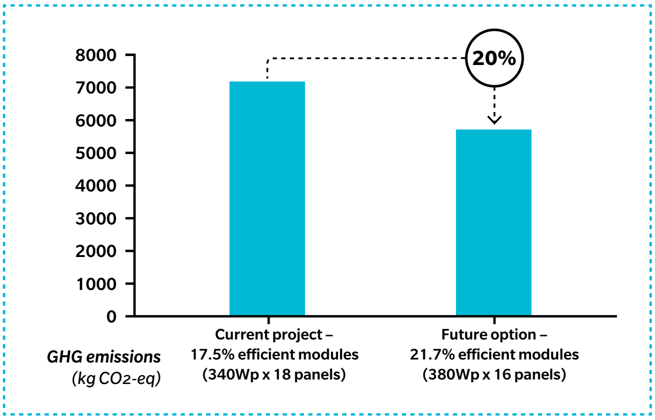
[101] Solar Reviews, 2021. Types of solar panels: which one is the best choice? Available in https://www.solarreviews.com/blog/pros-and-cons-of-monocrystalline-vs-polycrystalline-solar-panels

Figure 74: GHG mitigation potential by selecting higher efficiency polycrystalline PV panels



4.2.10 Scenario analysis summary table for ColdHubs cold room

	VARIABLE ANALYSED IN EACH SCENARIO	**BRIEF DESCRIPTION OF ALTERNATE SCENARIO**	**CLIMATE IMPACT – 10 YEAR LIFESPAN (kgCO2-eq)**					**% EMISSIONS CHANGE FROM CURRENT SCENARIO TO ALTERNATE SCENARIO**	**KEY TAKEAWAY**
			EMISSIONS FROM VARIABLE ANALYSED IN CURRENT SCENARIO	**EMISSIONS FROM VARIABLE ANALYSED IN ALTERNATE SCENARIO**	**TOTAL LIFE CYCLE EMISSIONS WITH CURRENT SCENARIO**	**TOTAL LIFE CYCLE EMISSIONS WITH ALTERNATE SCENARIO**	**NET CHANGE IN EMISSIONS**		
4.2.1	Refrigerant	Impact of using HFC-134a instead of natural refrigerant (HC-290)	2.53	1877.83	24,924.06	26,799.36	1875.30	**+8%**	Using HFC-134a would increase the life cycle emissions of the fridge compared to the natural refrigerant used.
4.2.2	Blowing agent	Impact of using HFC (HFC-245fa) instead of blend used (90% pentane, 10% HFC)	3382.0	43,355.5	24,924.1	64,897.6	39,973.5	**+160%**	Using HFC-245fa would increase the emissions of the fridge by 160% compared to the natural blowing agent used.
		Impact of using 100% natural blowing agent (100% pentane) instead of blend used (90% pentane, 10% HFC)	3382.0	85.45136032	24,924.1	21,627.5	-3296.5	**-13%**	
4.2.3	Recycling fridge and PV	Impact of open dumping instead of informal recycling	157.66	2921.57	24,924.06	27,687.97	2763.90	**+11%**	Any kind of recycling is better than no recycling, but if it's possible formal recycling would be a better choice when there is harmful gas like HFCs present.
		Impact of formal recycling instead of informal recycling	157.66	-3342.91	24,924.06	21,423.49	-3500.57	**-14%**	Formal recycling has a big GHG emission reduction compared to informal recycling in this case, because there are HFC gases used in the PU panel and formal recycling can avoid the release of HFC gas during the end-of-life processes. Despite this is a pure GHG emissions analysis, formal recycling has shown its potential. If you were to include other aspects (e.g. black carbon, human health safety considerations) climate impact of formal recycling would be more staggering.
4.2.5	Lifetime	Impact of extending lifespan to 25 years instead of 20	24,924.06	22,048.07	24,924.06	27,560.09	-2875.99	**-12%**	For comparison purposes, we choose to demonstrate average emissions over 20 years, and when the lifetime increases to 25 or 30 years. Increasing the lifetime of the system reduces emissions per 20-year period. This is because we are replacing the parts of the system which require changing. For the components that can last longer, we are maximising their lifetime.
		Impact of extending lifespan to 30 years instead of 20	24,924.06	19,390.25	24,924.06	29,085.38	-5533.81	**-22%**	
4.2.6	Batteries	Impact of using lithium-ion batteries instead of lead acid	8882.70	8371.78	24,924.06	24,413.14	-510.92	**-2%**	Lithium-ion battery systems would result in lower overall emissions.

	VARIABLE ANALYSED IN EACH SCENARIO	BRIEF DESCRIPTION OF ALTERNATE SCENARIO	CLIMATE IMPACT – 10 YEAR LIFESPAN (KGCO_2-eq)					% EMISSIONS CHANGE FROM CURRENT SCENARIO TO ALTERNATE SCENARIO	KEY TAKEAWAY
			EMISSIONS FROM VARIABLE ANALYSED IN CURRENT SCENARIO	EMISSIONS FROM VARIABLE ANALYSED IN ALTERNATE SCENARIO	TOTAL LIFE CYCLE EMISSIONS WITH CURRENT SCENARIO	TOTAL LIFE CYCLE EMISSIONS WITH ALTERNATE SCENARIO	NET CHANGE IN EMISSIONS		
4.2.7	Non-virgin materials	Not for table since multiple scenarios exist. Refer to Section 4.2.7 for details.							
4.2.8	Different energy sources	Impact of using grid electricity instead of a solar system	17615.35669	77,836.32	24,924.06	85,145.03	60,220.96	**+242%**	The grid electricity factor is assumed to be Nigeria grid electricity emission factor.
		Impact of using diesel back-up generator instead of a solar system	17615.35669	109,622.88	24,924.06	116,931.59	92,007.52	**+369%**	
4.2.9	PV panel efficiency	Impact of increasing PV panel efficiency from 17.5% to 21.7%	7189.51	5758.92	24,924.06	23,493.47	-1430.59	**-6%**	Increasing PV efficiency decreases the overall emissions due to a smaller number of PV panels needed.

4.3 Summary and conclusion

The net life cycle emissions in PV power production in the ColdHubs case are 17,615 kg CO_2-eq from a 20-year PV system lifespan with informal recycling as the end of the disposal method. The estimated emissions per unit of electricity production is 69 g CO_2-eq/kWh. In general, PV systems would last between 25 to 30 years with proper maintenance. The estimated emissions from the PV system with 25 and 30 years of serviceable life amounts to 64 g CO_2-eq/kWh and 58 g CO_2-eq/kWh, respectively. Emissions per unit of electricity production from the 20, 25 and 30-years cold room lifespans are considerably lower when compared to the grid emission factor in Nigeria (573 g CO_2-eq/kWh).

Net life cycle emissions from the ColdHubs 20m^3 cold room were estimated by accounting for the cooling unit and cold room emissions after considering all life cycle phases. The raw material extraction and manufacturing phase contributes to 74% of life cycle emissions (70% from the cold room cell (walls and door) and 4% from the cooling system). Emissions from the logistical movement of the items used in the cold room are 1%. Escaping blowing agents and refrigerants at the use phase contribute to 6% of life cycle emissions. Resource recovery from informal recycling at the end of the life cycle shows emissions savings. However, climate impact from the end of the life blowing agent offsets the savings and contributes to the remaining 19% of emissions at the end of the life cycle. Estimated net emissions from the ColdHubs cold room amount to 7,309 kg CO_2-eq for 20 a year lifespan.

Net life cycle emissions from the ColdHubs cold room are 24,924 kg CO_2-eq within a 20 year lifespan. The highest emissions are from lead acid battery bank use, followed by the PV panels, cold room cell and walls and the blowing agent. Emissions per functional unit amount to 1,226 kg CO_2-eq per yearly stored food. Expanding the PV system and cold room serviceable life to 25 and 30 years would contribute to a 11.5% and 22.2% emission reduction per tonne of stored food, compared to the cold room with a 20 year lifespan.

Emissions per tonne of food storage in a ColdHubs cold rooms are very low (1.2-1.5 kg CO_2-eq/tonne) compared to the potential emissions that would otherwise occur from post-harvest losses. In the absence of a cold room, some of the food would be spoiled and disposed of in surrounding dumpsites. The estimated climate impact caused by the methane emissions from the degradation of food wase amounts to 500 kg CO_2-eq/tonne of food waste. Implementing PV power-based cold rooms in off-grid areas would contribute to massive levels of emissions savings (up to 99.7%) by avoiding post-harvest losses and corresponding emissions from open dumping.

Summary of various scenario analyses: natural refrigerants like HC-600a can lower 99.9% of emissions that would otherwise be caused by use of HFC-134a, an HFC refrigerant. ColdHubs cold room uses polyurethane panels that are blown with a blended system comprising of 10% HFCs and 90% natural gas. This blended system has a climate impact of 173 kg CO_2-eq/kg. Assessment results proved that avoiding use of HFC gases as blowing agents is crucial in emissions mitigation. The use of natural blowing agents like pentane has the potential of reducing emissions from blowing agents by 99.8%.

Despite the emissions saving potential from all the items under informal recycling, net emissions from informal recycling resulted in a positive value of 158 kg CO_2-eq. The end-of-life management of the blowing agent caused significant emissions that offset savings through resource recovery from informal recycling. The real climate impact from informal recycling is expected to be higher if black carbon emissions from the burning of plastics are accounted for in the analysis. Among the various disposal options analysed, formal recycling of resources shows the highest emissions mitigation potential. Implementing a formal recycling mechanism would contribute to maximum savings by recovering blowing agents and resources at the end of the life. The total emissions saving potential from formal recycling amounts to 3,343 kg CO_2-eq.

Expanding the lifespan of the PV system and cold room by following appropriate maintenance procedures would contribute to significant emissions savings. If ColdHubs extends the lifespan of the PV system and $20m^3$ cold room to 25 years and 30 years, emissions per functional unit (per tonne of food stored) can be reduced by 11.5% and 22.2% compared to a 20 year lifespan system with informal recycling at end-of-life. Extending cold room lifespans up to 30 years could dramatically reduce the fossil energy/virgin resource consumption that would otherwise be required in manufacturing a replacement system.

Power storage is an integral part of the PV power production system. Using PbA batteries results in higher emissions than using lithium-ion batteries. The analysis revealed that emissions caused from use of battery banks can be reduced by 6% by shifting to lithium-ion batteries from lead acid batteries. Incorporating climate-friendly storage options like thermal storage or hybrid battery systems using both lead acid and lithium-ion chemistries in symbiotic combinations can help significantly reduce the cold room's carbon footprint.

The raw material analysis scenario revealed that the highest emissions related to raw material extraction is a result of the use of lead for manufacturing the battery bank, followed by steel, plastics, glass, polyurethane, aluminium, copper and PCB. Virgin production process chains of all types of raw materials cause significant emissions. Recycling all kinds of metals and materials like aluminium and plastics could contribute to substantial emissions savings. Implementing an appropriate mechanism for formal recycling of end-of-life PV systems and cold rooms would maximise the recovery of secondary resources, enhance the successfully recycled mass of materials, and reduce the mining of virgin ores.

Analysis emissions from logistical movements revealed that only 2.6% of life cycle emissions occur from transportation. International transport causes 58% of emissions and the remaining 42% of emissions are from local transportation. Manufacturing items locally can help reduce transport emissions.

The efficiency of the PV panels is recognised as a critical factor in maximising electricity production and minimising the number of panels used, thereby reducing emissions related to the PV panels manufacturing and disposal. The analysis revealed that if the ColdHubs cold room is powered using 21.7% efficient 380 Wp ×16 panels, instead of the 17.5% efficient 340 Wp ×18 panels used in the existing system, emissions related to PV panels could be cut by 20%. However, it should be noted that more efficient solar panels tend to cost more than their less efficient counterparts. Cost and emission mitigation trade-offs need to be analysed sufficiently to keep the balance between climate and affordability goals.

Chapter 5: Market Projections

Previous chapters have quantified emissions for three different cooling technologies. These unit estimates are now used to approximate the sector level emission mitigation benefits that could be achieved if the most carbon friendly technologies were deployed and access to refrigeration in off- and weak-grid areas was enabled.

To calculate these emissions, authors of the report initially estimated the number of units (cold rooms or refrigerators) required for each region and converted them into an equivalent GHG emission figure. An appropriate growth index was applied to these results to project these figures into the future. The GHG reduction projections are presented separately for refrigerators and cold rooms in Sub-Saharan Africa and South Asia.

5.1 GHG reduction projection for off-grid refrigerators

The off-grid refrigerator considered in this report is a 65L household refrigerator. The Efficiency for Access (EforA) Coalition published 'The State of the Off-grid Appliance Market' report in 2019. This report describes obtainable market as those households which have no or intermittent access to grid electricity, who can both afford off-grid appliances and are in serviceable areas for off-grid solar companies. The obtainable households for the off-grid refrigerator industry in 2018 are estimated at 3.5 million in Sub-Saharan Africa and 6.4 million in South Asia.[102] Not all of obtainable households would purchase a fridge of the same size. However, in order to estimate total emissions that would be caused in servicing refrigerator demand for the obtainable household market, the authors have made a conservative yet simplistic assumption about the representative size of refrigerator such households will purchase. The Global LEAP Award database shows that the medium size of certified off-grid fridges is 104.5L.[103] Therefore, for the purposes of estimating GHG reduction potential by servicing this demand using a low carbon fridge, it is assumed that an average of 100L fridge will be purchased by these households. The GHG emissions for the baseline fridge are 1.80 kg CO_2-eq per litre of cooling unit per year with a product lifetime of 10 years and informal recycling as end-of-life (EoL) treatment presented in Chapter 2.2. In contrast, the GHG emissions for the SureChill fridge are 0.46 kg CO_2-eq per litre of cooling unit per year with the same product lifetime and EoL treatment. For this projection, we are assuming that the technical specifications of 100L fridges are consistent with the 65L fridges mentioned in Chapter 2.2. Using the number of refrigerators required and GHG emissions for each type, the total GHG emissions are calculated for the baseline and SureChill fridges in each region. The difference between the two is the potential GHG reductions in 2018 if the obtainable market had been addressed by using the 100L SureChill technology instead of the baseline refrigerator technology.

For projecting the 2018 GHG reduction figures to 2030, authors chose a growth index calculated from the projection of global obtainable households for the off-grid appliance industry for refrigerators from the State of the Off-Grid Appliance Market report.[102] This report applies a holistic view to determine the index, incorporating income and population growth, increased financing access, reductions in appliances costs, and solar off-grid and mini-grid market dynamics. Using the global index would requires an assumption that the growth rate is consistent in both Sub-Saharan Africa and South Asia, but this report's growth index for the number of obtainable households for off-grid refrigerators is directly linked with our market projection calculation.

Figure 75: GHG emissions of the off-grid refrigerator market by baseline vs SureChill refrigerators in different regions

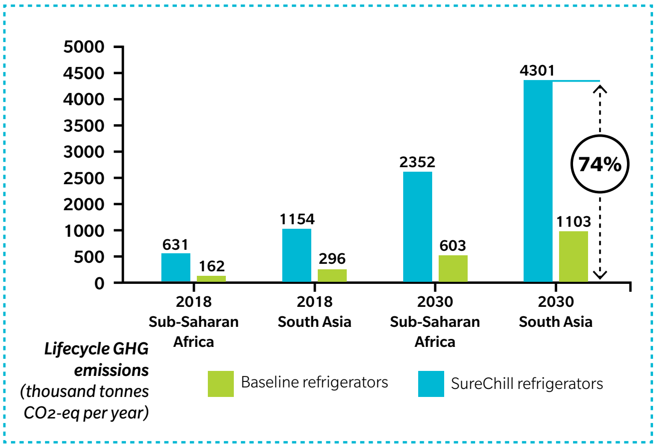


Figure 75 shows the GHG emissions projection for each technology and regional market after application of the growth index. The SureChill refrigerator shows a 74% reduction in GHG emissions across all regions. In absolute terms, the GHG reduction potential for using SureChill fridges instead of baseline fridges in South Asia in 2030 is staggering at 3.2 Mt CO_2 eq per year, which is equivalent to flying from London Heathrow to Sydney 980 times,[104] before even considering that the off-grid appliances market in these regions is expected to grow over that period.[102]

It is important to understand the main contributors to this significant GHG reduction potential. Figure 76 shows the breakdown of the 3.2 Mt CO_2 eq per year savings projected for South Asia 2030 when using SureChill fridges to support the obtainable off-grid market instead of conventional fridges. Leakage of blowing agent in use phase, disposal phase and manufacturing of PV power system are the leading emission saving contributors at 49% and 30% respectively, followed by leakage of refrigerant in use phase and disposal phase at 12%.

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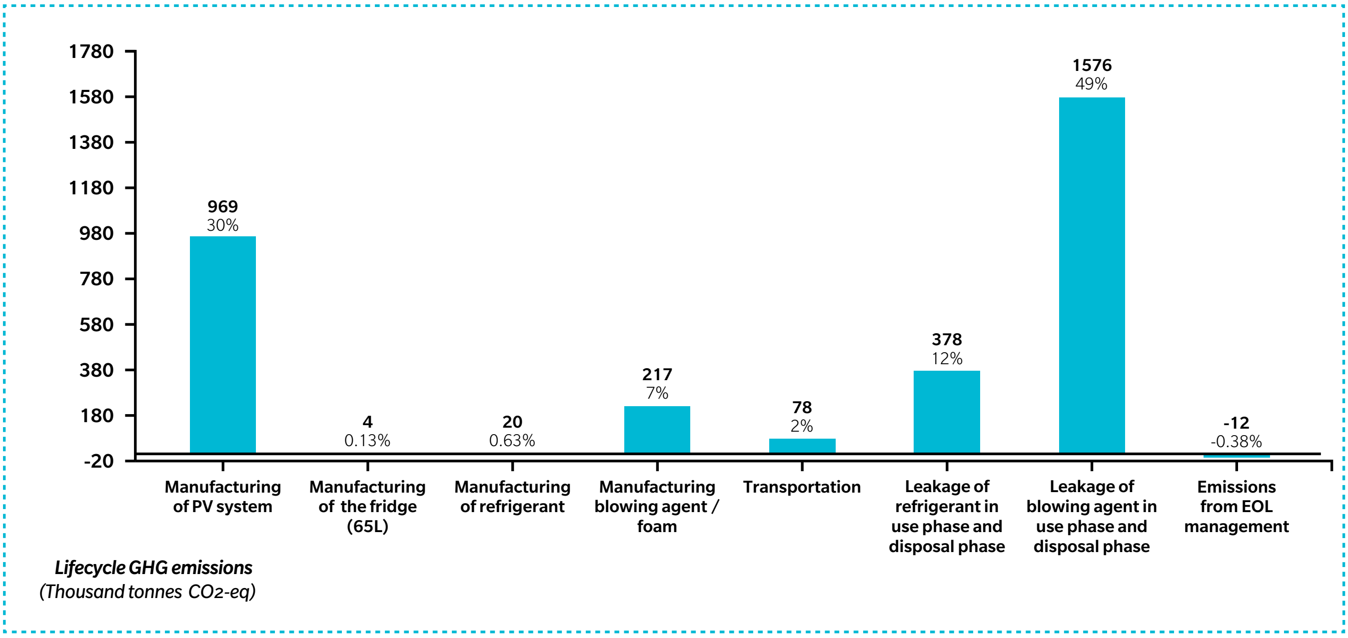
[102] Efficiency for Access (2019). 2019 State of the Off-Grid Appliance Market Report

[103] Verasol Database,2020. Available in: https://data.verasol.org/products/ref

[104] This is emission equivalent is unpublished calculation from Energy Saving Trust. If you have any question regarding this equivalent, please contact InsightAnalytics@est.org.uk

Figure 76: GHG emissions reduction of using SureChill fridges in South Asia in 2030 breakdown by processes



5.2 GHG reduction projection for off-grid cold rooms

Cold rooms help to mitigate food losses, providing key cold chain facilities for each stage of the food production supply chain with the specific cooling requirements changing from stage to stage. The off-grid cold room technologies in this report are designed to chill fruits and vegetables in the post-harvest phase at the farm gate, preserving more food which can then proceed to processing stage.

To estimate the number of cold rooms that would be required to mitigate a reasonable level of post-harvest food losses, authors considered the food losses estimates in Sub-Saharan Africa (SSA) and South Asia published by Food and Agriculture Organization of the United Nations (FAO). FAO published a series of reports on global food waste and its associated carbon footprint from 2007 to 2012 which provide specific data for fruits and vegetables in SSA and South and Southeast Asia.[105] The method for calculating food loss in post-harvest handling and storage stage is also presented.[106] In 2007, the fruit and vegetable food waste in post-harvest handling and storage stage was 82.6 million tonnes in Sub-Saharan Africa and 23.5 million tonnes in South and Southeast Asia. See Annex C-2 for details of the calculation method. FAO report post-harvest losses of fruit and vegetables amount to 8.4% and 7.7% in Sub Saharan African and South and Southeast Asia, respectively.

Food waste estimates for South Asia are not readily available so it is inferred from the South and Southeast Asia data based on the population distribution in 2007[107] (see Annex C-3 for the scaling methodology). By scaling so, we are assuming an even distribution of food waste based on population, omitting geographic variations within South and Southeast Asia, however it should still be more precise that the food wastage estimates considered in published studies. Such studies may be region specific but they consider food wastage across all stages of the food supply chain for all food commodities, instead of those specific to post-harvest stage and to fruits and vegetables.

The team has consulted technical experts from both cold room manufacturers considered in this study to determine the mass of food stored by each cold room in a year. Even if the size and set point temperature of each cold room can be assumed to be identical across all technologies, the food stored per year is vastly different due to the different use cases and design assumptions. As discussed in Sections 3.1.12 and 4.1.12, there are various food storage scenarios for each cold room: 2.2 tonnes per day or 3 tonnes per week for the ColdHubs and 500 kg per day for SelfChill. For the purpose of comparing the cooling emissions for different technologies, GHG emissions per kWh cooling energy used is considered the most appropriate metric as it accounts for differences in the set point temperature, initial temperature of food stored and the ambient temperature. However, for the purposes of estimating the emission mitigation potential from avoided food waste, the use of emissions per tonne of food stored for each cold room is more appropriate.

The number of cold rooms required to prevent a reasonable level of fruits and vegetables losses are calculated for each region based on the food wastage in that region and annual tonnes of food storage that is possible in each cold room. For this calculation, the authors have assumed all edible portions of the post-harvest food waste in fruit and vegetables estimates by FAO are avoided reducing food waste by 8.44% in SSA and 7.65% in South Asia (please refer to Annex C-2 for detailed calculation process). In reality, it is likely that this figure might be higher. There is a

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[105] FAO. 2011a. Global food losses and food waste - Extent, causes and prevention. Rome. Available at http://www.fao.org/docrep/014/mb060e/mb060e00.pdf

[106] FAO. 2013. Food Wastage Footprint: Impacts on natural resources – Technical Report. Available at http://www.fao.org/3/ar429e/ar429e.pdf

[107] World Bank. 2020. "Population, Total | Data." Worldbank.org. 2020. https://data.worldbank.org/indicator/SP.POP.TOTL

need to develop better estimates informed by a primary data collection exercise. Using the GHG emissions for a 20-year lifetime and informal recycling scenario for each technology presented in Sections 3.1.11 and 4.1.11, we have calculated the cumulative emissions for the total number of cold rooms required to mitigate the food waste in each different region (see Figure 77 and Figure 78).

In order to demonstrate the GHG emissions saved by using cold rooms, authors calculated the equivalent GHG emissions from fruit and vegetable food waste. Authors have used the IGES calculator to estimate the GHG emissions from food waste in both Sub-Saharan Africa and South Asia and India. For Sub Saharan Africa authors have assumed shallow unmanaged dump sites giving emissions of 500 kg CO_2-eq per tonne of food waste. For South Asia and India, authors have assumed deep unmanaged dumpsites, giving emissions of 1000 kg CO_2-eq per tonne of food waste.[108] In contrast, the range of GHG emissions per tonne of food stored from using cold room technologies is 1.5 to 8 kg CO_2-eq per tonne of food waste.

FAO have a set of growth index of arable land (ha) and crop yield (tonnes / ha) from 2012 to 2030 with growth scenarios such as “towards sustainability”, “stratified societies” and “business as usual”.[109] The authors chose the “towards sustainability” scenario index assuming that sustainable practices will occur, whilst at the same time being more conservative than some other scenarios. Since there is no growth index provided by FAO between the years 2007 (the year of our food waste figures) and 2012 (where FAO start their growth indexes), we have estimated one based on the total food production (million tonnes) of these two years. This method assumes the percentage of food waste related to each commodity stay constant throughout the years, which might be underestimating the sustainability progress in food supply chain, but we hope the towards sustainability growth index from FAO would fill in for that.

Figure 77: GHG emission of perishable food waste in post-harvest vs cold rooms in Sub-Saharan Africa (y-axis is in logarithmic scale). Numbers above and below dotted box indicate the range of possible emissions from cold rooms

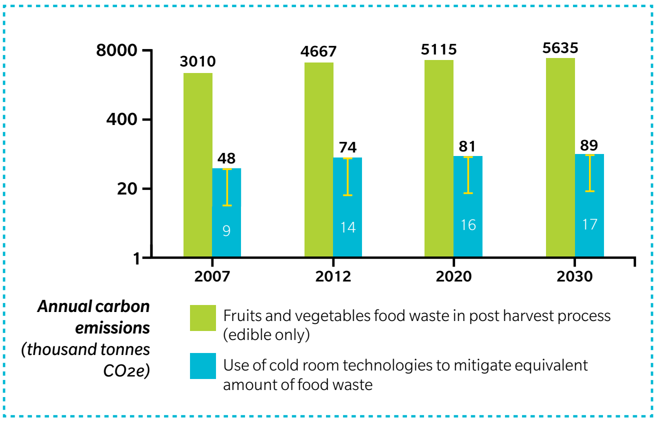

Figure 78: GHG emission of perishable food waste in post-harvest vs cold rooms in South Asia (y-axis is in logarithmic scale) Numbers above and below dotted box indicate the range of possible emissions from cold rooms

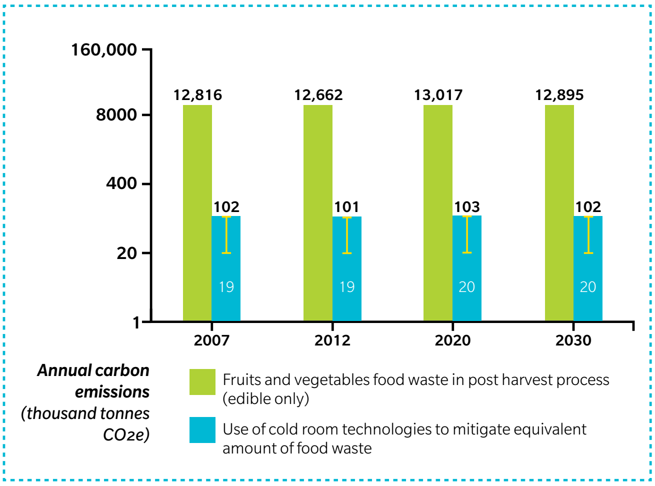

Figure 77 and Figure 78 show the calculation results for SSA and South Asia, respectively in a logarithmically scaled bar plot. The orange bars in the graphs represent the GHG emissions from decomposition of fruit and vegetable waste in the post-harvest stage per year in both regions that would occur in the absence of cold rooms. The green bars represent the GHG emissions[110] equivalent to the numbers of cold rooms needed to mitigate the fruit and vegetable food waste in the post-harvest stage per year in that region. The dotted box in 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 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 3 tonnes per week loading rate). The graphs help demonstrate the staggering contrast between positive emissions from cold room installations and the emissions that can be avoided with cold room installations; if we were to use cold rooms to mitigate this food waste, the annual GHG emissions from cold rooms would only be 0.3% to 1.6% of emissions of the emissions from food waste on an annual basis.

Figure 77 shows a reduction in GHG emissions of around 99% when using any type of cold room to mitigate food wastage for SSA in 2030. To put these GHG emissions savings into perspective, the lowest GHG reduction potential from avoided food waste via cold room installations is 5.546 million tonnes CO_2-eq per year in SSA in 2030, which is similar to Mozambique’s total annual carbon emissions in 2016.[111] The GHG savings potential in South Asia in 2030 is more than double that of SSA at 12.8 million tonnes, which is similar to the total annual carbon emissions of Panama or Lithuania in 2016.[111] Figure 78 suggests that there will be no growth in food production in South Asia from 2007 to 2030. This is mainly due to the decline in arable land in South

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[108] Menikpura, Nirmala, and Janya Sang-Arun. 2013. GHG Calculator for Solid Waste Ver. II-2013. Available in https://www.iges.or.jp/en/pub/ghg-calculator-solid-waste-ver-ii-2013/en

[109] FAO. 2018. The future of food and agriculture – Alternative pathways to 2050. Rome

[110] This GHG emission per year from cold rooms is the Net life cycle emission of these cold rooms divided by their lifetime, 20 years in this case

[111] Worldometers.info. 2016. CO_2 Emissions - Worldometers.” 2016. Available in https://www.worldometers.info/co2-emissions/

Asia in the 'towards sustainability' scenario considered in the FAO analysis from 2007 to 2030.

There are methodological limitations in the analysis that need to be understood due to data availability issues. For example, analysis of emissions from food waste emissions assume that all emissions from post-harvest fruit and vegetables are mitigated when using cold rooms, when in reality this is likely not true, with some level of food waste still occurring. Authors have selected linear scaling factors for projecting food waste, arable land and land productivity for each region which may not be the case. At the same time, the significant potential of emissions mitigation from avoided food waste via cold rooms cannot be denied. It is recommended that further research is undertaken to improve upon these estimates.

Chapter 6: Conclusions and Recommendations

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 cooling system based on the expected loading scenario to avoid oversizing;
- Once the appliance or cold room is built, maximise 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;
- Try and choose solar panels with high efficiencies to reduce the number of panels required;
- Consider thermal storage (ice storage) as an alternative to chemical batteries to reduce storage emissions;
- Encourage the development of 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
- Use low GWP 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 energy based cold room.

It should be noted that there are some limitations to the analysis presented here. This analysis only covered GHG 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 GHG emissions gains are only modest.

It should also be noted that the emissions presented here will change in 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 vs 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 (e.g. DC compressors, low GWP 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 Africa and South Asia.

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Case Study I: Life cycle GHG emissions from the SureChill off-grid refrigerator

A-1 Life cycle inventories and GHG emissions from solar PV power production

A-1.1 Solar panels

Two polycrystalline 120Wp solar panels power the SureChill refrigeration unit. The total mass of a single panel and a frame amount to 8.4 kg. Solar PV panels are fitted with aluminium frames. The panel frame plays a fundamental role in protecting the internal components from thermal and mechanical tensions and providing mounting attachment points. The detailed specifications of the solar panels are summarised in Table 26.

Table 26: Specification of polycrystalline solar panels obtained from questionnaire to SureChill

DESCRIPTION	UNIT	AMOUNT
Type of PV modules	Name	Polycrystalline
Manufacturer and the country	Name	Solinc, China
Life expectancy	Years	25 years
Description of irradiance	kWh/m^2/yr	Not yet measured
Dimension of the panel (height × width)	m	0.665 × 1.12
Area of the panel	m^2/panel	0.745
No. of panels used in the solar system	Number	2
Installation type	Type	On the roof
Total generator area of the PV panels in the system	m^2	1.49
The efficiency factor of the PV modules	%	16
The maximum power voltage (Vmpp)	Volts	18.7
Generating capacity of the PV panel	Wp	120
Warranty period	Years	25 years
Total mass of the panel and the frame	kg	8.4

GHG emissions from solar panels: the Ecoinvent database is used to gather energy and emissions data related to raw material extraction and manufacturing. Unit process raw data for 1m^2 polycrystalline PV panel production was extrapolated to find the 2 × 0.745 m^2 panel emissions. It should be noted that the Ecoinvent database has not been updated recently, and at present power production capacity of a similar size solar PV panel, the power rating would be significantly higher. For example, the average panel conversion efficiency has increased from 15% to well over 20% in recent years. This large jump in efficiency resulted in the power rating of a standard size panel increase from 250Wp up to 370Wp. Although the efficiency of the panels at present is relatively high, the amount of materials used per m^2 of panel manufacturing and related emissions can be assumed to be the same.

Activities of LCI includes production of the cell-matrix, cutting of foils and washing of glass, production of laminate, isolation, aluminium frame of the panel and disposal after end of the use. GHG emissions are linked to the amount of fossil fuel consumed for raw material extraction and manufacturing of the solar PV panels. Therefore, the amount of fossil energy required and the related GHG emissions from the production of two polycrystalline 120Wp panels was derived based on Ecoinvent database version 3.7.[112] Net GHG emissions per m^2 of polycrystalline panel production is 199.15 kg CO_2-eq. Estimated GHG emissions from two 120Wp panels used in this case study are 296.66 kg CO_2-eq (see Table 27).

Table 27: Fossil energy consumption and GHG emissions from the manufacturing of two polycrystalline 120Wp panels

DESCRIPTION	TYPE OF RAW MATERIALS/ ENERGY	UNIT	INPUT/ OUTPUT FOR PER m^2 PANEL[113]	INPUT/ OUTPUT FOR 2 × 0.745m^2 PANELS
Type of fossil energy used	Hard coal	kg	55.145	82.144
	Brown / soft coal	kg	18.290	27.245
	Natural gas	m^3	21.794	32.464
	Crude oil	kg	12.487	18.601
GHG emissions	Carbon monoxide (CO_2)	kg	183.099	272.745
	Methane (CH_4)	kg	0.567	0.845
	Nitrous oxide (N_2O)	kg	0.006	0.009
TOTAL GHG EMISSIONS		kgCO_2-eq	**199.157**	**296.665**

A-1.2 Mounting structures and solar array cable

The total mass of the supporting structures used to install the solar PV panels amounts to 2.4 kg. Plant specific information related to energy and material consumption data and GHG emissions from the manufacturing of mounting structures is not available. The Ecoinvent database represents the production of the structural components necessary for mounting a 1m^2 solar PV panel on a slanted roof, which was used to extract the required data. This data includes materials and packaging for the production and energy use for metal processing. Estimated GHG emissions from supporting structures used for 2 × 0.745 m^2 panels amounted to 53.86 kg CO_2-eq. It should be noted that 95% of the supporting system mass is aluminium and the primary aluminium production process would be the major contributor to GHG emissions.

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[112] Ecoinvent v3.7, 2020. Available in https://v37.ecoquery.ecoinvent.org/

[113] De Wild-Scholten, 2020. Ecoinvent v3.7, 2020. Available in https://v37.ecoquery.ecoinvent.org/

Table 28: Fossil energy consumption and GHG emissions from the manufacturing of supporting structures for the solar PV system

DESCRIPTION	TYPE OF RAW MATERIALS / ENERGY	UNIT	INPUT / OUTPUT OF MANUFACTURING OF SUPPORTING STRUCTURE PER m^2 PANEL AREA[112]	INPUT / OUTPUT OF MANUFACTURING OF SUPPORTING STRUCTURE FOR 2× 0.745m^2 PANEL AREA
Type of fossil energy used	Hard coal	kg	12.096	18.018
	Brown / soft coal	kg	1.788	2.663
	Natural gas	m^3	1.848	2.752
	Crude oil	kg	1.427	2.126
GHG emissions	Carbon monoxide (CO_2)	kg	33.022	49.190
	Methane (CH_4)	kg	0.116	0.173
	Nitrous oxide (N_2O)	kg	0.001	0.001
TOTAL GHG EMISSIONS		kg CO_2-eq	**36.162**	**53.867**

A solar array cable with a mass of 2.4 kg has been used to connect the solar panel and the smart box. The cable is made from copper (70%) and plastic (30%). The Ecoinvent LCI of cable production with similar material composition was used to estimate the GHG emissions.[116] The estimated GHG emissions from 2.4 kg of solar array cable production are 15.329 kg CO_2-eq (see Table 29).

Table 29: Fossil energy consumption and GHG emissions from the manufacturing of solar array cable (6 mm^2) used in the solar PV system

DESCRIPTION	TYPE OF RAW MATERIALS / ENERGY	UNIT	INPUT / OUTPUT OF MANUFACTURING OF 1 kg MASS OF CABLE	INPUT/OUTPUT OF MANUFACTURING OF 2.4 kg OF CABLES
Type of fossil energy used	Hard coal	kg	1.442	3.318
	Brown / soft coal	kg	0.424	0.974
	Natural gas	m^3	0.785	1.805
	Crude oil	kg	0.923	2.124
GHG emissions	Carbon monoxide (CO_2)	kg	6.039	13.890
	Methane (CH_4)	kg	0.017	0.039
	Nitrous oxide (N_2O)	kg	0.001	0.002
TOTAL GHG EMISSIONS		kg CO_2-eq	**6.665**	**15.329**

A-1.3 Life cycle inventory of end-of-life recycling of a solar PV system – formal recycling

Recycling of solar PV modules and materials recovery is a relatively complex task.[114] Once the materials/layers of a solar PV module are separated, metals such as lead, copper, gallium, cadmium, aluminium and silicon can be recovered and reused in new products. Recycling mono- or poly-crystalline silicon modules begins with removing the solar PV module's cables, junction box, and frame. The module is then shredded, sorted and separated. The separation of the materials allows them to be sent to specific recycling processes associated with each material.[115]

Some of the metals used in the solar PV modules are precious (e.g. silver) or otherwise valuable or scarce (e.g. indium), and some are toxic (e.g. lead). Precious, valuable, scarce, and toxic materials are usually present in small quantities and, therefore, were not accounted for in this study. As shown in Table 5, a typical crystalline silicon (c-Si) PV module contains approximately 75% of the total mass in the module surface (glass), 10% polymer (encapsulant and back sheet foil), 8% aluminium (mostly the frame), 5% silicon (solar cells), 1% copper (interconnectors) and less than 0.1% silver and other metals like tin and lead.[115] The rest of the components have a small percentage of the module mass and are accounted as others. Recyclability of different materials has been considered from the Huang et al. study (2017),[116] and the potential amount of material recovery per panel is shown in Table 30. However, as the PV recycling technologies are still in a developing phase, the mechanical treatment is being used as the primary method. There is still very limited public information available regarding solar PV module recycling processes when it comes to environmental effects and, more generally, options for decommissioning and disposal of solar PV systems. Therefore, potential GHG emissions from end-of-life recycling of the solar PV system was assessed in this study with reasonable assumptions.

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[114] Lunardi, M.M., Alvarez-Gaitan, J.P.,Bilbao, J.I. and Corkish, R. 2018. A Review of Recycling Processes for Photovoltaic Modules. Available in https://www.intechopen.com/predownload/59381

[115] Huang, B., Zhao, J., Chai, J., Xue,B., Feng Zha, F. Xiangyu Wang, X. 2017. Environmental influence assessment of China's multi-crystalline silicon (multi-Si) photovoltaic modules considering recycling process. Solar Energy 143 (2017) 132–141

[116] Levova, T. 2020. Ecoinvent version 3.7. Available in https://v37.ecoquery.ecoinvent.org/

Table 30: Composition of materials of polycrystalline silicon and their recyclability

COMPOSITION OF CRYSTALLINE SILICON (C-SI)	COMPOSITION OF MATERIALS (%) IN THE SOLAR PV PANEL[116]	MASS OF MATERIALS (kg)	RECYCLING RATE (%)[116]	POTENTIAL AMOUNT OF RECOVERY (kg)
Glass (module surface)	75	6.3	89	5.607
Polymer mainly EVA and PET (encapsulant and back sheet foil)	10	0.84	80	0.672
Aluminum (mostly frame)	8	0.672	81	0.544
Silicon (mostly solar cells)	5	0.42	80	0.336
Copper (interconnectors)	1	0.084	89	0.075
Other metals (silver, lead)	0.1	0.0084	89	0.007
Other mixed materials	0.9	0.0756	89	0.067
TOTAL GHG EMISSIONS	**100**	**8.4**		**7.309**

According to the study done by IEA (2018),[30] the electricity consumption of the recycling processes was reported to be in the range of 50 to 100 kWh per tonne of module input for the mechanical processes. Therefore, in this assessment, it was assumed that on average, 75kWh of electricity is used for the mechanical processes. Due to the lack of data about the recovery of less valuable materials, it was assumed that polymer fraction, silicon fraction and other mixed materials are being landfilled. It was assumed that valuable materials such as glass, aluminium and copper were recycled in a recycling plant in Kenya.

Climate impact from the recycling of solar PV panels: it's possible to recover 12.452 kg of materials from recycling two 120Wp panels. GHG emissions factors for recycling each type of scrap are also presented in Table 31.

Table 31: GHG emissions and avoided potentials from recycling and material recovery from two 120Wp panels under formal recycling mechanism

TYPE OF MATERIALS	INPUT SCRAPS PER TWO PANELS (kg)	POTENTIAL RECOVERY OF MATERIALS FROM RECYCLING (kg)[116]	EMISSIONS FACTOR OF RECYCLING (kg CO2-eq/kg OF RECOVERED)	GHG EMISSIONS FROM RECYCLING (kg CO2-eq/ 2× 120WP PANELS)	THE EMISSION FACTOR OF VIRGIN PRODUCTION (CO2-eq/kg)	AVOIDED GHG EMISSIONS FROM RESOURCE RECOVERY (kg CO2-eq/ 2× 120WP PANELS)
Glass	12.600	11.214	0.320[117]	3.585	0.661	7.417
Polymers	1.680	Assumed this portion of mixed material is landfilled				
Aluminum	1.344	1.089	0.588[118]	0.640	16.513[118]	17.976
Silicon	0.840	Assumed to be landfilled				
Copper	0.168	0.150	0.316[20]	0.047	3.345[119]	0.500
Other metals (silver, lead)	0.017	Data is not available on recycling scraps, silver and lead. Impact assumed to be negligible from small quantities.				
Other	0.160	Assumed this portion of mixed material is landfilled				
Total GHG emissions	16.809	12.452		4.272		25.893
NET GHG EMISSIONS (GHG EMISSIONS FROM RECYCLING – GHG EMISSIONS FROM VIRGIN PRODUCTION)						**-21.621 kg CO2-eq**

Materials recovered from recycling can be credited in the LCA to avoid virgin production of equivalent materials and related emissions. Therefore, GHG emissions related to the virgin production processes can be avoided. Total avoided GHG emissions from resource recovery of two 120Wp panels would be 25.892 kg CO2-eq. The estimated net negative GHG emissions from recycling two 120Wp panel resource recovery amounted to -21.621kg CO2-eq. Recycling PV panels results in negative GHG emissions due to the credited impacts of avoiding climate impact from virgin production. Material recovered from the recycling processes has been accounted for by avoiding the virgin production processes. Net GHG emissions from the informal recycling of two 120Wp panels are presented in the main chapter.

Climate impact from the recycling of supporting structures: the total weight of the supporting structures is 2.4 kg and this consists of 95% aluminium and 5% steel. Both aluminium and steel are valuable metals and are assumed to be recycled under formal and informal recycling routes. GHG emissions from the recycling of supporting structures under formal and informal recycling are estimated and presented in Table 32. The estimated net GHG emissions from the recycling of supporting structures is -32.016 kg CO2-eq. As a result of recovering 90% aluminium from supporting systems, a significant amount of GHG savings can be achieved by avoiding virgin production of primary aluminium.

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[117] US EPA, 2019. Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARN), U.S. Environmental Protection Agency Office of Resource Conservation and Recovery

[118] The International Aluminium Institute (IAI), 2020. GHG emission data Aluminium sector. Available in https://www.aluminum.org/sites/default/files/LCA_Report_Aluminum_Association_12_13.pdf

[119] European Copper Institute, 2020. https://copperalliance.eu/resources/environmental-profile-copper-products-cradle-gate-life-cycle-assessment-copper-tube-sheet-wire-produced-europe

Table 32: GHG emissions from the formal or informal recycling of supporting structure

TYPE OF MATERIALS	COMPOSITION (%)[120]	MASS (kg)	RECYCLABILITY (%)	POTENTIAL RECOVERY OF MATERIALS FROM RECYCLING (kg)	EMISSIONS FACTOR OF RECYCLING (kg CO_2-eq/kg OF RECOVERED)	GHG EMISSIONS FROM RECYCLING (kg CO_2-eq/ 2× PANELS)	EMISSION FACTOR OF VIRGIN PRODUCTION (CO_2-eq/kg)	AVOIDED GHG EMISSIONS (kg CO_2-eq)
Aluminum	95	2.280	90	2.052	0.588[118]	1.207	16.513[118]	33.884
Steel	5	0.120	85	0.102	1.800[121]	0.184	2.810[94]	0.287
Total	100	2.400		2.154		1.390		34.170
NET GHG EMISSION FROM SUPPORTING STRUCTURE RECYCLING								**-32.016 kg CO_2-eq**

Climate impact from the recycling of cables under formal recycling: The SureChill solar power system utilises 2.3 kg of solar array cable which comprises of 70% copper and 30% plastic. Cable plastic mainly consists of PVC, PE and other mixed components (copper, aluminium rubber) at 68%, 28% and 4%, respectively.[122] GHG emissions from informal recycling are presented in the main chapter. The estimated GHG emissions from the formal recycling of the cable are presented in Table 33. The estimated net GHG emissions amounted to -5.050 kg CO_2-eq which means the recycling of the cable would contribute 5.050 kg of GHG savings (see Table 8).

Table 33: GHG emissions from the recycling of the solar array cable

TYPE OF MATERIALS	COMPOSITION (%)	MASS (kg)	RECYCLABILITY (%)	POTENTIAL RECOVERY OF MATERIALS FROM RECYCLING (kg)	EMISSIONS FACTOR OF RECYCLING (kg CO_2-eq/kg OF RECOVERED)	GHG EMISSIONS FROM RECYCLING (kg CO_2-eq)	EMISSION FACTOR OF VIRGIN PRODUCTION (CO_2-eq/kg)	AVOIDED GHG EMISSIONS (kg CO_2-eq)
Copper	70	1.610	85	1.369	0.316	0.432	3.345	4.578
Plastic PE	8	0.193	80	0.155	0.5504	0.085	1.78	0.275
Plastic (PVC)	20	0.469	88	0.413	0.431	0.178	2.161	0.892
Mixed plastic	1	0.028			Assumed to be landfilled			
Total	100	2.300		1.936		0.695		5.745
NET GHG EMISSIONS FROM CABLE RECYCLING								**-5.050 kg CO_2-eq**

Summary of GHG emissions from formal recycling of PV system

The summary of potential GHG emissions was estimated by accumulating GHG emissions from formal recycling of solar PV panels, mounting systems, and solar array cables (see Table 34).

Table 34: GHG emissions, GHG avoidance and net GHG emissions from the formal recycling of solar PV systems

DESCRIPTION	GHG EMISSIONS (kg CO_2-eq)	GHG AVOIDANCE (kg CO_2-eq)	NET GHG EMISSIONS (kg CO_2-eq)
Transportation	0.796		0.796
Mechanical processes	0.760		0.760
Recycling of solar PV panels	4.272	-25.893	-21.621
Recycling of supporting structures	1.390	-34.170	-32.780
Recycling solar array cable	0.695	-5.745	-5.050
TOTAL EMISSIONS	**7.913**	**-65.809**	**-57.896**

Table 35: Total power generation potential from two 120Wp solar PV system on an annual basis

YEAR	1	2	3	4	5	6	7	8	9	10
(a) Power production per panel (Wp)*	120	119.4	118.8	118.2	117.6	117.0	116.4	115.9	115.3	114.7
(b) Power production from two panels (a) ×2 (Wp)	240.0	238.8	237.6	236.4	235.2	234.1	232.9	231.7	230.6	229.4
(c) Annual power production (kWh) (b) ×4** ×365/1000 (kWh/year)	350.4	348.6	346.9	345.2	343.4	341.7	340.0	338.3	336.6	334.9
TOTAL POWER PRODUCTION (kWh)										**3426**

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[120] Personal communication with the installed company

[121] World Steel Association, 2018. Life Cycle Inventory Study. https://www.worldsteel.org

[122] Lindahl, M. and Winsnes, M. 2006. Recycling of Cable Plastics - A Life Cycle Assessment of Several Different Alternatives. Eco Design 2005. Available in https://www.researchgate.net/

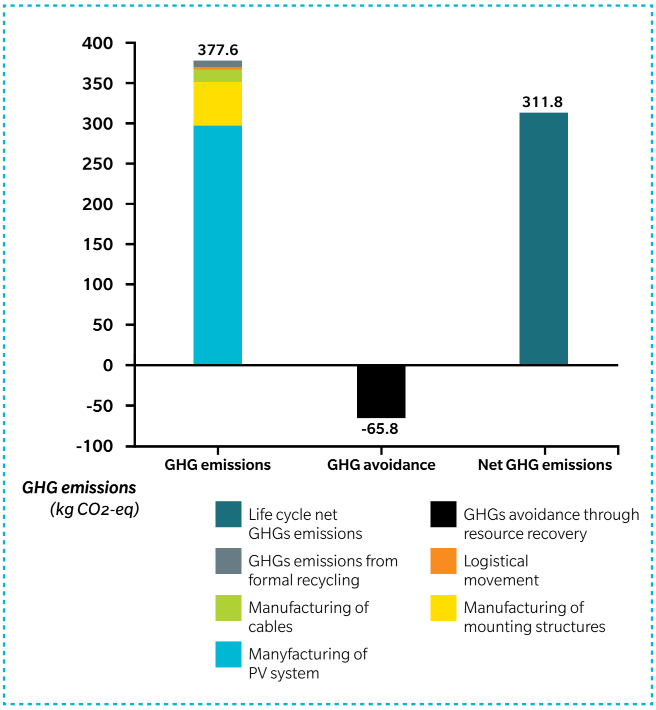
Table 36: GHG emissions per kWh of electricity production from the solar PV system in the SureChill case study

DESCRIPTION	UNIT	LIFESPAN		
Lifetime of solar PV panels	Years	10	20	30
Total power production from two 120Wp solar PV panels	kWh	3426	6685	9784
GHG emissions per kWh of electricity production	kg CO_2-eq /kWh	0.092	0.047	0.032

A-1.4 Life cycle net GHG emissions from solar PV power production: formal recycling as the end-of-life disposal option

The net life cycle GHG emission values from the solar PV power production system with formal recycling as the end-of-life disposal option is summarised in Figure 79.

Figure 79: Life cycle GHG emissions from the solar PV power production system under formal recycling



A-2 Life cycle inventory of the smart power box and the refrigerator

Smart power box: there is a smart power box (L 130mm × W 130 mm × H 25 mm) in this refrigeration model, which is useful for the management control of the refrigeration circuits. The smart power box is 477g in mass and the outer body is made from polycarbonate plastic. The main items inside the smart power box and the specifications are summarised in Table 37. For the analysis, the smart power box is divided into three major parts: outer polycarbonate box, printed circuit board with different items attached and connecting wire.

Table 37: Major components in the smart power box

COMPONENTS/ITEMS INCLUDED IN THE SMART BOX	NUMBER OF EACH ITEM IN A SMART BOX	MASS OF EACH COMPONENT (g)
Outer box / Polycarbonate box	1	320
Full Printed Circuit Board Assembly (PCBA)		
Capacitor	19	127
Resistor	47	
IC	7	
LED	2	
Transistor	3	
Regulator	4	
Varistor	6	
Diode	7	
Fuse	2	
Switch	1	
Wire	4	30
TOTAL MASS (g)		**477**

In this study, the SureChill 65L off-grid refrigerator was used for the carbon assessment. Table 38 summarises the specifications of the 65L refrigerator.

Table 38: Specifications of the off-grid 65L DC domestic refrigerator

DESCRIPTION	UNIT	AMOUNT
Brand name of the refrigerator	Brand name	SureChill
Manufacturer	Name	Midea
Working voltage	Voltage (Vdc)	12-36
Rated current	Amps (A)	8
Electrical power	Watt (W)	90
Average running time of the compressor per day	Hours/day	4.5
Mass of the refrigerator	kg	30
Lifetime	Years	10+
External dimension of the refrigerator	(L × W × H) m	0.6 × 0.6 × 0.75
Thickness of insulation (average)	mm	40mm
Thermal conductivity of insulation	W/m K	Approx 0.025
Cooling volume	L	65

Table 39: Mass balance of the material composition of individual components of the 65L refrigerator

MAIN PARTS OF THE REFRIGERATOR	TOTAL MATERIAL MASS (kg) OF EACH COMPONENT	MATERIAL COMPOSITION (%) OF EACH PART
Compressor	3.900	84% iron + 7% copper + 9% aluminum
Compressor controller	0.700	50% PCB + 25% epoxy + 25% polycarbonate (PC)
Steel mountings for compressor	0.750	100% steel
Refrigeration circuit	0.502	Aluminum alloy 1060
Cabinet back	0.857	100% Steel
Cabinet outer skin	4.900	Side panels: steel + top cover: ABS
Cabinet foam	2.940	60% isocyanate + 40% polyol DSD
Door seal	0.291	100% PVC
Door skin	1.900	100% steel
Door foam	0.588	60% isocyanate + 40% polyol DSD
Door liner	0.600	100% HIPS
Cabinet liner	1.900	100% HIPS
Shelves	4.000	Steel 90%, epoxy 10%
SureChill liner	4.200	100% PE
Crisper drawer	0.770	100% GPPS
Plastic trim	1.250	PE
TOTAL MASS OF THE REFRIGERATOR		**30.048**

Various types of metal and materials have been used to manufacture the SureChill 65L refrigerator. GHG emissions from virgin production of each type of material were extracted from different literature sources and summarised in Table 40. In addition, GHG emissions factors of recycling and recovery of each material are also gathered to calculate GHG emissions savings potentials at the end of the life cycle, see Table 40.

A-2.1 GHG emissions from the manufacturing phase

GHG emissions from raw material extraction for manufacturing the 65L refrigerator is presented in the main body of the report. GHG emissions from the manufacturing phase are estimated based on the energy consumption data presented in Table 41.

The main parts of the refrigerator production process are cabinet manufacturing, door manufacturing, forming of the cabinet and the door, infection moulding, refrigeration system manufacturing (compressor and assembly) and final assembly. Their contributions to different sources of energy consumption are shown in Table 41. The energy requirement for manufacturing was estimated by extrapolating data presented in Xiao et al. (2015) study.[34]

Table 40: GHG emissions from virgin production and recycling of different types of materials used in the 65L refrigerator

TYPE OF MATERIAL	GHG EMISSIONS FROM 100% VIRGIN PRODUCTION (kg CO2-eq/kg MATERIAL)	GHG EMISSIONS FROM 100% RECYCLING (kg CO2-eq/kg RECYCLED MATERIAL)	SOURCES USED TO EXTRACT GHG EMISSIONS FACTORS
Steel	2.81	1.53	World Steel Association[94]
Aluminium	16.51	0.59	International Aluminium Institute[118]
Copper	3.35	0.32	Copper Development Association,[123] Jingjinga et al study[20]
Polyurethane (PUR)	4.20	0.15	Plastic Europe[32]
Acrylonitrile butadiene styrene (ABS)	3.11	0.41	Plastic Europe,[124] Campolina et al. study [125]
High impact polystyrene (HIPS)	2.43	0.35	Plastic Europe,[124] Campolina et al. study [125]
PVC	2.16	0.43	US EPA,[127] Turner et al. study[128]
Epoxy	8.2	0.059	Devasahayam et al. study[129]
Polyethylene (PE)	1.78	0.55	Plastic Europe,[130] ARP[131]
General purpose polystyrene (GPPS)	3.25	2.82	Devasahayam[129]
Polycarbonates (PC)	3.35	1.4[132]	Devasahayam[129]
EPS	3.26	Recycling emissions factor is not available	Frankling Associates[133]
Corrugated cardboard	0.34185	Assumed to be landfilled	FEFCO[134]

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[123] Copper Development Association, 2019. Life Cycle Assessment of Copper Tube and Sheet. Available in https://www.copper.org/

[124] Plastic Europe, 2015. Styrene Acrylonitrile (SAN) and Acrylonitrile Butadiene Styrene (ABS). Available in https://www.plasticseurope.org/en/resources/eco-profiles

[125] Campolina, J.M., Sigrist, C.A.L., de Paiva, J.M.F., Nunes, A.O., Moris. V.A.D. 2019. A study on the environmental aspects of WEEE plastic recycling in a Brazilian company. Int J Life Cycle Asses, DOI 10.1007/s11367-017-1282-2

[126] Plastic Europe, 2012, General-Purpose Polystyrene (GPPS) and High-Impact Polystyrene (HIPS). Available in https://www.plasticseurope.org/en/resources/eco-profiles

[127] US EPA, 2015. WARM Version 13. US EPA Archive Document. Available in https://archive.epa.gov/epawaste/conserve/tools/warm/pdfs/Plastics.pdf

[128] Turner, D.A., Williams, I.D. and Kemp, S. 2015. Greenhouse gas emission factors for recycling of source-segregated waste materials.Resources, Conservation and Recycling 105 (2015) 186–197

[129] Devasahayam, S., Bhaskar Raju, G.B. and Hussain, C.M. 2019. Utilization and recycling of end of life plastics for sustainable and clean industrial processes including the iron and steel industry. Materials and Science for Energy Technologies, 634-646

[130] Plastic Europe, 2014. High-density Polyethylene (HDPE), Low-density Polyethylene (LDPE), Linear Low-density Polyethylene (LLDPE) PlasticsEurope. Available in https://www.plasticseurope.org/en/resources/eco-profiles

[131] APR, 2018. Life Cycle Impact for postconsumer Recycled Resin: PET, HDPE, PP. Submitted by Franklin Associates, A Division of Eastern Research Group (ERG). Available in https://plasticsrecycling.org/images/library/2018-APR-LCI-report.pdf

[132] There is no data on recycling of polycarbonate scraps. Therefore, recycling GHG emissions from mixed plastic were used

[133] Franklin Associates, 2016. Cradle-to-gate life cycle analysis of polystyrene resin. Available in https://www.epsindustry.org/

[134] FEFCO, 2018. European Database for Corrugated Board Life Cycle Studies. Available in https://www.fefco.org/download/file/fid/2626

Table 41: Type and amount of energy required for manufacturing the 65L refrigerator

TYPE OF ENERGY USE	PRODUCTION OF CABINET AND DOOR	FORMING OF CABINET AND DOOR	INJECTION MOLDING (SHELVES/DRAWERS)	REFRIGERATION SYSTEM (COMPRESSOR)	FINAL ASSEMBLY	TOTAL ENERGY
Electricity (kWh)	2.144	1.242	0.267	1.262	0.568	**5.483**
Natural gas (m^3)	0.111			0.024		**0.135**
Steam (kg)	3.895					**3.895**
Compressed air (m^3)	4.825	2.795	0.602	0.024	1.278	**9.524**

A-2.2 Life cycle inventory of the blowing agent

The manufacturing company of the SureChill 65L refrigerator is not willing to share the actual data related to the blowing agent. Therefore, the amount of blowing agent used in the refrigerator is estimated, as shown in Table 42. Cyclopentane has been used as the blowing agent in the refrigeration model considered in this study. The thickness of the insulation foam of the refrigerator is 40 mm. The amount of insulation foam used in this off-grid refrigeration model is 0.1m^3, and the weight is 3.5 kg. As reported in the literature, Cyclopentane content in the foam as a blowing agent is 5% W/W.[135] Based on these figures, the estimated amount of blowing agent in this refrigeration model is 176 g, see Table 42.

Table 42: Estimating of the amount of blowing agent used in the insulating foam (estimated values by authors)

DESCRIPTION	UNIT	AMOUNT
Dimensions of the refrigerator	(L × W × H) m	0.6 × 0.6 × 0.75
Total area	m^2	2.52
The thickness of the insulating foam	mm	40
Amount of insulating foam	m^3	0.1008
Density of insulating foam	kg/m^3	35
Total mass of the insulating foam	kg	3.528
Form used in the door (1/6 of total)	kg	0.588
Form used in cabinet	kg	2.940
Proportion of blowing agent in foam	%	5[135]
Amount of blowing agent	g	176.4
GWP of foam-blowing agent cyclopentane	kg CO$_2$-eq/kg	11

A-2.3 Life cycle inventory and GHG emissions from end-of-life disposal of the 65L refrigerator

Life cycle inventory data related to the end-of-life management phase is estimated based on the literature's mass balance analysis results and resource recovery data. The recommended lifespan of the refrigerator is 10 years. At the end of the 10 years of service life, both the solar power production system and the refrigerator need to be disposed of. However, there is a high chance of using both the solar PV system and refrigerator even for 20-30 years. Therefore, the end-of-life GHG emissions from the solar PV system and the refrigerator were assessed with respect to 10, 20 and 30 years of lifespan scenarios.

Unlike in developed countries, there is no proper mechanism of end-of-life WEEE disposal in Africa. Therefore, three possible scenarios will be assessed with respect to the end-of-life product management as follows:

Scenario 1: 100% end-of-life product disposing at dumpsites

Scenario 2: Partial recycling of end-of-life products by the informal recyclers: current scenario

Scenario 3: Implementing a proper recycling mechanism: Formal recycling mechanism in the future

Scenario 1: Complete dumping scenario

Used and end-of-life refrigerators are kept at the site or disposed of at a nearby dumpsite or landfill. Although there are serious environmental and health risks from the open dumping of end-of-life refrigerators, there are hardly any GHG emissions associated with the disposal phase. There might be very limited GHG emissions associated with the logistics movements which can be assumed as negligible. In addition, the refrigerant in the end-of-life compressor will be leaked to the environment, and blowing agent in the polyurethane form, which was used as an insulation material, will escape to the environment. Therefore, end-of-life GHG emissions from the 100% open dumping scenario is summarised in Table 43. GWP of the refrigerant (HC-600a) and the blowing agent (cyclopentane) is very low, and therefore it has resulted in a very low climate impact that amounts to 1.91 kg CO$_2$-eq from the 100% open dumping scenario.

Table 43: GHG emissions from 100% open dumping scenario of the end-of-life solar PV system and the 65L refrigerator (estimated values by authors)

DESCRIPTION	UNIT	AMOUNT
Climate impact leaked refrigerant at the end-of-life	kg CO$_2$-eq/kg	0.09
Climate impact from escaping of the blowing agent	kg CO$_2$-eq/kg	1.82
Total climate impact from end-of-life open dumping	kg CO$_2$-eq/kg	1.91

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[135] UNEP, 1994. Cyclopentane: A Blowing Agent for Polyurethane Forms for Insulation in Domestic Refrigerators and Freezers.
NOTE: There is considerable variation in published values of the GWP of cyclopentane. GA appliances, one of the leading appliances companies in the USA stated that the Global warming potential of cyclopentane 10 kg CO$_2$-eq/kg (https://pressroom.geappliances.com/news/reducing-greenhouse-gas-emissions-190718). EU regulation 517/2014 of the European Parliament and of the council has mentioned that GWP of cyclopentane is 5 kg CO$_2$-eq/kg, however this is using a default value based on the GWP of other hydrocarbons so may not be specific to cyclopentane. A recent proposal to repeal this regulation (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0150), COM/2022/150 final, suggests a figure of 0 kg CO$_2$-eq/kg for cyclopentane. Because of these various values, the authors have decided to use the conservative value of 11 kg CO$_2$-eq/kg which may underestimate the potential savings from switching to cyclopentane. However, the exact value use (whether 0 or 11 kg CO$_2$-eq/kg) does not change the findings or affect the results significantly (<1% of life cycle emissions).

Informal recycling – current scenario

Informal recycling is assumed to be the current practice of the end-of-life management, and climate impact is presented in the main chapter of the SureChill case study.

Formal recycling – future scenario

GHG mitigation potential under the formal recycling mechanism was assessed to compare the currently used recycling technologies with the world's best available technologies. In this scenario, a proper mechanism for the collection of used solar PV panels and refrigerators should be available within the country. Predominantly retailer shops or the municipalities can collect these used refrigerators and then transport them to the designated stockyards. The WEEE stockyards then transport the collected end-of-life refrigerators to the dismantling facility, which can accommodate and disassemble the end-of-life refrigerators.

The basic steps for recycling used domestic refrigerators would be to start with removing the refrigerant and oil inside the motor, followed by manually drilling the refrigerator's internal workings to drain the remaining fluids away.[136] Manual dismantling of foam will result in a blowing agent loss of 10 to 33%.[137] The motor can then be removed and sent out for recycling. The rest of the refrigerator then can be sent into a sealed chamber to extract the gases in the refrigerators' insulation foam. The refrigerator is then dropped inside a large shredder, where heavy-duty steel chains spin around. This motion forms a vortex that breaks the outer shell of the refrigerator into smaller pieces. The insulation foam is smashed into powder to release more of the gases. The rest of the refrigerator remains are dropped onto a heated conveyor. The heat, again, helps to release and neutralise any leftover gases. The remaining components are sent through four different filtration systems to separate the different materials from each other. Plastics, metals and foam are sorted into individual storage containers. These are then shipped on to be recycled into other products, potentially even another refrigerator.

It was assumed that formal dismantling facilities are located 500 km away from the study location and transported by trucks. Estimated GHG emissions from transportation would be 1.1 kg CO_2-eq for logistical movement of the 65L refrigerator.

GHG emissions at the dismantling facility mainly occur due to the use of fossil fuels to operate the machines. The type and the amount of energy consumption for the dismantling activities of the end-of-life refrigerator were derived from Menikpura et al. study.[138] The major energy sources used for the dismantling activities are grid electricity, light oil and liquefied petroleum gas (LPG). The derived values for dismantling the 30 kg refrigerator are summarised below. Total GHG emissions from the dismantling activities are 2.807 kg CO_2-eq (see Table 44).

Table 44: Total GHG emissions from the dismantling activities of the 65L refrigerator (estimated by authors based on Menikpura et al. study)[138]

DESCRIPTION	AMOUNT	GHG EMISSIONS (kg CO_2-eq)
Diesel consumption per unit (L/unit)	0.010	0.027
Electricity consumption per unit (kWh/unit)	4.257	2.567
LPG consumption per unit (kg/unit)	0.070	0.213
TOTAL GHG EMISSIONS FROM THE DISMANTLING OF THE 65L REFRIGERATOR		**2.807**

As mentioned by GIZ, it was assumed that 20% of blowing agent (35 g of cyclopentane) in the form will be leaked into the atmosphere during the dismantling process, and related GHG emissions would be 0.39 kg CO_2-eq. In addition, 10% of refrigerant (HC-600a) can escape into the atmosphere during the end-of-life recovery process.[137] As both blowing agent and refrigerant have very low GWP values, the estimated GHG emissions from the end-of-life leakages of gases would amount to 0.341 kg CO_2-eq.

Table 45: Global warming impacts associated with the blowing agent and refrigerant emissions at the end-of-life phase

DESCRIPTION	UNIT	VALUE
Amount of blowing agent emissions during dismantling	%	20[137]
Amount of blowing agent scraping	kg	0.030
Amount of GHG emissions	kg CO_2-eq/kg	0.332
Recovery rate of the refrigerant	%	90
Escaping amount of the refrigerant	%	10[137]
Amount of the refrigerant	kg	0.003
GWP from non-recovered refrigerant	kg CO_2-eq/kg	0.009
TOTAL GHG EMISSIONS FROM END-OF-LIFE MANAGEMENT OF THE REFRIGERANT AND THE BLOWING AGENT	**kg CO_2-eq/kg**	**0.341**

There is very limited literature information related to the recovery rate of metals/materials and the yield radio in the African region. According to the home appliance research done by Murakami et al.[37] in Japan, the recovery rate of individual major metals components was considered 75%, and 50% for plastics. In this study, it was considered that the recyclability / yield ratio of all the metals would be 95% and the recyclability of plastic would be 80% due to impurities.[37]

Based on the assumptions made above, the total recovered amount of materials from the 65L refrigerator after the dismantling process would be 15.187 kg. GHG emissions from recycling of those metals and materials amount to 18.747 kg CO_2-eq. In order to quantify the overall GHG emissions from the recycling process of the refrigerator through the formal route, the estimated emissions from different phases of the life cycle were added up. Even though the logistical movement is a complex process, it contributes to less GHG emissions as

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[136] AO Recycling, 2020. Fridge and WEEE Recycling. Available in https://ao-recycling.com/our-services/fridge-recycling/

[137] GIZ, 2017. Management and Destruction of Existing Ozone Depleting Substances Banks. Guideline on the Manual Dismantling of Refrigerators and Air Conditioners. Available in https://www.international-climate-initiative.com/fileadmin/Dokumente/2017/171219_EN-weee.pdf

[138] Menikpura, S.N.M., Sato, A. and Hotta. Y. 2014. Assessing the climate co-benefits from Waste Electrical and Electronic Equipment (WEEE) recycling in Japan, Journal of Cleaner Production, 74 (183-190)

compared to the dismantling and smelting phases. Total GHG emissions from all the phases of the recycling process amounted to 23.06 kg CO2-eq (see Figure 80).

Materials that are recuperated from the end-of-life refrigerator can be used to minimise the utilisation of virgin materials. This means that the use of substantial amounts of energy and virgin resources can be avoided whilst, at the same time, environmental degradation can be kept to a minimum. The life cycle GHG emissions from the recycling process were compared with the virgin production of the equivalent amount of materials, which amounted to 48.67 kg CO2-eq (see Figure 80).

The overall climate impact or benefit of formal recycling of the end-of-life refrigerator recycling will depend on the net GHG emissions, accounting for both emissions from recycling (see Figure 80) and the indirect, downstream GHG savings via resource recovery. Estimated GHG emissions savings potential via resource recovery would be -48.67 kg of CO2-eq. The resulting net negative values indicate a significant contribution from the recycling of all kinds of metals and plastics for GHG emissions mitigation. These GHG emissions would otherwise occur during the virgin resource production processes. This result is a very good indication of the effects of end-of-life refrigerator recycling for achieving climate co-benefits.

Figure 80: GHG emissions from the formal recycling process of the SureChill 65L domestic refrigerator under the formal recycling

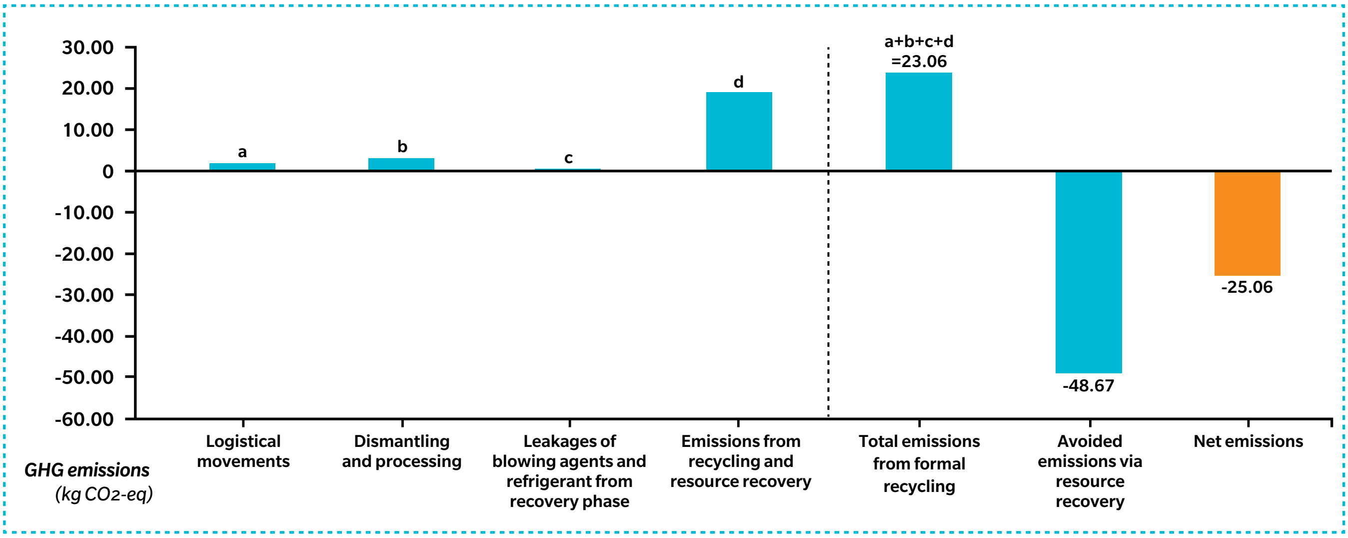

Table 46: Summary of material rec§overy, GHG emissions and GHG emissions avoidance potential from the end-of-life formal recycling of the 65L domestic refrigerator

TYPE OF MATERIALS	TOTAL MASS OF EACH METAL/ MATERIAL (kg)	RECOVERY RATE (%)[37]	POTENTIAL RECOVERED AMOUNT (kg)	YIELD RATIO[37]	ACTUAL RECOVERED AMOUNT (kg) (A)	GHG EMISSIONS (kg CO2-eq) FROM RECYCLING PER kg OF METAL[139] (B)	TOTAL GHG EMISSIONS FROM SMELTING (kg) (A × B)	GHG EMISSION FROM VIRGIN PRODUCTION OF MATERIALS PER (kg CO2-eq) (C)	TOTAL AVOIDED GHG (kg CO2-eq) (A × C)
Steel	15.186	75	11.389	95	10.820	1.530	16.554	2.810	30.404
Aluminum	0.849	75	0.637	95	0.605	0.588	0.356	16.513	9.990
Copper	0.451	75	0.338	95	0.321	0.316	0.102	3.345	1.075
Polyurethane foam (PUR)	3.528					Landfilled			
Acrylonitrile butadiene styrene (ABS)	0.098	50	0.049	80	0.039	0.412	0.016	3.109	0.122
High impact polystyrene (HIPS)	2.500	50	1.250	80	1.000	0.350	0.350	2.431	2.430
Polyvinyl chloride (PVC)	0.291	50	0.146	80	0.116	0.431	0.050	2.161	0.251
Epoxy	0.575		Thermosets and composites such as epoxy cannot be re-formed. So assumed to be landfilled						
Polycarbonates (PC)	0.175	50	0.088	80	0.070	1.400	0.098	3.348	0.234
Polyethylene (PE)	5.450	50	2.725	80	2.180	0.550	1.200	1.777	3.874
General purpose polystyrene (GPPS)	0.770					Landfilled			
Printed circuit board (PCB)[140]	0.175	50	0.070	50	0.035	0.614	0.021	8.141	0.285
TOTAL	**30.048**				**15.187**		**18.747**		**48.666**

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[139] Various literature sources have been used to find the emission factors and reference list has shown in Table 15

[140] Out of the total mass, only 40% is metal. It was assumed that 50% of the total available metal of PCB is recycled

Life cycle inventory and GHG emissions from end-of-life disposal of the smart power box

GHG emissions from 100% open dumping of the smart power box: The lifespan of the smart power box is ten years and at the end of the life cycle, it might be disposed of in the open dumpsite or kept in the plant. There are hardly any GHG emissions from landfilling/open dump of the smart power box except a negligible amount that would be emitted during transportation. However, various other negative impacts would occur due to the disposal of electronics in the landfills and the release of highly toxic emissions to the environment. Net life cycle GHG emissions caused from 100% open dumping at the end-of-life of the smart power box are assumed to be negligible.

GHG emissions from formal recycling of the smart power box – Future scenario: GHG emissions from formal recycling and resource recovery are considered at the end of the life cycle. There is the possibility of recovering precious and rare metals, and avoiding toxic substances being released to the environment. Although collecting and recycling electronics are not yet established in Kenya, assessing the future scenario will be useful for initiating an appropriate recycling mechanism in the future.

GHG emissions from the recycling of polycarbonate box, PCB and copper wire were assessed separately. Calculating GHG emissions from PCB is complicated as there is no available information on the recovery rate of PCB in smart power boxes, such as small equipment. Some literature sources state that recovering the metal contents of PCB scraps can add up to 30% of the total mass. More than 70% of PCB scraps cannot be efficiently recycled and recovered and have to be incinerated or landfilled.[141] Some literature sources state up to 80% of the recovery rate[142] by adopting advanced technologies. Therefore, in this study, it was assumed that 50% of recoverable metal is recovered from the end-of-life PCB. Metals represent around 40% of the PCB overall value, while non-metal elements constitute the rest, such as organics (30%), and ceramics (30%).[127] The nonmetallic fraction containing large amounts of carbon is either burnt to provide energy during recycling or trashed as a waste by-product. This study assumed that the non-metallic part of PCB would be disposed of at landfills. The estimated GHG emissions from shredding and recycling PCB amounted to 155 g CO_2-eq. Summary of GHG emissions and avoided potential due to the resource recovery from the smart power box is presented in Table 47. Total GHG emissions from end-of-life recycling is 0.530 kg CO_2-eq, and the avoided GHG emissions from resource recovery is 1.910 kg CO_2-eq. The estimated net GHG emissions from the smart power box considering all the life cycle phases are -1.380 kg CO_2-eq, which indicates possible GHG emissions savings. Therefore, improvement of the recycling rate has the potential of reducing net GHG emissions.

Table 47: Summary of net climate impact from formal recycling of the smart power box in future scenario (estimated values by authors)

MAJOR PARTS OF THE SMART POWER BOX	END-OF-LIFE FORMAL RECYCLING (kg CO_2-eq) (A)	AVOIDED EMISSIONS FROM VIRGIN RESOURCE RECOVERY (kg CO_2-eq) (B)	NET GHG EMISSIONS (kg CO_2-eq) (A)-(B)
Polycarbonate outer box	0.358	0.857	-0.499
Printed Circuit Board (PCB)	0.155	1.034	-0.878
Wire (copper)	0.016	0.019	-0.003
TOTAL	**0.530**	**1.910**	**-1.380**

A-2.4 Net life cycle GHG emissions from the 65L refrigerator with respect to the different end-of-life treatment options

Net life cycle GHG emissions – 100% end-of-life product of the solar PV system and the refrigerator being disposed of at dumpsites

100% open dumping was considered for both the solar PV system and the refrigerator at the end-of-life. The lifespan of the refrigerator was considered to be 10 years. It was assumed that solar PV panels would be used for at least 20 years to power a refrigerator with similar specifications. Therefore, only 50% of the life cycle GHG emissions of the solar PV system was allocated within the 10-year lifespan of the refrigerator. Emissions from the solar PV power production are mainly due to the raw material extraction and manufacturing phase and 50% of emissions from solar PV system manufacturing have been allocated to the manufacturing phase (see Figure 81).

This scenario would be the most basic option, as the end-of-life management is limited to open dumping for both the solar PV system and the refrigerator. GHG emissions from the end of the life cycle are limited to the climate impact caused by the refrigerant and blowing agent release. A significant amount of GHG emissions are associated with raw material extraction, processing and manufacturing of the solar PV system and the refrigerator, which amounts to 97% of life cycle emissions. GHG emissions from transportation phases contributed to only 2.3% of life cycle emissions. GHG emissions due to the releasing of blowing agent during the use phase is contributed to 0.03% of life cycle emissions. GHG emissions produced as a result of the blowing agent and the refrigerant during the disposal phase amounted to 0.54% of life cycle emissions. Life cycle GHG emissions from this scenario amounted to 351.53 kg CO_2-eq (see Figure 81).

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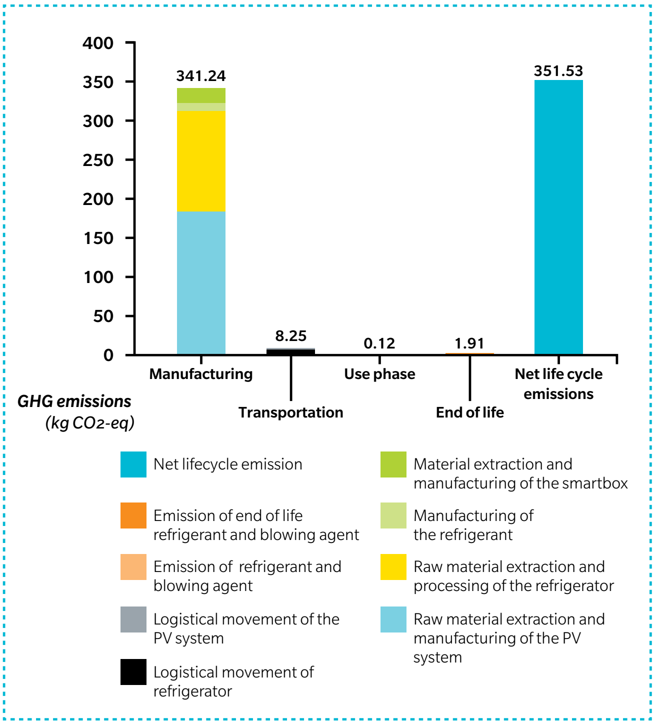
[141] Kaya, M., 2016. State of the Art in Printed Circuit Board (PCB) Recycling Technology. 15th International Mineral Processing Symposium (IMPS-2016), Istanbul 19-21 Ekim, 2016 Proceeding

[142] Vermes, H., Tiuc, A.E. and Purcar, M. 2019. Advanced Recovery Techniques for Waste Materials from IT and Telecommunication Equipment Printed Circuit Boards. Sustainability 2020, 12, 74; doi:10.3390/su12010074

Figure 81: Net life cycle GHG emissions from the SureChill 65L domestic DC refrigeration model in 100% open dumping scenario

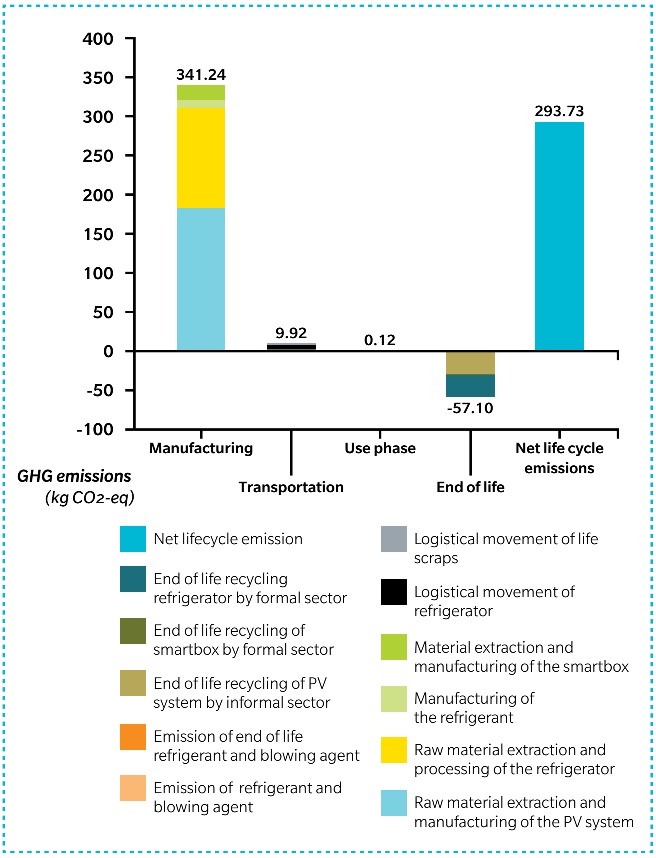


Net life cycle GHG emissions from the 'future scenario': formal recycling of both the solar PV system and the refrigerator

Formal recycling was considered for the end-of-life management of the solar PV system and the refrigerator. The lifespan of the refrigerator was considered to be ten years. Net life cycle GHG emissions from the current scenario are presented in the SureChill main chapter. The main difference in this scenario from the current practice is that the formal recycling mechanism would be adapted to treat the end-of-life of the solar PV system, the smart power box and the refrigerator to reduce the substantial environmental pollution that would be caused by open dumping or informal recycling activities. Life cycle GHG emissions are quantified by aggregating the potential climate impact from the different life cycle phases. The raw material extraction and production phase of the solar PV system and the refrigerator contributed to significant GHG emissions, which amounts to 97.17% of total emissions. GHG emissions from logistical movements of both the refrigerator and the end-of-life scraps were 2.7%. Release of the blowing agents during the use phase contributed only 0.03% of life cycle GHG emissions. End-of-life GHG emissions of the refrigerant and the blowing agents contributed to 0.1% of emissions. As seen in Figure 82, the end-of-life formal recycling process resulted in a net negative impact due to resource recovery and avoided virgin production of equivalent materials. Life cycle GHG emissions from the domestic 65L refrigerator was estimated by aggregating the total potential emissions and the avoided potential. The estimated net life cycle climate impact from the 65L refrigerator amounted to 293.73 kg CO_2-eq.

If the 65L refrigerator lifespan was extended to 20 years and 30 years, net GHG emissions from the entire life cycle would be 467.65 kg CO_2-eq and 485.66 kg CO_2-eq, respectively with formal recycling at the end of the life cycle. The effectiveness of the extended lifespan of the 65L refrigerator was compared by calculating GHG emissions for three different lifespans. Extending the 65L refrigerator lifespan to 20 years and 30 years would reduce the GHG emissions by 20% and 45%, respectively, compared to the 10-year lifespan of the 65L refrigerator.

Figure 82: Life cycle GHG emissions from the SureChill 65L domestic DC refrigeration model in the 'future scenario'



A-3 Scenario analysis

Amount of blowing agent used and its climate impact:

The amount of blowing agents required for manufacturing PU foams for the cold room and the climate impacts are presented in Table 48. A comparative assessment was performed to assess the climate impact of natural and HFC blowing agents used to manufacture the polyurethane panels.

Table 48: Estimation of the blowing agent amount required for manufacturing PU foams for the 65L refrigerator and total climate impacts

DESCRIPTION	UNIT	CURRENT CASE (SURECHILL)	BASE SCENARIO - BAU
Production of PU foam			
Type of blowing agent	Name	Cyclopentane	HFC-245fa
(a) GHG emissions from the manufacturing of PU foam	kg CO_2-eq/ kg PU form	4.20[143,32]	23.48[144]
(b) Amount of foam required for insulation	kg for the 65L refrigerator	3.528	3.125
(c) GWP from manufacturing of foams (a) × (b)	kg CO_2-eq	14.829	73.370
(d) Proportion of blowing agent in foams	%	5[55]	13.3[54]
(e) Amount of blowing agent (b) × (d) × 1000	g	176.40	415.60
(f) GWP values of blowing agent	kg CO_2-eq/kg	11	1030
(g) Max GWP from blowing agent leakages	kg CO_2-eq	1.94	428.07
(h) Total climate impact from foam production and leakage of blowing agent (a) × (b) + (g)	kg CO_2-eq	16.77	501.44

Emissions reduction potential by increasing the serviceable life of the refrigeration system

GHG emissions per unit (kWh) of electricity production concerning three possible lifespan scenarios were analysed. In the first scenario, the lifetime of the solar PV panels is considered to be 10 years since the SureChill off-grid powered refrigerator warranty period is ten years and both the refrigerator and the solar PV system are assumed to be discarded after ten years. Detailed analysis is presented in Table 49. The same approach was followed to estimate GHG emissions per unit of electricity production from lifespans of 20, 25 and 30 years.

Emission factor for diesel back-up generator

When neither solar PV nor grid electricity is available, fossil fuel back-up generators are the last resort. Nearly 9% of the electricity consumed in Sub-Saharan Africa and 2% in Asia is powered by fossil fuel back-up generators.[73]

Figure 83: Generator fuel consumption curves for the four generator categories considered in the BUGS modeling framework[73]

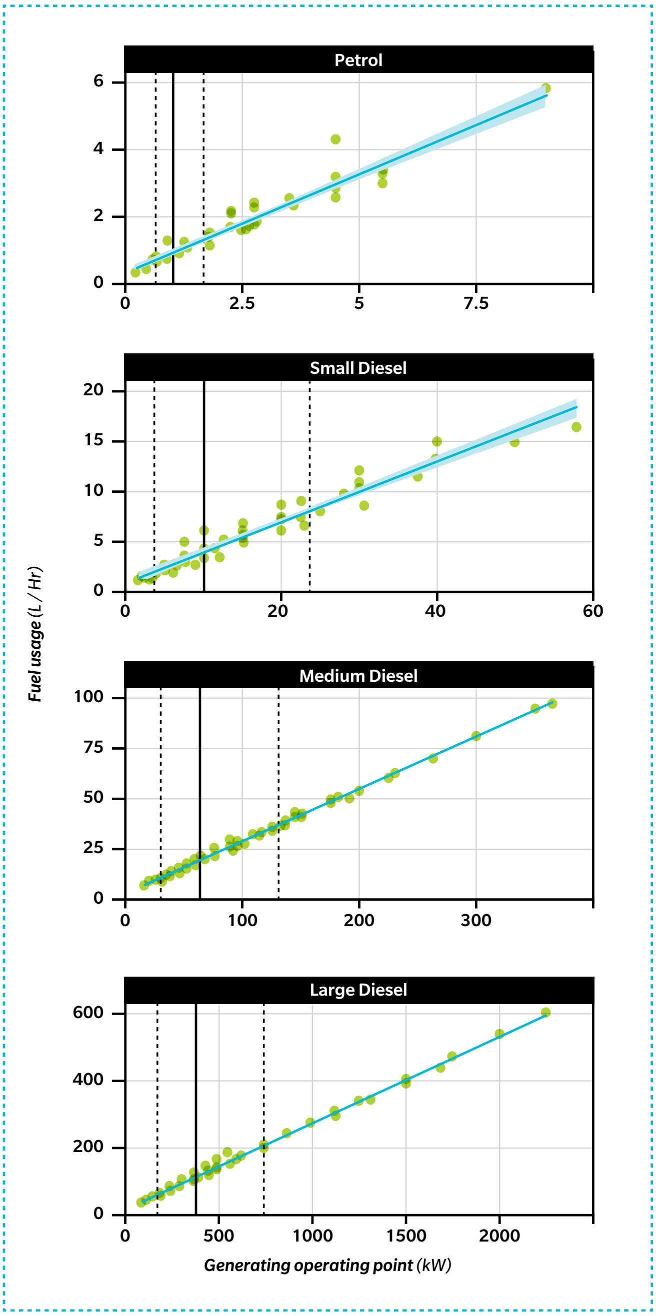


Table 49: Estimation of GHG emissions per unit of electricity production (kg CO_2-eq/kWh) for the solar PV system based on a lifespan of ten years

YEAR	1	2	3	4	5	6	7	8	9	10
Power production per solar PV panel (Wp)*	120	119.4	118.8	118.2	117.6	117.0	116.4	115.9	115.3	114.7
Power production from 2 solar PV panels (Wp)	240.0	238.8	237.6	236.4	235.2	234.1	232.9	231.7	230.6	229.4
Annual power production (kWh) (Wp/1000 × 4 hrs/day × 365 days/year)	350.4	348.6	346.9	345.2	343.4	341.7	340.0	338.3	336.6	334.9
Total power production in 10 years (kWh)	3426.2									
Life cycle GHG emissions from solar PV system ** (kg CO_2-eq)	316.5									
GHG emission per kWh (kg CO_2-eq/kWh)	0.092									

* The efficiency of the PV panel will fall by 0.5% since the PV panel is degraded each year as part of a natural degradation process.[145]

** End-of-life disposal option in this scenario is informal recycling

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143 There is no literature information about PU foam production with cyclopentane as the blowing agent. The data is for pentane uses as the blowing agent

144 There is no literature about PU foam production/manufacturing with HFC245fa as the blowing agent. The information is for HFC-134a uses as a blowing agent. (Ecoinvent)

145 Interview with the refrigerator manufacturer

As Figure 83 shows, the fridge falls into the operating point (KW) of petrol and small diesel categories, and cold room in the small diesel category. To be consistent for all cooling technologies discussed in this report, the authors assume a small diesel back-up generator as the default back-up generator for both the refrigerator and cold room. To estimate the carbon factor (kg CO_2 eq/kWh) of a small diesel back-up generator, the generator fuel curve slope is in units of litres per kWh (litres / kWh) which gives 0.3 litres / kWh. The carbon factor of diesel oil is 10.18 kg CO_2 eq /gallon,[146] which gives 2.69 kg CO_2 eq /litre. The product of diesel oil carbon factor is 2.69 kg CO_2 eq / litre and small diesel generator fuel consumption is 0.3 litres / kWh gives 0.807 kg CO_2 eq/kWh for the small diesel generator's carbon factor.

A-4 Refrigerator energy consumption and component sizing

To compare the SureChill fridge to an appropriately similar battery powered fridge, a model was developed to determine the appropriate component sizes. This used power data obtained from SureChill to ensure the only difference was the energy storage medium (i.e. chemical batteries instead of ice). This model was also used to determine the thermal cooling energy requirements of both the SureChill and baseline fridges for the calculation of the 'GHG emissions per unit of cooling energy' functional unit.

A-4.1 Methods

Solar PV data

Solar PV data was obtained from the European PVGIS service for a location approximately 100 km east of Nairobi.[147] This includes temperature and PV power data for the desired location. A slope of 2 degrees was chosen and an azimuth of 0 degrees for the panels which would provide maximum power capture.

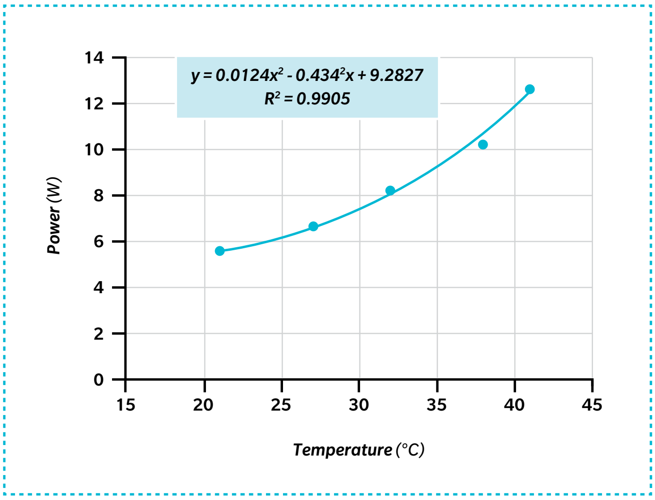
Fridge energy consumption profile

Using data from SureChill, the electrical energy consumption for the fridge at each hour was calculated based on the temperature. A polynomial fit was applied to the consumption data shown in Table 50 provided by SureChill to give the power at any temperature. The temperature does deviate below this range (down to 15°C) which will add a degree of inaccuracy, however the R2 value is high so it is believed that the trend will hold out with this range. The local temperature data used is the shaded external temperature. If the fridge is located indoors which is likely, it would be expected that a more consistent temperature would be maintained, with fewer especially high or low temperatures. However, in the absence of more reliable data, this proxy was considered suitable.

Table 50: Fridge daily energy use at various temperatures. Obtained from SureChill

TEMPERATURE	DAILY CONSUMPTION (kWh)
21	0.133
27	0.161
32	0.196
38	0.245
41	0.301

Figure 84: Polynomial fit to determine fridge power from temperature data



The data in Table 50 gives the power consumption for a closed fridge with no openings (also known as infiltration losses). Therefore, the power was scaled to account for a more realistic domestic scenario. Research suggests opening the door increases the power consumption between 7% and 30%.[40] A value of 30% was chosen to account for the level of door opening.

To determine the cooling energy from thermal and infiltration losses (for the calculation of the functional unit), the electrical consumptions were multiplied by the average COPs of the baseline and SureChill fridges which are 1.92 and 1.75 respectively. These values were obtained from SureChill. These average values will result in some error due to the temperature effects from different regions, however more detailed data on this was not available for this study.

To account for food being taken out of and replaced in the fridge, an assumed occupancy of the fridge was made (see Table 51) and a weighted average heat capacity (effectively per L) was determined. 10% of the total capacity of the fridge was assumed to be replaced each day so it was on average 70% full. This is a suitable occupancy for a well-stocked fridge with an ideal being around 75%.[148] This results in 6.5L of produce being replaced each day. For a food temperature difference of 10°C

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146 US EPA. 2018,. Greenhouse Gases Equivalencies Calculator - Calculations and References | US EPA. US EPA. https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

147 EU Science Hub, 2021. Available in https://ec.europa.eu/jrc/en/pvgis

148 D & T Applince. 2020. Available in https://www.dtappliance.com/blog/does-a-refrigerator-work-better-full-or-empty/

(15°C before and 5°C after it goes in – we assume to food going in is partially chilled already) this gives an average extra cooling energy of 62.3kWh per day to chill the additional food. This was spread evenly over an assumed usage time of 9am to 9pm local time. Using the COPs of 1.92 for the baseline refrigerator and 1.75 for the SureChill refrigerator, the electrical energy required was calculated by dividing the cooling energy by the COP.

Table 51: Density and heat capacity of various food groups to calculate average heat capacity of the food in the fridge

PRODUCT	VOLUME (%)	DENSITY (kg/M^3)	MASS (%)	HEAT CAPACITY (kJ/kg°C)[149]
Meat/Fish	20%	1	20%	3.6
Drinks (milk/water/juice)	30%	1	30%	4.1
Veg/Fruit	30%	0.8	24%	3.7
Other (beans, chocolate, cheese)	20%	0.9	18%	3.4
Average heat capacity of food (kJ/L°C)				3.45

PV battery modelling

To determine the baseline fridge PV and battery sizes, the PV generation profile was scaled linearly to the applicable peak power output. Overall system losses were assumed to be 14% to give a conservative estimate. This is the typical value used when including AC inverter losses so the actual value is possibly more like 11-12% for the DC scenario we have here.

Using an adapted version of EST's PV battery model, for every hour, the difference between the electrical generation and consumption was calculated and the battery charged or discharged accordingly to power the fridge. The model was run for fridge lifetimes of 10, 20 and 30 years. For each year, a degradation rate was applied to the solar panels (reducing solar generation), fridge (increasing fridge energy consumption) and battery (reducing usable battery capacity). The solar panel and fridge degradation rates were a simple linear calculation (i.e. x% after 1 year and 5x% after 5 years). The battery degradation rate was based on both the number of cycles and calendar life of the battery.
For each year, degradation rate for the cycles and calendar life was calculated and the maximum of the two used as the annual degradation rate. The battery was replaced when it reached either of its lifetime limits. The model was iteratively run with the battery and PV panel sizes varied such that there were zero hours of no operation of the fridge across its lifetime, and that the fridge could function for three days without solar energy and not exceed an internal temperature of 12°C (to be comparable to the SureChill model).

A-4.2 Assumptions

Table 52: Battery chemistry assumptions[150]

BATTERY TYPE	LIFETIME (CYCLES)	CALENDER LIFETIME (YEARS)	ROUND TRIP EFFICIENCY	DoD
Lead acid (LA)	1867	9.9	81%	50%
Lithium iron phosphate (LFP)	3008	13.6	86.5%	90%
Lithium nickel metal chloride (LNMC)	2406	13.6	92.5%	90%

Table 53: Other assumptions

DESCRIPTION	VALUE	REASONING
Charge controller size	1.25 times the solar panel output	Needs to be slightly larger due to environmental factors[151]
Fridge degradation rate	0.5% per year	SureChill recommendation
PV panel degradation	0.5% per year	Typical factor
Battery capacity at EoL	80%	Typical definition of EoL
Fridge opening addition energy	30%	Defined in paper by Khan et al[40]
PV generation losses	14%	Typical value used in EU PVGIS[147]

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[149] The Engineering Tool Box,2020. https://www.engineeringtoolbox.com/specific-heat-capacity-food-d_295.html

[150] IRENA, 2017. Electricity storage and renewables: Costs and markets to 2030. Available in https://www.irena.org/publications/2017/Oct/Electricity-storage-and-renewables-costs-and-markets

[151] RENOGY, 2020. Solar charge controller sizing and how to choose one. Available in https://www.renogy.com/blog/solar-charge-controller-sizing-and-how-to-choose-one

B-1 Case Study I: Life cycle GHG emissions from the 20m^3 SelfChill cold room

B-1.1 PV power production

Solar panel: six monocrystalline 350Wp solar PV panels power the 20m^3 SelfChill cold room. The total mass of a single panel and a frame amount to 24 kg. Solar PV panels are fitted with anodized aluminium frames. The panel frame plays a fundamental role in protecting the internal components from thermal and mechanical tensions and providing mounting attachment points. 90% of the rated power output of these panels can be expected for 10 years and 80% rated power output for 25 years. The detailed specifications of the solar PV panels used in the 20m^3 SelfChill cold room are summarised in Table 54.

Table 54: Specifications of the solar PV panels used in the 20m^3 SelfChill cold room

DESCRIPTION	UNIT	AMOUNT
Type of PV modules	Name	Monocrystalline
Manufacturer	Name	Europe
Life expectancy	Years	20 years
Dimensions of the solar PV panel (height × width)	m	1.956 × 0.992
Area of the solar PV panel	m^2 / Panel	1.940
No. of solar PV panels used in the solar system	Number	6
Installation type	Type	On roof
Total generator area of the solar PV panels in the plant	m^2	11.642
Efficiency factor of the PV modules	%	20
The maximum power voltage (Vmpp)	Volts	24
Generating capacity of the solar PV panel	Wp	11.642
Warranty period	Years	25
Total mass of the solar PV panel and the frame	kg	24

GHG emissions from the production of six monocrystalline 350Wp solar PV panels were based on the Ecoinvent database version 3.7.112 It should be noted that the Ecoinvent database has not been updated recently, and the efficiency of PV panels has improved significantly in recent years. It was assumed that though the efficiency is relatively high in new panels, the volume of materials required to produce each m^2 of panel is more or less similar. Based on the LCI of Ecoinvent, net GHG emissions per m^2 of a monocrystalline solar PV panel production is 260.706 kg CO_2-eq. Estimated GHG emissions from the six 350Wp solar PV panels used in this case study was 3035.087 kg CO_2-eq.

Mounting structures and cables: it was assumed that a roof with a tilt mount is used as the mounting system for the solar PV system. It enables the maintenance of the solar PV panel tilting angles while resisting extreme wind experienced over the solar PV panel's lifetime. Mounting structures are mainly manufactured from aluminium trails and legs. Ecoinvent data developed for solar PV mounting system production for flat-roof installation in Europe was considered.[152]

Table 55: GHG emissions from manufacturing six monocrystalline 350Wp solar PV panels

TYPE	TYPE OF RAW MATERIALS/ ENERGY AND EMISSIONS	UNIT	INPUT/OUTPUT PER m^2 OF SOLAR PV PANEL	INPUT/OUTPUT FOR 6 SOLAR PV PANELS (6 × 1.940 m^2)
Type of fossil energy used	Hard coal	kg	74.598	868.455
	Brown / soft coal	kg	24.374	283.757
	Natural gas	m^3	27.760	323.176
	Crude oil	kg	13.699	159.481
GHG emissions	Carbon dioxide (CO_2), fossil	kg	239.880	2792.639
	Methane (CH_4), fossil	kg	0.730	8.494
	Nitrous oxide (N_2O)	kg	0.009	0.101
TOTAL GHG EMISSIONS		kg CO_2-eq	260.706	3035.087

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[152] Jungbluth, N. 2020. Ecoinvent version 3.7. Available in https://v37.ecoquery.ecoinvent.org/

Table 56: GHG emissions from the manufacturing of on-roof PV mounting system

TYPE	TYPE OF MATERIALS/ENERGY	UNIT	INPUT/OUTPUT OF MANUFACTURING THE SUPPORTING STRUCTURE PER m^2 OF SOLAR PV PANEL AREA[152]	INPUT/OUTPUT OF MANUFACTURING THE SUPPORTING STRUCTURE FOR 6 SOLAR PV PANELS (6 × 1.9403 m^2)
Type of fossil energy used	Hard coal	kg	12.619	146.908
	Brown / soft coal	kg	1.712	19.934
	Natural gas	m^3	2.829	32.930
	Crude oil	kg	3.2451	37.779
GHG emissions	Carbon dioxide (CO_2), fossil	kg	38.675	450.246
	Methane (CH_4), fossil	kg	0.143	1.660
	Nitrous oxide (N_2O)	kg	0.001	0.010
TOTAL GHG EMISSIONS		kg CO_2-eq	42.488	494.634

The total mass of the solar array cable is 3.96 kg. The cable is made from plastic (30%) and copper (70%). The cross-section area is 4 mm^2. Ecoinvent LCI of cable production with similar material composition were used to estimate the GHG emissions.[114] The calculated results are shown in Table 57.

Table 57: GHG emissions from the manufacturing of solar array cable

TYPE	TYPE OF MATERIALS/ENERGY	UNIT	INPUT/OUTPUT TO MANUFACTURE 1 kg MASS OF CABLE[114]	INPUT/OUTPUT TO MANUFACTURE 3.96 kg OF CABLES
Type of fossil energy used	Hard coal	kg	1.442	5.712
	Brown / soft coal	kg	0.424	1.677
	Natural gas	m^3	0.785	3.107
	Crude oil	kg	0.923	3.657
GHG emissions	Carbon dioxide (CO_2), fossil	kg	6.039	23.915
	Methane (CH_4), fossil	kg	0.017	0.068
	Nitrous oxide (N_2O)	kg	0.001	0.003
TOTAL GHG EMISSIONS		kg CO_2-eq	6.665	26.393

Charge controller: There is no data available for Ecoinvent LCI of the remote controller or the charge controller. Therefore, data was extrapolated from a 500W inverter (1.6 kg) to quantify the emissions from a 580W charge controller.[153] GHG emissions from the 580W charge controller amounted to 43.294 kg CO_2-eq.

Table 58: GHG emissions from manufacturing the charge controller

TYPE	TYPE OF MATERIALS/ENERGY	UNIT	INPUT/OUTPUT OF MANUFACTURING THE 500W INVERTER[153]	INPUT/OUTPUT OF MANUFACTURING THE 580W CHARGE CONTROLLER
Type of fossil energy used	Hard coal	kg	9.6165	11.155
	Brown / soft coal	kg	3.3896	3.932
	Natural gas	m^3	3.988	4.626
	Crude oil	kg	2.0534	2.382
GHG emissions	Carbon dioxide (CO_2), fossil	kg	34.142	39.604
	Methane (CH_4), fossil	kg	0.108	0.125
	Nitrous oxide (N_2O)	kg	0.002	0.002
TOTAL GHG EMISSIONS		kg CO_2-eq	37.322	43.294

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[153] Tuchschmid, M. 2020. inverter production, 0.5kW, RER. Ecoinvent version 3.7. Available in https://v37.ecoquery.ecoinvent.org/

Battery bank: six AGM lead acid batteries (120Ah, 12V) are used to store the excess power and then used in the night-time and rainy days. The mass of each battery is 30.6 kg, and the maximum depth of discharge (MDOD) is 40%. LCI of lead acid battery is extracted from Spanos et al. study (2015).[47] The table below shows the LCI and the estimated emission per kg of PbA battery production.

Table 59: GHG emissions from manufacturing the PbA battery[47]

RAW MATERIALS/ENERGY CONSUMPTION	UNIT	AMOUNT PER kg (kg)	GHG EMISSIONS FROM MANUFACTURING (kg CO_2-eq/kg OF MATERIAL)	GHG EMISSIONS PER kg OF PBA BATTERY
Lead	kg	0.7100	1.1524[154]	0.8182
Casing (PP)	kg	0.0750	1.9700	0.1478
Fiber glass mat separator	kg	0.0250	3.0900	0.0773
Copper terminals	kg	0.0050	1.8500	0.0093
GRID ALLOYING ADDITIVES				
Calcium (0.058% of alloyed lead, expressed as carbide)	kg	0.0003	3.8600	0.0012
Aluminum	kg	0.0001	8.8000	0.0009
Tin	kg	0.0040	22.4000	0.0896
Silver (0.02% of alloyed lead)	kg	0.0001	106.0000	0.0106
NEGATIVE ELECTRODE ADDITIVES				
Barium sulfate (0.8% of oxide mass)	kg	0.0012	0.2710	0.0003
Carbon black (0.25% of oxide mass)	kg	0.0004	2.3900	0.0010
Sodium lignosulfonate (0.35% of oxide mass)	kg	0.0005	0.9690	0.0005
ELECTROLYTE (37WT%H2SO4)				
H2SO4	kg	0.0630	0.1410	0.0089
Water (dilute to 37%)	kg	0.1080	0.0014	0.0001
BALANCING AND CONTROL ELECTRONICS				
Integrated circuit (0.025wt% of controller)	kg	0.0000	1010.0000	0.0020
Printed wiring board (4.975 wt% of controller)	kg	0.0004	56.7000	0.0227
ABS plastic casing for controller (95wt% of controller)	kg	0.0076	4.3900	0.0334
GHG EMISSIONS (kg CO_2-eq) PER kg OF PBA BATTERY		1.0006		1.2236

Table 60: GHG emissions from the manufacturing of a PbA battery bank in the SelfChill cold room

DESCRIPTION	UNIT	AMOUNT
GHG emissions from raw materials production	kg CO_2-eq/kg	1.22
GHG emissions from energy consumption for manufacturing	kg CO_2-eq/kg	0.68[47]
Total GHG emissions from the production of the PbA battery	kg CO_2-eq/kg	1.90
Mass of the PbA battery	kg	30.6
GHG emissions from manufacturing the PbA battery	kg CO_2-eq/ battery	58.25
Number of PbA batteries used at a time		6
Total GHG emissions from 6 PbA batteries	kg CO_2-eq	349.49

Note: Material composition of the compressor was obtained from Xiao et al study (2015),[34] and the other items' composition was obtained from SelfChill via a questionnaire survey.

B-1.2 SelfChill $20m^3$ cold room

Cooling system: Compressor, condenser, evaporator plates, pipes and fans are the major components of the cooling system. The total mass of the cooling system is around 10 kg, and six cooling units are used in the $20m^3$ cold room. Mass balance and material composition of the major materials in the cooling system are shown in Table 61.

[154] GHG emission from 70% secondary (recycled) lead and 30% virgin lead

Table 61: Mass balance and materials composition of the SelfChill colling system

TYPE OF MATERIAL	COMPRESSOR (kg)	EVAPORATOR PLATE (kg)	CONDENSER (kg)	PIPES (kg)	FAN (kg)	TOTAL MASS (kg)	COMPOSITION MATERIALS OF THE COOLING SYSTEM (%)
Steel	5.041					5.041	54.819
Aluminum	0.534	1	1			2.534	27.555
Copper	0.425			1	0.016	1.441	15.669
Plastic					0.152	0.152	1.653
Other					0.028	0.028	0.304
Total	6.000	1.000	1.000	1.000	0.196	9.196	100.000

Note: Material composition of the compressor was obtained from Xiao et al study (2015),34 and the other items' composition was obtained from SelfChill via a questionnaire survey

Water chiller: the SelfChill 20m^3 cold room uses a water chiller to produce cold air to maintain the setpoint temperature. The water chiller is made by using a 500L polyethylene box and polyethene pallet. The box is covered with 100% closed-cell elastomeric foam insulation. Mass balance and material composition of the waste chiller is presented in the Table 62.[156] The estimated climate impact from the different components of the water chiller amounted to 244.16 kg CO_2-eq.

Table 62: Mass balance and materials composition of the SelfChill water chiller

MAIN COMPONENT OF THE WATER CHILLER	NO OF UNITS/ SPECIFICATIONS	TOTAL MATERIAL MASS OF ALL THE UNITS (kg)	MANUFACTURING GHG EMISSIONS (kg CO_2-eq)[156]	MATERIAL COMPOSITION (%)
500L PE box	1	32	100.625	PE 100% Dimensions (mm): 1200 × 800 × 600
Cover for the 500L PE box	1	4.8	15.094	PE 100% Dimensions (mm) : 1200 × 800 × 50
PE pallet	1	13	40.879	PE 100% Dimensions (mm): 1200 × 800 × 100
Supporting structures	2	15	25.290	60% steel, 40% wood
Thermal insulation foam (with foil inner surface)	4	8	39.374	100% closed-cell elastomeric foam insulation (Armaflex)
DC water pump	1	0.2	Negligible	
Pipes	20 m water hose	4	7.460	PVC
Insulation materials for pipes	Armaflex	3	14.765	100% closed-cell elastomeric foam insulation (Armaflex)
Water stop valves	10	0.2	0.671	PVC
TOTAL		80.2	244.158	

Cold room: the 20m^3 SelfChill cold room dimensions are 3.00 m × 3.00 m × 2.16 m. The expected lifespan is 20 years. The major parts of the cold room and the material composition are summarised in Table 63.

Table 63: Mass balance and materials composition of the 20m^3 SelfChill cold room

NAME OF THE MAIN PARTS	ITEMS IN EACH COMPONENT AND THEIR SPECIFICATIONS	TOTAL MATERIAL MASS (kg)	MATERIAL COMPOSITION (%)
Cold cell	18 polyurethane panels with galvanized sheet steel	596	Dimension of a panel: 1 m × 2.2 m × 80 mm; Thickness of steel: 1 mm both sides; Amount of steel: 483 kg ; Amount of polyurethane foam: 113 kg
Doors	Polyurethane panels with galvanized sheet steel (80 mm thickness)	25	Dimension of a panel: 1 m × 2.2 m × 80 mm; Thickness of steel: 1 mm both sides; Amount of steel 20 kg; Amount of polyurethane foam: 5 kg
Thermostat		0.5	Assumed to have negligible climate impact
Lighting		0.1	Assumed to have negligible climate impact
Cables		1	Mass of cables: 2 kg; Gauge of cables: 1.5 mm^2
Heat exchanger		16	Material composition is steel 40% aluminium 60%

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[155] Authors derived emissions from emissions factors of each type of materials

[156] Information gathered from SelfChill through the questionnaire survey

GHG emissions from the use of blowing agents in polyurethane foams in SelfChill cold room

The estimated mass of the polyurethane foam in the panels used in the $20m^3$ SelfChill cold room is 117.48 kg. The blowing agent used to make polyurethane foam is HC-601 (N pentane). Blowing agents can have proportions of 9.8% in the foam.[157] As reported, approximately 5% of the blowing agent can be emitted during the first year and then it will be released at a rate of 0.5%/yr.[127] Based on these figures, the total blowing agent released within a 20-year use phase would be 1.569 kg. The global warming potential of the HC-601(N-pentane) is 5 kg CO_2-eq/kg.[158]

Table 64: GHG emissions from the blowing agents used in the polyurethane panels in the $20m^3$ SelfChill cold room

DESCRIPTION	AMOUNT	UNIT
Total foams used in the cold room	117.484	kg
Proportion of blowing agent in foam	9.8[157]	%
Amount of the blowing agent (HC-601)	11.513	kg
Amount of the blowing agent released during the first year	5[81]	%
Amount released first year	0.576	kg of HC-601
Released rate from first year	5[81]	% / year
Total amount released during the 20-year use phase	1.569	kg of HC-601
GWP value of HC-601	5[158]	kg CO_2-eq/kg
GHG emissions from releasing the blowing agent from the panels in the use phase	7.846	kg CO_2-eq

Therefore, the estimated GHG emissions due to the release of the blowing agent during the use phase would be 7.846 kg CO_2-eq.

Life cycle inventory of end-of-life recycling of the solar PV panels: formal recycling

A typical crystalline silicon (c-Si) solar PV module contains approximately 75% of the total mass from the module surface (glass), 10% polymer (encapsulant and back sheet foil), 8% aluminium (mostly the frame), 5% silicon (solar cells), 1% copper (interconnectors) and less than 0.1% silver and other metals like tin and lead.115 The rest of the components have a small percentage of the module mass and are accounted as 'others'. Recyclability of different materials was based on the study done by Huang et al (2017).[116] The potential amount of material recovery per panel is shown in Table 65.

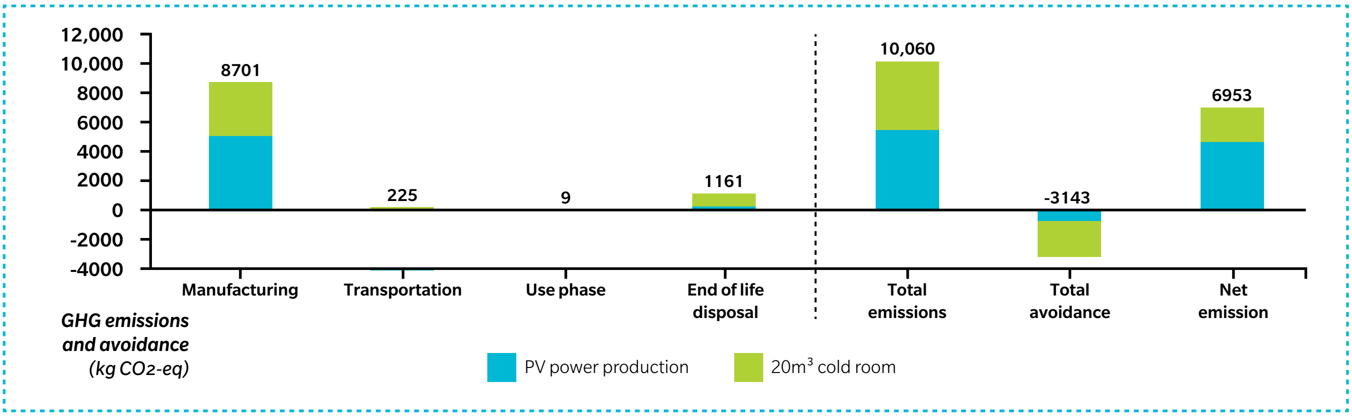
B-1.3 Life cycle GHG emissions from 25 year and 30 year lifespans

The solar PV system and the $20m^3$ SelfChill cold room would be utilised for over 20 years with careful management. Estimated net life cycle emissions from 25 years and 30 years lifespans under the informal recycling option at the end of the life cycle are presented in Figure 85 and Figure 86.

Table 65: Composition of materials of crystalline silicon and their recyclability under formal recycling

COMPOSITION OF CRYSTALLINE SILICON (C-SI)	COMPOSITION OF MATERIALS (%) IN THE SOLAR PV PANEL[115]	WEIGHT OF MATERIALS (kg)	RECYCLING RATE (%)	THE POTENTIAL AMOUNT OF RECOVERY PER SOLAR PV PANEL (kg)
Glass (module surface)	75	18	89	16.020
Polymer mainly EVA and PET (encapsulant and back sheet foil)	10	2.4	80	1.920
Aluminum (mostly the frame)	8	1.92	81	1.555
Silicon (mostly solar cells)	5	1.2	80	0.960
Copper (interconnectors)	1	0.24	89	0.214
Other metals (silver, lead)	0.1	0.024	89	0.021
Other mixed materials	0.9	0.216	89	0.192
Total	100	24		20.882

Figure 85: Total GHG emissions, GHG avoidance and net emissions from 25 years lifespan of the $20m^3$ SelfChill cold room under informal recycling (authors estimation)



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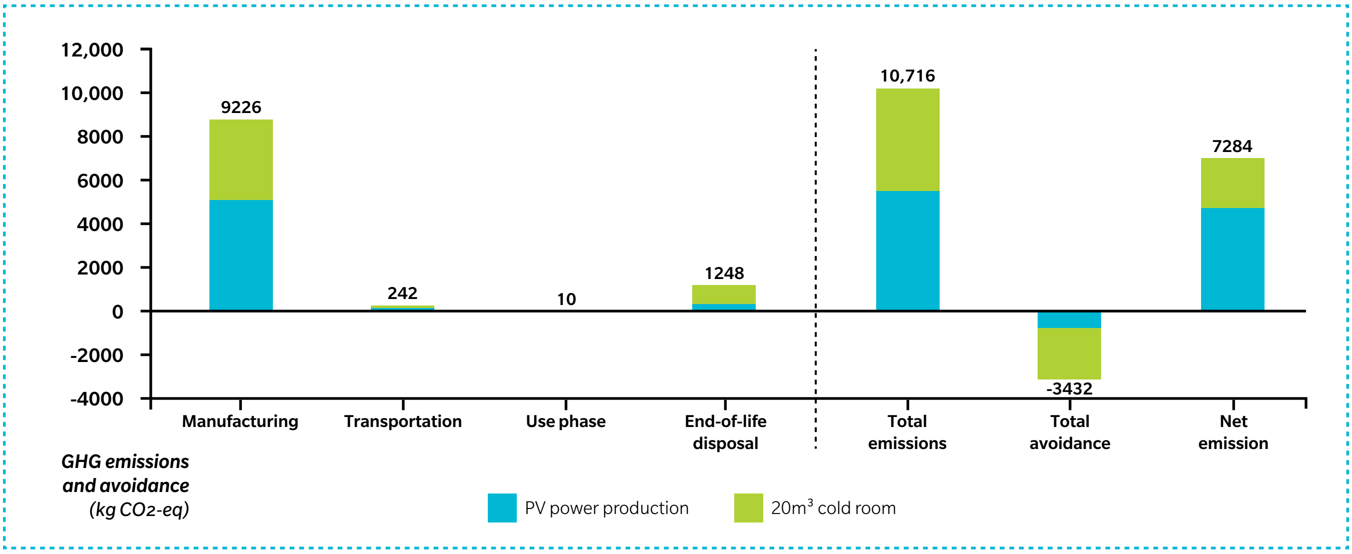
[157] Esmaeilnezhad, E., Rezaei, M and Razav, M.K. 2009. The Effect of Alternative Blowing Agents on Microstructure and Mechanical Characteristics of Rigid Polyurethane Foam. Available online in http://journal.ipp

[158] German Environment Agency, 2019. Global Warming Potential (GWP) of certain substances and mixtures. Available in https://www.umweltbundesamt.de/en/document/global-warming-potential-gwp-of-certain-substances

Figure 86: Total GHG emissions, GHG avoidance and net emissions from 30 years lifespan of the 20m^3 SelfChill cold room under informal recycling (authors estimation)



B-1.4 Scenario analysis

Amount of blowing agent and climate impact: the estimated amount of blowing agent required for manufacturing the PU foams for the 20m^3 SelfChill cold room and its climate impacts are shown in Table 66. GHG emissions potential from the use of HC-601(N-pentane) and HFC-245fa as a blowing agent in the PU panels was estimated. In the absence of proper recovery methods of the blowing agent from the PU foams at the end of the cold room life cycle, it would escape to the environment and contribute to the climate impact.

Table 66: The estimated amount of natural and HFC blowing agent required for manufacturing the PU foams for the 20m^3 SelfChill cold room and its climate impacts

DESCRIPTION	UNIT	HC-601	HFC-245FA
Total foams used in the cold room	kg	117.484*	117.484**
Proportion of blowing agent in foam	%	9.8[157]	13.3[157]
Amount of the blowing agent (HC-601)	kg	11.513	15.625
Percentage of the blowing agent released in the first year	%	5[81]	5[81]
Amount of the blowing agent released in the first year	kg of HC-601	0.576	0.781
Released rate after the first year	%/year	0.5[81]	0.5[81]
Total amount released during the 20-year use phase	kg of HC-601	1.569	2.130
GWP value of HC-601	kg CO$_2$-eq / kg	5[158]	1030[158]
GHG from releasing the blowing agent during the use phase	kg CO$_2$-eq	7.846	2193.648
GHG emissions at the end of the life cycle in the absence of treatment	kg CO$_2$-eq	49.721	13,900.432
Total climate impact from the blowing agent	kg CO$_2$-eq	57.567	16,094.080

* The data was obtained for pentane used as a blowing agent.[32]

** There is no literature about PU foam production/manufacturing with HFC-245fa used as a blowing agent. The information is for HFC-134a used as a blowing agent. It was assumed that HFC-245fa and HFC-134a have similar properties as the blowing agent used in the 20m^3 SelfChill cold room.

B-2 Case Study II: Life cycle GHG emissions from the 20m^3 ColdHubs cold room

B-2.1 PV power production

PV panels: 18 polycrystalline 340Wp solar PV panels power the 20m^3 ColdHubs cold room. The total mass of a single panel and a frame mass to 22.5 kg. Solar PV panels are fitted with anodized aluminium frames. The panel frame plays a fundamental role in protecting the internal components from thermal and mechanical tensions and providing mounting attachment points. The detailed specifications of the solar PV panels used in the 20m^3 ColdHubs cold room are summarised in Table 67.

Table 67: Specifications of the solar PV panels used in the 20m³ ColdHubs cold room

DESCRIPTION	UNIT	AMOUNT
Type of PV modules	Name	Polycrystalline
Manufacturer	Name	Europe
Life expectancy	Years	25 years
Description of irradiance	kWh/m^2/yr	Not yet measured
Dimensions of the solar PV panel (height × width)	m	1.956 × 0.992
Area of the solar PV panel	m^2/Panel	1.940
No. of solar PV panels used in the solar system	Number	18
Installation type	Type	On roof
Total generator area of the solar PV panels in the plant	m^2	34.926
Efficiency factor of the PV modules	%	20
The maximum power voltage (Vmpp)	Volts	24
Generating capacity of PV panel	Wp	340
Warranty period	Years	25
Total mass of the solar PV panel and the frame	kg	22.5

LCI of a solar PV panel includes production of the cell matrix, cutting of foils and washing of glass, production of laminate and isolation, production of the aluminium frame of the panel, and disposal after the end of use. GHG emissions are linked to the amount of fossil fuels consumed for raw material extraction and manufacturing of the solar PV panel. Therefore, the amount of fossil energy required and the related GHG emissions from the production of 18 polycrystalline 340Wp solar PV panels were derived based on the Ecoinvent database version 3.7.[113] Based on LCI from Ecoinvent, net GHG emissions per m^2 of a polycrystalline solar PV panel production is 199.157 kg CO_2 eq. Estimated GHG emissions from 18 polycrystalline 340Wp solar PV panels used in this case study are 6,955.841 kg CO_2-eq.

Mounting structures and cables: it was assumed that a roof with a tilt mount is used as the mounting system for the solar PV system. It enables maintaining solar PV panel tilting angles while resisting extreme wind experienced over the solar PV panel's lifetime. ColdHubs' mounting structures are mainly manufactured from 100% galvanized angle steel. Total mass of the supporting structures used to install the solar PV panels in the 20m³ ColdHubs cold room is 350 kg. The mounting system is made with hot-dip galvanised steel to ensure safety and healthy growth and development. Hot-dip galvanizing, the process of metallurgically bonding zinc to steel, has been used to protect steel for more than 150 years and provides maintenance-free corrosion protection for decades.[159] GHG emissions from hot-dip galvanised steel is 2.81 kg CO_2-eq per kg.[94] Based on this figure, estimated GHG emissions from the mounting system is 983.5 kg CO_2-eq. The amount of zinc used for galvanisation was assumed to be negligible.

The total mass of the solar array cable is 12 kg. The cable is made from plastic (40%) and copper (60%). The gauge of the cable is 6mm. Ecoinvent LCI of cable production with similar material composition were used to estimate the GHG emissions.[114] The estimated results are shown in Table 69.

Table 68: GHG emissions from manufacturing 18 polycrystalline 340Wp solar PV panels

TYPE	TYPE OF MATERIALS/ENERGY	UNIT	INPUT / OUTPUT PER m^2 OF SOLAR PV PANEL[113]	INPUT / OUTPUT FOR 18 SOLAR PV PANELS (18 × 1.940 m^2)
Type of fossil energy used	Hard coal	kg	55.145	1926.013
	Brown / soft coal	kg	18.290	638.803
	Natural gas	m^3	21.794	761.185
	Crude oil	kg	12.487	436.125
GHG emissions	Carbon dioxide (CO_2), fossil	kg	183.099	6394.992
	Methane (CH_4), fossil	kg	0.567	19.814
	Nitrous oxide (N_2O)	kg	0.006	0.220
TOTAL GHG EMISSIONS		kg CO_2-eq	199.157	6955.841

Table 69: GHG emissions from the manufacturing of solar array cable

TYPE	TYPE OF MATERIALS/ENERGY	UNIT	INPUT / OUTPUT TO MANUFACTURE 1 kg MASS OF CABLE[114]	INPUT / OUTPUT TO MANUFACTURE 12 kg OF CABLES
Type of fossil energy used	Hard coal	kg	1.442	17.309
	Brown / soft coal	kg	0.424	5.082
	Natural gas	m^3	0.785	9.416
	Crude oil	kg	0.923	11.081
GHG emissions	Carbon dioxide (CO_2), fossil	kg	6.039	72.471
	Methane (CH_4), fossil	kg	0.017	0.206
	Nitrous oxide (N_2O)	kg	0.001	0.008
TOTAL GHG EMISSIONS		kg CO_2-eq	6.665	79.978

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[159] American Galvanizers Association (AGA), 2009. Hot-Dip Galvanazing for Sustainable Design. Available in https://galvanizeit.org/education-and-resources/publications/hot-dip-galvanizing-for-sustainable-design

Inverters: There is no LCI for the exact capacity of the inverters. Tschümperlin et al. (2016),[95] published LCI for a 2.5kW inverter, which was extrapolated to estimate the LCI of the 5kW and 6kW inverters, respectively. Extrapolation was done using a non-linear mass versus power relationship as reported in scientific literature. LCI of the Tschümperlin et al. study provides the GHG emissions from manufacturing and recycling (see Table 17). Recycling emissions shows a net negative impact (-70.719 kg CO_2-eq for the 5kW inverter and -117.865 kg CO_2-eq for the 6kW inverter) due to the resource recovery. GHG emissions from manufacturing were estimated and shown in Table 70. Authors estimated GHG emissions from the manufacturing of the 5kW and 6kW inverters as 479.46 kg CO_2-eq and 799.11 kg CO_2-eq, respectively.

Table 70: Inverter specifications based on the Tschümperlin et al. study[95]

TYPE	LCI OF A 2.5 kW (OLD) INVERTER (ECOINVENT)	LCI OF THE AVERAGE INVERTER	DERIVED LCI BASED ON THE WEIGHT OF A 2.5 kW NEW INVERTER	
			5KW	6KW
Unit	kg	kg	kg	kg
Total mass	18.7	11.2	15	25
Copper	5.5	1.9	2.545	4.241
Aluminium	1.4	5	6.696	11.161
Steel	9.8	0.9	1.205	2.009
Other individual components	0.3	2.2	2.946	4.911
Printed board assembly	1.7	1.2	1.607	2.679
Printed wiring board	0.7	0.3	0.402	0.670
CO_2 emissions (manufacturing and recycling after use)		358	479.464	799.107

Battery bank: 24 valve-regulated lead acid (VRLA) batteries (990Ah, 2V) are used to store the excess power and then used in the night-time and rainy days. The mass of each battery is 61.3 kg, and the maximum depth of discharge (MDOD) is 80%. LCI of a typical VRLA battery is extracted from Spanos et al. (2015) study.[47] The table below shows the LCI and the estimated emissions per kg of PbA battery production. The estimated GHG emissions from manufacturing the 61.3 kg PbA battery is 116.643 kg CO_2-eq (see Table 71 and Table 72).

Table 71: GHG emissions from the manufacturing of a PbA battery

RAW MATERIALS/ENERGY CONSUMPTION	UNIT	AMOUNT PER kg[47]	MASS OF MATERIAL IN THE 61.3 kg BATTERY	GHG EMISSIONS (kg CO_2-eq) PER kg OF PBA PRODUCTION	GHG EMISSIONS PER kg OF PBA BATTERY
Lead	kg	0.7100	43.523	1.1524	50.156
Casing (PP)	kg	0.0750	4.598	1.970	9.057
Fiber glass mat separator	kg	0.0250	1.533	3.090	4.735
Copper terminals	kg	0.0050	0.307	1.850	0.567
GRID ALLOYING ADDITIVES					
Calcium (0.058% of alloyed lead, expressed as carbide)	kg	0.0003	0.018	3.860	0.071
Aluminum	kg	0.0001	0.006	8.800	0.054
Tin	kg	0.0040	0.245	22.400	5.492
Silver (0.02% of alloyed lead)	kg	0.0001	0.006	106.000	0.650
NEGATIVE ELECTRODE ADDITIVES					
Barium sulfate (0.8% of oxide mass)	kg	0.0012	0.074	0.271	0.020
Carbon black (0.25% of oxide mass)	kg	0.0004	0.025	2.390	0.059
Sodium lignosulfonate (0.35% of oxide mass)	kg	0.0005	0.031	0.969	0.030
ELECTROLYTE (37WT%H2SO4)					
H2SO4	kg	0.0630	3.862	0.141	0.545
Water (dilute to 37%)	kg	0.1080	6.620	0.001	0.009
BALANCING AND CONTROL ELECTRONICS					
Integrated circuit (0.025wt% of controller)	kg	0.0000	0.000	1010.000	0.124
Printed wiring board (4.975 wt% of controller)	kg	0.0004	0.025	56.700	1.390
ABS plastic casing for controller (95wt% of controller)	kg	0.0076	0.466	4.390	2.045
GHG EMISSIONS (kg CO_2-EQ)		1.0006			75.004

Table 72: GHG emissions from manufacturing the PbA battery used in the $20m^3$ ColdHubs cold room

DESCRIPTION	AMOUNT	UNIT
GHG emissions from raw materials production (kg CO_2-eq) (a)	74.959	kg CO_2-eq / 61.3 kg battery
GHG emissions from energy consumption for manufacturing (b)	0.68[47]	kg CO_2-eq / kg of battery
Mass of the battery (c)	61.3	kg
GHG emissions from energy consumption of the battery (d) = (b) × (c)	41.68	kg CO_2-eq / 61.3 kg battery
Total GHG emissions from manufacturing the battery (g) = (a) + (d)	116.643	kg CO_2-eq

Cables and wires: different gauge cables and wires are utilised in the ColdHubs solar PV power system to connect devices. Detailed specifications of the cables and the wires are shown in Table 73. The total mass of the cables and the wires is 11.5 kg and 1.5 kg, respectively. According to the Ecoinvent database, 66% of the mass of the cables and the wires is copper, and the remaining 34% is plastic.[114]

Table 73: Mass balance analysis of cables and wires used and their material composition

SPECIFICATIONS	TOTAL WEIGHT (kg)	PERCENTAGE OF COPPER (66%)	PERCENTAGE OF PLASTIC (34%)
Diameter 16 mm, length 100 m cable	5	3.3	1.7
Diameter 6 mm, length 100 m cable	3	1.98	1.02
Diameter 4 mm, length 100 m cable	2	1.32	0.68
Diameter 1.5 mm, length 100 m cable	1.5	0.99	0.51
TOTAL MASS OF THE CABLES	**11.5**	**7.59**	**3.91**
Diameter 1.5 mm, length 5 m copper wire	1.5	1.2	0.3
TOTAL MASS OF THE CABLES AND THE WIRES	**13**	**8.79**	**4.21**

Table 74: LCI of cables (Ecoinvent, 2020)[114]

TYPE	TYPE OF MATERIALS/ENERGY	UNIT	INPUT / OUTPUT TO MANUFACTURE 1 kg MASS OF CABLE	INPUT / OUTPUT TO MANUFACTURE 12 kg OF CABLES
Type of fossil energy used	Hard coal	kg	1.442	16.588
	Brown / soft coal	kg	0.424	4.871
	Natural gas	m^3	0.785	9.024
	Crude oil	kg	0.923	10.619
GHG emissions	Carbon dioxide (CO_2), fossil	kg	6.039	69.451
	Methane (CH_4), fossil	kg	0.017	0.197
	Nitrous oxide (N_2O)	kg	0.001	0.008
TOTAL GHG EMISSIONS		kg CO_2-eq	6.665	76.646

Vega et al. (2015),[160] published information on GHG emissions required for wire manufacturing, which was used in this study. GHG emissions from copper wire production is 4.83 kg CO_2-eq/kg, and estimated GHG emissions from 1.5 kg copper wire production is 7.25 kg CO_2-eq.

In addition, there is a 5 kg wire trunk used to store the wire and cable which is made from 100% HDPE. The estimated GHG emissions from the wire trunk is shown in Table 75. Total GHG emissions were accounted for by adding emissions caused by raw material extraction and energy consumption for injection moulding.

Table 75: GHG emissions from the manufacturing of wire trunk

DESCRIPTION	AMOUNT	UNIT
Total mass of the wire trunk	5	kg
Materials used in the wire trunk	100	% HDPE
GHG emissions from raw materials extraction	1.78[130]	kg CO_2-eq / kg
Total GHG emissions from raw materials extraction	8.89	kg CO_2-eq
GHG emissions from injection molding	1.37[161]	kg CO_2-eq / kg
Total GHG emissions from injection molding	6.84	kg CO_2-eq
Total GHG emissions from the wire trunk	15.72	kg CO_2-eq

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[160] Vega, M., Zaror, C., Peña, C. and Scarinci, C. 2015. Life cycle assessment of Chilean copper wire rods. International Conference on Life Cycle Assessment, CILCAAt: Mendoza, Argentina

[161] Keoleian, G., Miller, S., Kleine, R., Fang, A. and Mosley, J. 2012. Life Cycle Material Data Update for GREET Model. Centre for Sustainable Systems. University of Michigan. Available in https://greet.es.anl.gov

B-2.2 Inventory related to ColdHubs cold room

Cooling system: ColdHubs uses Rmonoblock system as the cooling unit which has a mass of 52 kg. The lifespan is 15 years. Material composition and mass balance of the materials is not available. Therefore, it was derived from the study done by Cascini et al. (2016).[93] Inventory data of a refrigeration unit with medium refrigerating temperature (MRT) was used to derive the material composition of the cooling system. Material composition (%) of MRT cooling system and derived material mass of the 52 kg Monoblock system are presented in Table 76.

Table 76: Mass balance and materials composition of the ColdHubs cooling system

TYPE OF MATERIALS	MATERIAL COMPOSITION (%) OF THE MRT COOLING SYSTEM[93]	DERIVED MATERIALS MASS IN THE 52 kg COOLING SYSTEM (kg)
Steel	79.73	41.460
Copper	9.76	5.075
Aluminum	6.22	3.234
Plastic	3.66	1.903
Other (assumed PCB)	0.63	0.328
Total	100	52.000

Cold room cell (20 m^3): The 20 m^3 ColdHubs cold room can store approximately 2.2 tonnes of perishable fruit and vegetables. Dimensions of the cold room are 10 ft × 10 ft × 8 ft. The cold cell is made from polyurethane panels (PU) and 0.7 mm thick steel layer cover both sides of the polyurethane panels. The major parts of the cold room and the material composition are summarised in Table 77.[162]

B-2.3 Scenario analysis

Amount of blowing agent and climate impact: the estimated amount of blowing agent required for manufacturing the PU foams for the 20m^3 ColdHubs cold room and its climate impacts are shown in Table 78. A comparative assessment was performed to assess the climate impact of (i) 100% natural blowing agent (GWP-5), (ii) a natural and HFC blend used in the ColdHubs case (GWP-172) and (iii) 100% HFC-245fa blowing agent (GWP-1030).

Table 77: Major component of the ColdHubs cold cell and the mass balance

ITEMS IN THE COLD CELL	TYPE OF MATERIALS	NUMBER OF UNITS	MASS PER UNIT (kg)	TOTAL MASS (kg)	AMOUNT OF STEEL IN THE PU PANELS (kg)
Walls	PU panels	15	35	525	328.37
Roof	PU panels	3	35	105	65.67
Floor	Aluminium- Chaka Plate - 100%, PU sheet	2.5, 3	10, 55	25, 165	103.20
Door	PU sheet	1	50	50	31.27
Creates	HDPE	150	1.5	225	
TOTAL				1095	528.51

Table 78: Estimation of climate impacts from different blowing agents in the polyurethane panel

DESCRIPTION	UNIT	(i) PENTANE (NATURAL BLOWING AGENT)	(ii) BLEND USE IN THE COLDHUBS CASE (90% PENTANE + 10% HFCS)[163]	100% HFC-245FA BLOWING AGENT
Total foams used in the cold room	kg	316.487	316.487	316.487
Proportion of blowing agent in foam	%	5.4[157]	6.19[157]	13.3[157]
Amount of the blowing agent in the panels	kg of blowing agent	17.090	19.591	42.093
Amount of the blowing agent released in the first year	%	5.00	5.00	5.00
Amount of the blowing agent released in the first year	kg	0.855	0.980	2.105
Released rate after the first year	% / year	0.5[81]	0.5[81]	0.5[81]
Total amount released during the 20-year lifespan	kg of blowing agent	2.329	2.670	5.737
GWP value	kg CO_2-eq / kg	5[158]	172.63[158]	1030[158]
GHG from releasing the blowing agent during the use phase (a)	kg CO_2-eq	11.647	460.969	5909.420
GHG emissions at the end of the life cycle in the absence of treatment (b)	kg CO_2-eq	73.804	2921.007	37446.068
Total climate impact from the blowing agent (a+b)	kg CO_2-eq	85.451	3381.976	43355.488

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[162] This information was gathered from ColdHubs though the questionnaire survey

[163] Author derived values based on 90% natural refrigerant and 10% HFCs

ANNEX C – FOOD WASTE CALCULATIONS

C-1 Assumptions

Various assumptions for estimating post-harvest food losses are listed below:

- The food production for each region in 2007 was taken from Figure 1 of FAO's Global Food Losses and Food Waste report.[105] The estimates for food production are 92.583 million tonnes in Sub Saharan Africa and 306.6 million tonnes in South and Southeast Asia.
- The method for calculating food waste for post-harvest stage used in this study is based on Annex 5 from FAO's Global Food Losses and Food Waste - Extent, Causes and Prevention report.[105] Annex C-2 includes an example for the method used for calculating food waste.
- The estimated waste percentage for fruit and vegetables in each step of the food supply chain for Sub-Saharan Africa and South and Southeast Asia are presented in Table 79.[105] Please note that the percentage of waste is relative to the amount of food yielded from the previous step in the food supply chain, not relative to the total food production.

Table 79: Estimated waste percentage for fruit and vegetables in each step of the food supply chain, relative to the food yielded from the previous step

ESTIMATED WASTE PERCENTAGE FOR FRUITS AND VEGETABLES	SUB-SAHARAN AFRICA	SOUTH AND SOUTHEAST ASIA
Agricultural production	10%	15%
Postharvest handling and storage	9%	9%
Processing and packaging	25%	25%
Distribution	17%	10%
Consumption	5%	7%

- The growth index figures for projecting food waste from 2007 to 2012, 2020 and 2030 are derived from FAO's food and agriculture projection to 2050 data porta, using (i) the arable land (ha) and crop yield (tonnes/ha) to calculate the food production (tonnes) in each region for a specific year; and (ii) calculating the growth index based on the food production (tonnes) for each year.
- Authors have selected 'towards sustainability' as the growth index scenario in FAO's food and agriculture projection to 2050 data portal.
- The countries included in the Southeast Asia region for this research are Bhutan, Cambodia, Indonesia, Iran, Laos, Malaysia, Myanmar, Philippines, Thailand and Vietnam.[107]
- The countries included in the South Asia region for this research are Afghanistan, Bangladesh, India, Nepal, Pakistan and Sri Lanka.[107]

C-2 Method for calculating food waste[105]

The fruit and vegetable losses and waste for this study were calculated for the first two steps in the food supply chain (please note, percentage losses are based on previous step's output).108 Using Sub-Saharan Africa in 2007 as an example:

Waste percentage considered in first two steps of the food supply chain:

Agricultural production = 10%

Postharvest handling and storage = 9.38%

Calculations on equivalent fruit and vegetables losses in first two steps of the food supply chain:

Total fruit and vegetable production in SSA = 92.583 million tonnes

Agricultural production waste: 10%*92.583 = 9.3 million tonnes

Postharvest handling and storage waste: 9.38%*(92.583-9.2583) = 7.8 million tonnes

Conversion factors considered for estimating edible part of food commodities:

Peeling by hand = 0.8; industrial peeling = 0.75; mean = 0.77

Applying these factors to the fruit and vegetable losses in the first two steps of the food supply chain result in following estimates:

Agricultural production waste: 9258*0.77 = 7.129 million tonnes

Postharvest handling and storage waste: 7817*0.77 = 6.019 million tonnes

The calculation of food waste amount that can be mitigated by cooling technology is as following:

$$FW\ (i,j\ \text{Post-harvest}) = \left(\sum (i,j,k)\ FS\ (i,j\ \text{Production}) \times \delta\ (i,j\ \text{Post-harvest})\right) \times \mu_j$$

$$FS\ (i,j,k\ \text{Production}) = FP\ (i,j) - FP\ (i,j) \times \delta_{(i,j\ \text{Production})}$$

Where:

FW (i,j Post-harvest) is food waste amount during post-harvest handling and storage stage in region j, with commodity i, expressed in million tonnes.

FS (i,j Production) is food survived amount through agricultural production stage in region j, with commodity i, expressed in million tonnes.

δ (i,j Post-harvest) is the percentage of food waste specifically at post-harvest handling and storage stage.

μ j is a general percentage of food that are edible for fruits and vegetables.

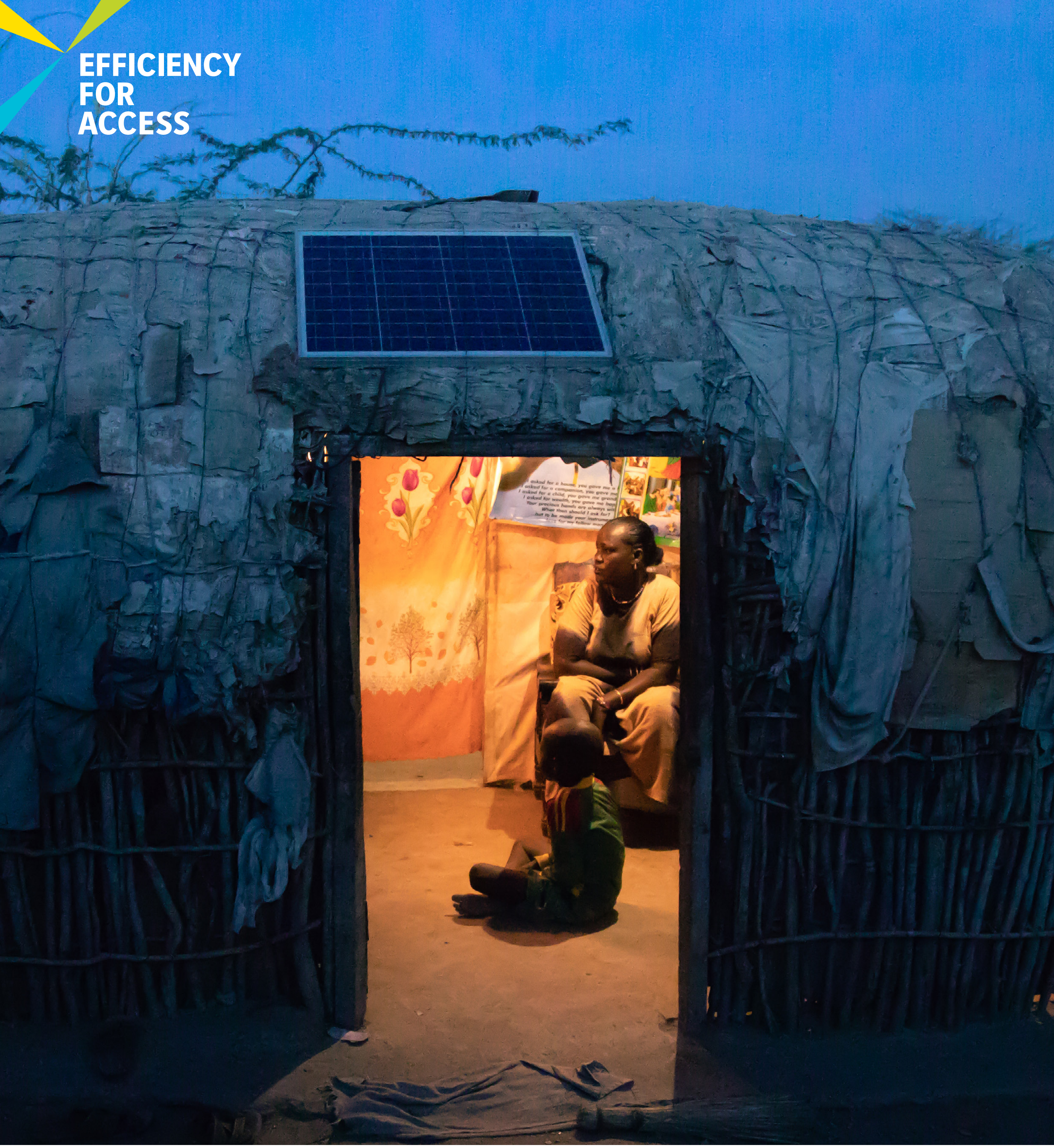
FP (i,j) is food production amount at the beginning of agricultural production stage in region j, with commodity i, expressed in million tonnes.

δ (i,j Production) is the percentage of food waste specifically at agricultural production stage.

C-3 South Asia scaling calculation

As discussed in Section 5.2, the FAO database have South and Southeast Asia figures for food production projection and estimate waste percentage for fruits and vegetables. To estimate the equivalent figures for South Asia alone, the authors decided to scale down the South and Southeast Asia figures to South Asia based on population distribution in 2007. The population figures are from Worldbank shown as below.[107]

SOUTH ASIA POPULATION 2007		**SOUTHEAST ASIA POPULATION 2007**	
Afghanistan	27,100,540	Bhutan	664,870
Bangladesh	142,660,380	Cambodia	13,679,950
India	1,183,209,470	Indonesia	232,374,240
Nepal	26,382,590	Iran	71,336,480
Pakistan	167,808,110	Laos	5,944,950
Sri Lanka	19,842,040	Malaysia	26,720,370
		Myanmar	49,621,480
		Philippines	89,405,480
		Thailand	66,182,060
		Vietnam	85,419,590
TOTAL	**1,567,003,130**		**641,349,470**



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