

Climate- and Environmentally-friendly Solar Cooling Technology Solutions



green
cooling initiative

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Abbreviations

A	AC	Alternating Current
	AR6	Sixth Assessment Report of IPCC
	ASTB	Aneka Sumber Tata Bahari (in Indonesia)
B	BAT	Best Available Technology
	BAU	Business-as-usual
	BMUV	German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (by their German acronym)
	BMZ	German Federal Ministry for Economic Cooperation and Development (by their German acronym)
	BTU/h	British thermal unit per hour, used as an alternative to kW (1 kW = 3412.12 BTU/h)
C	COP	Coefficient of Performance
	CO ₂	Carbon Dioxide
D	DC	Direct Current
	DTI	Danish Technological Institute
E	ECHA	European Chemical Agency
	EN	European Standard (Europäische Norm)
	EoL	End of Life (of old equipment)
F	FAO	Food and Agriculture Organization
G	GEF	Global Environment Facility
	GHG	GHG
	GIZ	Deutsche Gesellschaft für internationale Zusammenarbeit GmbH
	GPP	Green Public Procurement
	Gt	Gigatonne
	GWP	Global Warming Potential
H	HC	Hydrocarbons
	HCFC	Hydrochlorofluorocarbon
	HFC	Hydrofluorocarbon
	HFO	Hydrofluoroolefin
	HVAC	Heating, Ventilation and Air-conditioning
	H ₂ O	Water
I	IEC	International Electrotechnical Commission
	IKI	International Climate Initiative
	ILK	Institut für Luft und Kältetechnik (Dresden)
	IPCC	Intergovernmental Panel on Climate Change

	IPNLF	The International Pole and Line Foundation
	ISO	International Organization for Standardization
K	kWp	Kilowatt-peak (solar PV)
L	LiBr	Lithium bromide
	LiCl	Lithium chloride
	LiNO ₃	Lithium nitrate
N	NaSCN	Sodium thiocyanate
	NDC	National Determined Contribution
	NH ₃	Ammonia
	nZEB	nearly Zero Emission Building
O	ODS	Ozone Depleting Substance
	ODP	Ozone Depleting Potential
P	PATH	Programme for Appropriate Technology in Health
	PFAS	Per- and Polyfluoroalkyl Substances
	PTC	Parabolic-Trough Collector
	PU	Polyurethane
	PV	Photo Voltaic
	PVT	Photovoltaic thermal
	PQS	Performance, Quality and Safety (of WHO)
R	RAC	Refrigeration and Air-conditioning
S	SCE	Solar Cooling Engineering GmbH
	SDD	Solar Direct Drive
	SDG	Sustainable Development Goals
	SIM	Solar Ice Maker
	SRVC	Sustainable Rural Value Chain
T	TFA	Trifluoroacetic Acid
U	UNDP	United Nations Development Program
	UNEP	United Nations Environmental Program
	UNFCCC	United Nations Framework Convention on Climate Change
	UNICEF	United Nations Children's Fund
W	WE4F	Water & Energy for Food
	WHO	World Health Organization

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1 Introduction

Globally cold chains are growing significantly and are already responsible for around 2 percent of global GHG emissions.¹

According to the Food and Agriculture Organization (FAO) and International Institute of Refrigeration (IIR) globally only 45% of the food that deserves refrigeration is actually refrigerated and 12% of the agricultural production for human consumption is lost due to lack of refrigeration. These losses are responsible of an avoidable carbon emission of 1,004 million tons of CO₂ equivalent.²

Moreover, an estimated 822 million people or 60% of the sub-Saharan Africa population do not have a refrigerator. Access to cooling plays an important role to reach the Sustainable Development Goals (SDGs). Consequently, there is a global need to provide off-grid (mainly solar) cooling to those who do currently not have access to cooling. The off-grid refrigeration market is estimated to increase from US\$ 4.4 billion in 2018 to US\$ 14.3 billion by 2030.³

To address this growth and the emissions, future cold chains and off-grid refrigeration equipment need to be designed in a sustainable and climate resilient way.

Solar cooling technologies present a significant opportunity to contribute to the economic livelihood of communities and reaching at the same time global climate goals. Solar cooling technologies strengthen cold chains in communities with poor access to electricity and cooling by providing reliable, sustainable, and inclusive refrigeration options that reduce postharvest losses, enhance economic opportunities, and contribute to environmental sustainability.

By harnessing solar energy, these systems reduce reliance on conventional energy sources, thereby decreasing greenhouse gas (GHG) emissions. Many solar cooling projects

are using Photo Voltaic (PV) technology but are simultaneously using environmentally harmful batteries, that need to be replaced frequently and pose challenges in the End of Life (EoL) treatment (poor recyclability of the batteries) as well as create high replacement costs. Lithium-ion batteries also release per- and polyfluoroalkyl substances (PFAS)⁴, also called “forever chemicals”. PFAS are a large class of synthetic chemicals that have been increasingly identified as environmental pollutants and linked to negative effects on human health.⁵ In contrast, there are also solar cooling technologies that use thermal storage that are less harmful and do not need to be replaced after some years, which also comes at an economic cost each time and can also cause sustainability risks.

Apart from the energy source, solar cooling projects need to also consider the ecological impact of the refrigerant and insulation material used. There are many solar cooling technologies that are not environmentally and climate friendly, because they use synthetic refrigerants such as Hydrochlorofluorocarbons (HCFCs) or Hydrofluorocarbons (HFCs). HCFCs still have negative impact on the ozone layer and both HCFCs and HFCs have a high negative climate impact due to their high Global Warming Potential (GWP) and many also have a negative environmental impact. Besides this, many solar technologies also use insulation material that is often blown by HCFCs or Hydrofluoroolefins (HFOs). Most HFCs and HFOs are classified as Per- and polyfluoroalkyl substances (PFAS). Trifluoroacetic acid (TFA) is an ultra-short chain type of PFAS, commonly found in the breakdown of F-gases.⁶

Consequently, climate and environmentally friendly solar cooling technologies need to use natural refrigerants that have an ultra-low GWP and not emit other chemical pollutants, such as PFAS, to truly mitigate carbon emissions and have no negative environmental impact.

1 Peters et al. (2020) Understanding the cold-chain challenge for Covid-19 vaccination.

2 FAO (2019) The State of Food and Agriculture: Moving forward on food loss and waste reduction.

3 Efficiency for Access Coalition (2023) tech trends in energy access: assessing the off-grid refrigerator market.

4 Guelfo et al. (2024) Lithium-ion battery components are at the nexus of sustainable energy and environmental release of per- and polyfluoroalkyl substances.

5 ECHA (n.d.) Per- and polyfluoroalkyl substances (PFAS). Accessed May 6, 2024. <https://echa.europa.eu/hot-topics/perfluoroalkyl-chemicals-pfas> with many references to further readings.

6 ECHA (n.d.) Per- and polyfluoroalkyl substances (PFAS). Accessed May 6, 2024. <https://echa.europa.eu/hot-topics/perfluoroalkyl-chemicals-pfas> with many references to further readings.

Solar cooling technologies are varied and include solar thermal cooling (absorption and adsorption), and solar electric cooling systems. Each technology has its unique advantages and applications, from residential to industrial uses, especially for cold chain applications. GIZ showcases its experience regarding solar cooling in this publication by presenting selected examples from the many collaborative projects done by GIZ and its partners worldwide or other organisations, developers or manufacturers.

The process to acquire a solar cooling technology can be complex and complicated to navigate. This publication as well offers guidance for future project managers that wish to procure, install, and operate a solar cooling technology successfully. This requires careful navigation of policies, agreement of multiple stakeholders, adequate documentation of end-user needs and subsequent technical specification that satisfies those needs.

On-grid and off-grid cold chain technologies need to be integrated into national and international climate and development strategies, to support the implementation of Nationally Determined Contributions (NDCs) and align with the goals of the Paris Agreement, the Montreal Protocol, and its Kigali Amendment, while also achieving the completion of the SDGs.

With this publication we invite decision makers to consider solar cooling technologies with natural refrigerants and blowing agents as a solution for their cooling needs, especially to strengthen cold chains (refrigeration) and cooling in buildings (air-conditioning). These solutions are truly sustainable, climate and environmentally friendly, and also often can benefit the development of communities. We welcome any possible collaboration; we would be delighted to offer our expertise and guidance.



2 Background

In any location in the world, refrigeration equipment, air-conditioning and insulation foams are essential to achieve and maintain an adequate level of climate control for various applications, from food storage to the comfort of people in a room. Refrigeration and Air-conditioning (RAC) technologies and insulation foams are responsible for over 10% of the world's GHG (GHG) emissions⁷, which are harmful to the climate.

With the world population projected to increase to 9.8 billion by 2050 and 11.2 billion by 2100,⁸ hereby increasing living standards, the cooling demand is expected to drastically increase in the next decades. In addition, with little scope for increasing the global cultivated area, the food chain will need to be optimized to minimize food losses and thus improve food security.

According to the Food and Agriculture Organization (FAO) of the United Nations, around 14% of food produced is lost from the post-harvest stage up to, but excluding, retail stage.⁹ Furthermore, the United Nations Environment Programme (UNEP) estimated that, in 2019, 931 million tonnes of food waste was generated, which accounts for 17% of total food production. Most food waste from this share is generated in households (11%), followed by food service (5%), and retail (2%). Additionally, it is estimated that food loss contributes to 10% of global GHG emissions.¹⁰

Solar cooling can help prevent food loss by providing a sustainable and efficient way to cool and preserve food in areas with limited access to electricity. By using solar energy to power cooling systems, food can be stored at optimal temperatures, reducing spoilage, and extending shelf life. This is particularly important in regions with high temperatures and limited access to electricity, where food loss due to inadequate storage and cooling is a significant challenge.

The lack of access to cooling is a significant risk for 1.2 billion people in poor rural and urban settings worldwide, with 28 million more people at high risk compared to 2021. Countries with high temperatures and significant populations at high risk due to poverty and electricity access gaps, such as certain sub-Saharan countries, face challenges in implementing sustainable cooling solutions due to factors such as poverty, lack of reliable energy services, and the ongoing effects of the COVID-19 pandemic on global extreme poverty. While there are ongoing efforts to promote sustainable cooling solutions globally, there are still areas where these solutions are not yet fully supported or regulated.¹¹

Additionally, solar cooling can be a solution in favour of the achievement of SDGs 2, 7, 9, 12 and 13, as it tackles inadequate cold chains that compromise food security, lack of energy access, thermal comfort, access to medicine and vaccines, all while reducing the climate and environmental impact.¹²

The cooling sector is a significant contributor to global GHG emissions. On current growth trends, cooling equipment represents 20% of total electricity consumption today and is expected to more than double by 2050. Under a business-as-usual (BAU) scenario.¹³

Direct emissions in the cooling sector refer to the release of GHGs from refrigerants used in cooling systems, such as hydrofluorocarbons (HFCs), which have a high global warming potential. Indirect emissions, however, refer to the GHG emissions associated with the energy consumption of cooling systems, such as electricity generation from fossil fuels. Both direct and indirect emissions contribute to the carbon footprint of the cooling sector and are a significant contributor to climate change.

7 Dong, Y. et al. (2021) Greenhouse Gas Emissions from Air Conditioning and Refrigeration Service Expansion in Developing Countries

8 United Nations (n.d.) World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100. Accessed May 3, 2024. [World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100 | United Nations](#)

9 FAO (2019) The State of Food and Agriculture: Moving forward on food loss and waste reduction.

10 UNEP (2021) Food Waste Index: Report 2021.

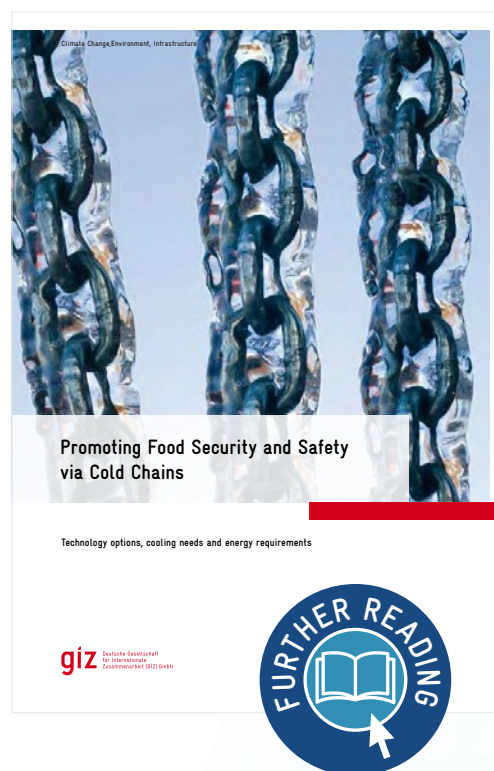
11 Global access to cooling gaps in 2022 (2022) Sustainable Energy for All | SEforALL.

12 United Nations (n.d.) The 17 Goals/Sustainable Development. Accessed May 3, 2024. [THE 17 GOALS | Sustainable Development \(un.org\)](#)

GIZ Proklima promotes “Green Cooling” through its many projects across the globe over the last 30 years. Green cooling refers to the use of cooling technologies and practices that minimize the environmental impact of cooling systems. This includes reducing GHG emissions associated with cooling, such as through the use of natural refrigerants with an ultra-low GWP (reducing direct emissions), improving energy efficiency, and utilizing renewable energy sources (reducing indirect emissions). Green cooling also involves reducing the environmental impact of cooling systems throughout their lifecycle, including the design, manufacturing, transportation, installation, operation, and end-of-life stages. The goal of green cooling is to provide sustainable cooling solutions that meet the needs of society while minimizing the impact on the environment and contributing to global efforts to mitigate climate change.

Solar cooling is consequently part of the Green Cooling approach by diminishing the indirect emissions related to the source of electric energy. When sourced from a national electricity grid, the emission intensity of all electricity sources is considered. For Europe, this was estimated to be 216.3 grams (g)CO₂eq/kWh in 2020, while it was 426.8 gCO₂eq/kWh for countries members of G20.¹⁴ Solar PV panels are varied, and therefore GHG emissions per kWh will be different depending on the solar cell used and other components, as well as the manufacturing and decommissioning process. For the most common type of solar cell, crystalline silicon, used for residential applications, the emission intensity was estimated to be 41 gCO₂eq/kWh,¹⁵ yet recent estimates from different production processes vary from 250 to just 9 gCO₂eq/kWh¹⁶. Even more so, solar cooling projects, as with most solar PV panels projects, that are targeted at remote places that do not have electricity and/or access to the national grid are complicated and costly. For this situation, the technology to be compared with under the BAU scenario is electricity generated by diesel generation and emission intensity can vary from 1,000 to 5,000 gCO₂eq/kWh, depending on the size and demand.¹⁷

Even though drops in on/offshore renewable technologies prices such as PV or wind make these sources very competitive against fossil fuels, higher initial investments and lack of financing mechanisms remain a major barrier for its quick implementation. Consequently, off-grid technologies (not only renewable) remain the only choice for areas without grid access.



13 UNEP (2023) Global Cooling Watch Keeping it Chill: How to Meet Cooling Demands while Cutting Emissions.

14 Climate Transparency (2022) The Climate Transparency Report 2021.

15 Schlömer et al. (2014) Annex III: Technology-specific cost and performance parameters. 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.

16 Clarke et al. (2022) Energy Systems. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

17 Jakhiani et al. (2012) Estimation of carbon footprints from diesel generator emissions.

3 Climate change goals

Several international commitments and agreements exist to motivate the implementation of mitigation and adaptation measures in the face of climate change. Solar Cooling, an approach that is part of Green Cooling solutions, finds itself aligned with these international commitments.

The Paris Agreement in 2015, within the work of the United Nations Framework Convention on Climate Change (UNFCCC) is historic because it succeeded in bringing together all nations in a common cause, based on the responsibilities that history, the present and the future demand of them. The agreement seeks to combat climate change and promotes measures and investments that seek to achieve a low-carbon future that is resilient and sustainable to climate change. As such, the agreement has a significant relationship with Green Cooling, as it encourages the adoption of sustainable cooling solutions that can help reduce GHG emissions and mitigate the effects of climate change. By promoting the use of energy-efficient and climate and environmentally friendly cooling technologies, the Paris Agreement supports the development of a sustainable and resilient future for all, while helping to achieve the goals of the agreement to limit global warming and pursue sustainable development.

The effort of the Paris Agreement is reflected in the countries' Nationally Determined Contributions (NDCs), which outline each country's individual goals and strategies for mitigating climate change and adapting to its impacts. The cooling sector is a significant contributor to GHG emissions, and as such, it is likely that many countries' NDCs will include targets and policies related to promoting sustainable and energy-efficient as well as renewable cooling solutions. By implementing these measures, countries can reduce their GHG emissions and contribute to global efforts to combat climate change. Additionally, promoting Green Cooling can have significant co-benefits, such as reducing energy consumption, costs, food losses, waste, improving air quality, increasing income, food security and enhancing public health. Countries' NDCs have the potential to play a critical role in accelerating the adoption of Green Cooling technologies and practices, and thereby reducing the environmental and climate impact of the cooling sector.

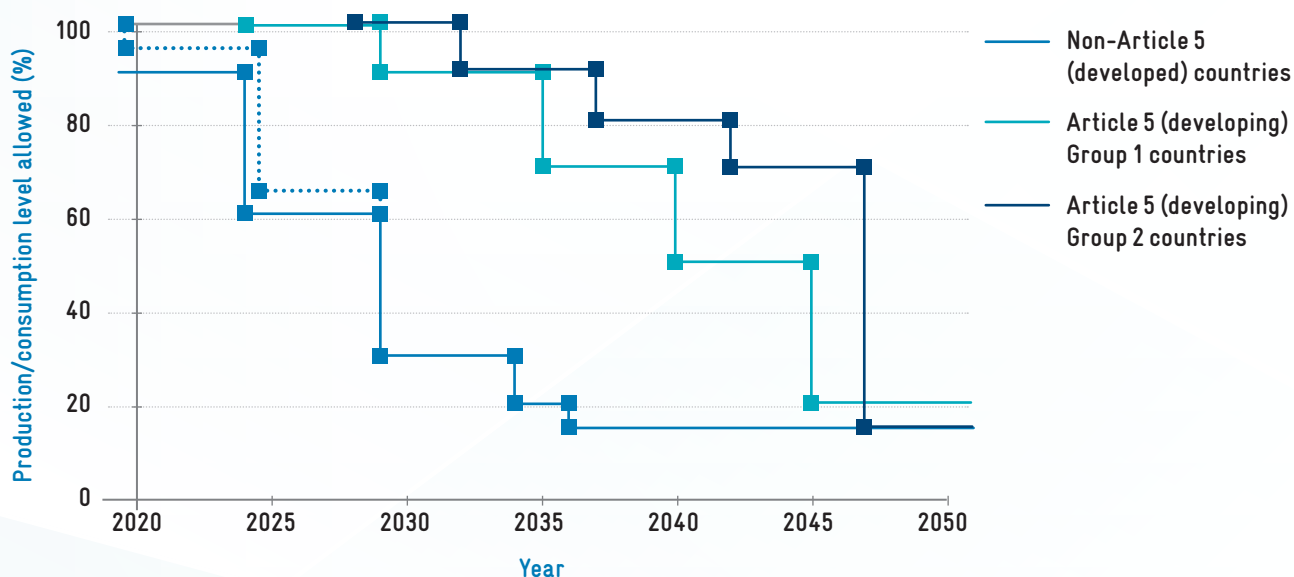


Figure 1: Phasedown schedule for allowed production and consumption, in percentages with respect to defined baselines, of controlled HFCs, expressed as CO₂eq, under the Kigali Amendment.¹⁸

¹⁸ World Meteorological Organization (2022) Scientific Assessment of Ozone Depletion.

The Kigali Amendment to the Montreal Protocol is an international agreement that aims to phase down the production and consumption of HFCs, which are potent GHG commonly used in refrigeration and air-conditioning systems (Figure 1). The amendment was adopted in 2016 and has been ratified by over 100 countries. The Kigali Amendment is expected to avoid up to 0.4 degrees Celsius of global warming by the end of the century and is considered a significant step towards achieving the goals of the

Paris Agreement. The amendment also provides an opportunity to promote the use of energy-efficient and climate- and environmentally friendly cooling technologies, such as natural refrigerants, which can help reduce GHG emissions and improve energy efficiency. The Kigali Amendment is also closely related to the concept of Green Cooling, which aims to promote sustainable and energy-efficient cooling solutions that minimize environmental impact.

3.1 Sustainable development goals

The Sustainable Development Goals (SDGs), established in 2016 by the United Nations, are universal goals for the adoption of measures to end poverty, protect the planet and ensure peace and prosperity for all people.¹⁹ Since the RAC sector is essential for achieving and maintaining a decent standard of living for people, especially in countries with high ambient temperatures, its use will continue to increase. Economic development of an area or a business sector is directly related to increased air-conditioning and cooling of spaces. In addition, the effect of climate change and global warming will make the implementation of these technologies more necessary. In this sense, the RAC sector presents a variety of opportunities for supporting many of the SDGs.²⁰ The following synergies can be found between specific SDGs and solar cooling:



SDG 2 (Zero Hunger): Solar cooling has the potential to contribute to this goal by reducing food waste and spoilage, by using energy-efficient, climate and environmentally friendly refrigeration technologies in the food supply chain. This can help ensure access to safe and nutritious food, reduce hunger, and promote sustainable agriculture.



SDG 7 (Affordable and Clean Energy): Solar cooling can contribute to this goal by promoting the use of renewable energy sources, such as solar energy, to power cooling systems. This can help ensure access to affordable, reliable,

and sustainable energy for all, while reducing GHG emissions and mitigating the impacts of climate change.



SDG 9 (Industry, Innovation, and Infrastructure): Solar cooling can contribute to this goal by promoting the development and adoption of innovative and sustainable cooling technologies, as well as by supporting the growth of the green cooling industry. This can help build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.



SDG 12 (Responsible Consumption and Production): Solar cooling can help achieve this goal by promoting the use of energy-efficient, climate and environmentally friendly cooling technologies, which can reduce the environmental impact of cooling appliances throughout their life cycle and reduce chemical waste. This can help ensure sustainable consumption and production patterns.



SDG 13 (Climate Action): Solar cooling has the potential to contribute significantly to this goal by reducing GHG emissions from cooling equipment and promoting the use of climate and environmentally friendly refrigerants and energy-efficient cooling technologies. This can help take urgent action to combat climate change and its impacts.

¹⁹ United Nations (n.d.) The 17 Goals/Sustainable Development. Accessed May 3, 2024. THE 17 GOALS | Sustainable Development (un.org)

²⁰ GIZ (2016a) Advancing Nationally Determined Contributions (NDCs) through environmentally compatible refrigeration and air-conditioning: Guidance for policymakers.

4 GWP of refrigerants and blowing agents

Global Warming Potential (GWP) is a measure that refers to how much a GHG contributes to global warming over a given period of time, relative to carbon dioxide. In the RAC sector, refrigerants and blowing agents for insulation with high GWP values can have a significant impact on climate change. Transitioning to ultra-low GWP refrigerants, such

as natural refrigerants like propane, ammonia, and carbon dioxide, is crucial for reducing GHG emissions and mitigating the impacts of climate change. The RAC sector is responsible for a significant portion of global GHG emissions, and the use of high GWP refrigerants is a major contributor to these emissions.

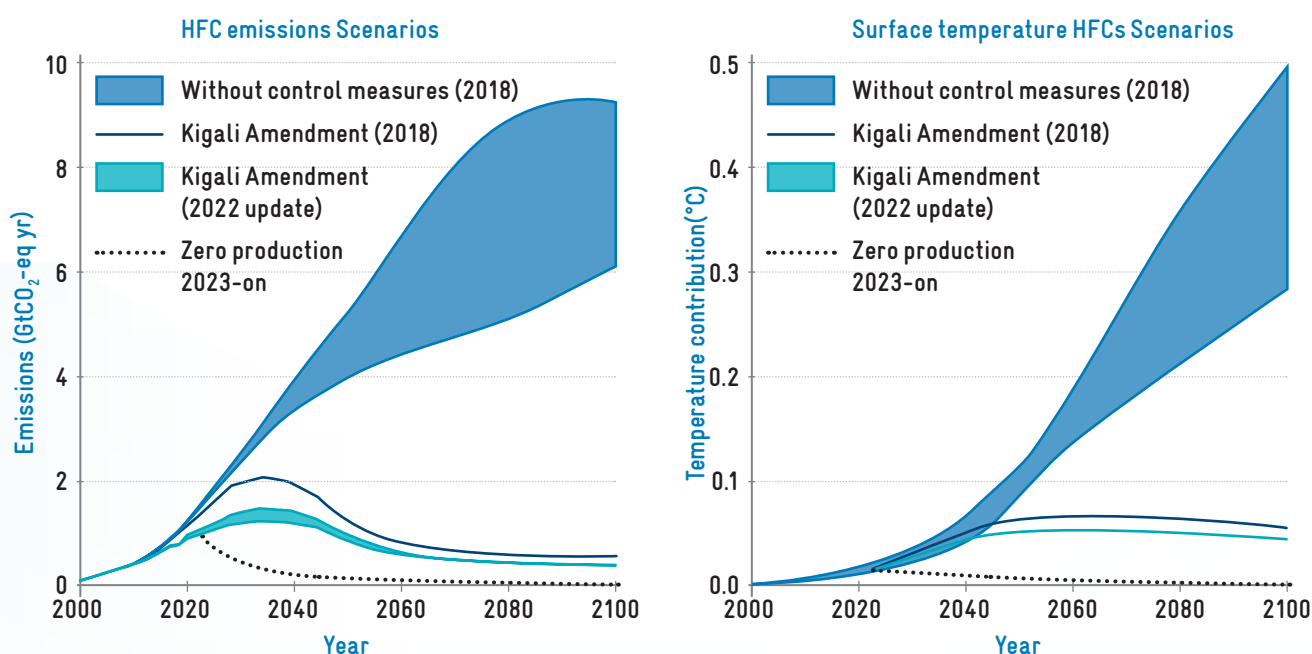
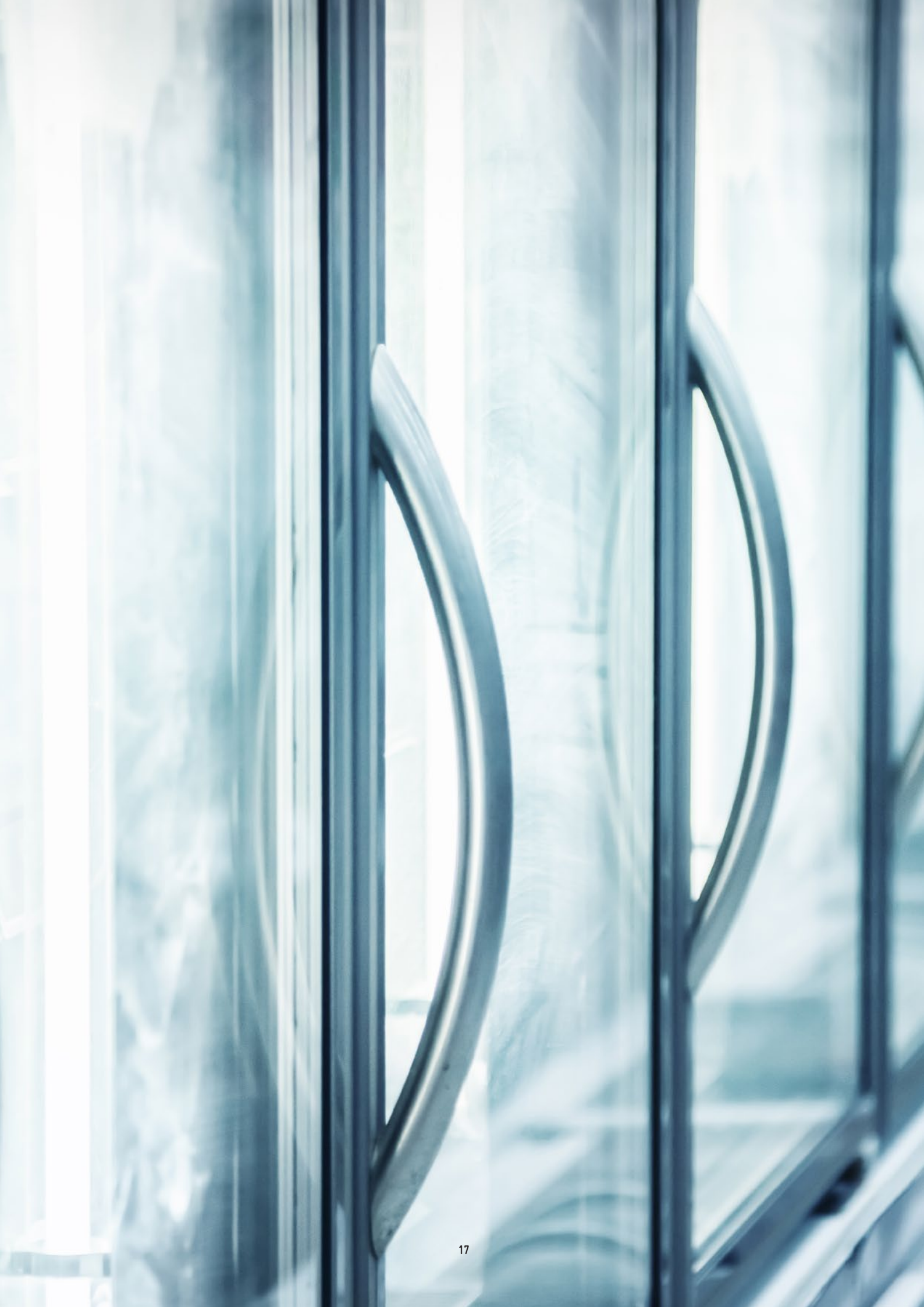


Figure 2: HFC emissions (left) and their impact on global average surface temperature (right).²¹

As per the objective of the Montreal Protocol and its Kigali Amendment, the phase down of HFCs is a crucial step in reducing GHG emissions and mitigating the impacts of climate change. Figure 2 shows the dimension of the impact that could be avoided when following the schedule presented in Figure 1, which is up to 9 gigatonnes (Gt) CO₂eq per year and a temperature increase contribution as high as 0.5 °C by 2100. Shown in areas with yellow and red colour are the emissions and projected surface temperature contribution as per the scenario proposed by the Kigali Amendment in 2018

and its latest update in 2022. The new scenario follows national controls on the consumption and production of HFCs in non-Article 5 countries, reflects lower reported consumption in China, is based on updated historical information on the use of HFCs in non-Article 5 countries, uses observed mixing ratios through 2020 as a constraint, and includes assumptions about reduced use of HFCs for commercial and industrial refrigeration. The new scenario also assumes that all countries adhere to the provisions of the Kigali Amendment.

²¹ World Meteorological Organization (2022) Scientific Assessment of Ozone Depletion: 2022.



is no known way to manage them once they are present in the environment. It is important for the RAC sector to consider the potential risks associated with the use of HFOs and to explore alternative refrigerants, such as natural refrigerants, which have been shown to be environmentally friendly and can avoid the potential health and environmental risks associated with HFOs.

When assessing refrigerants, it is important to consider the GWP up to 20 years, when estimating immediate effects, and up to 100 years, when estimating effects in a longer time

frame such as a mitigation potential. Flammability is considered as per the ASHRAE Standard 34²³, where A1 is not flammable, A2L lower flammability, A2 mild flammability, and finally A3 flammable. However, the training and certification requirements of technicians that are handling A2L and A3 refrigerants are similar. When recognizing the threat of PFAS, it is important to as well consider the presence of PFAS/TFA according to the composition of the refrigerant table (*Table 1*) highlights these specifications of known refrigerants to be used in solar cooling appliances.

Refrigerant	Type	Composition	Alternative for ²⁹	GWP 20	GWP 100	Flammability	PFAS	TFA
R22 ³⁰	HCFC	Pure		5960	1960	A1	No	No
R404A	HFC blend	R143a (52%) R125 (44%) R134a (4%)	R22, R502	7208	4728	A1	Yes (R125, R134a, R143a)	R134a (20%) R143a (10%)
R410A	HFC blend	R32 (50%) R125 (50%)	R22, R13B1	4850	2256	A1	Yes (R125)	No
R407F	HFC blend	R134a (40%), R125 (30%), R32 (30%)	R22, R404A	4566	1965	A1	Yes (R134a, R125)	R134a (20%)
R134a	HFC	Pure	R12, R22	4140	1530	A1	Yes (R134a)	R134a (20%)
R449A	HFC/HFO blend	R134a (25.7%) R1234yf (25.3%) R125 (24.7%) R32 (24.3%)	R404A, R507A	3448	1504	A1	Yes (R125, R134a, R1234yf)	R134a (20%) R1234yf (100%)
R32	HFC	Pure	R134a, R407A, R410A	2960	771	A2L	No	No
R454C	HFC/HFO blend	R1234yf (78.5%) R32 (21.5%)	R404A, R410A	638	166	A2L	Yes (R1234yf)	R1234yf (100%)
R1234yf	HFO	Pure	R407A, R410A, R134a	1.81	0.501	A2L	Yes (R1234yf)	R1234yf (100%)
R744	CO ₂	Pure	R134a, R404A, R407A, R410A, R22	1	1	A1	No	No
R717	Ammonia NH ₃	Pure	R134a, R404A, R407A, R410A, R22	0	0	B2L	No	No
R170	HC ethane	Pure	R23, R508B	1.57	0.437	A3	No	No
R600a	HC isobutane	Pure	R134a, R12	0,06	0,02	A3	No	No
R290	HC propane	Pure	R134a, R404A, R407A, R410A, R22, R502	0.072	0.02	A3	No	No

Table 1: List of the GWP values, flammability, PFAS, TFA presence of selected refrigerants (own illustration) ^{24, 25, 26, 27, 28}

²³ ASHRAE Store. (2022) ASHRAE 15-2022 (packaged w/Standard 34-2022). Accessed May 3, 2024. ASHRAE 15-2022 (packaged w/Standard 34-2022) | ASHRAE Store (accuristech.com)

²⁴ Smith et al. (2021) The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Note: R22 has also an Ozone Depletion Potential (ODP) and is harmful to the ozone layer.

²⁵ World Meteorological Organization (2022) Scientific Assessment of Ozone Depletion: 2022.

²⁶ Everitt, N. (2023) PFAS ban affects most refrigerant blends. Cooling Post.

²⁷ Behringer et al. (2021) Persistent degradation products of halogenated refrigerants and blowing agents in the environment: type, environmental concentrations, and fate with particular regard to new halogenated substitutes with low global warming potential.

²⁸ Linde Industrial Gases (n.d.) Refrigerants.

²⁹ Alternatives applies for various other applications, not only solar cooling.

³⁰ HCFC-22 is the only refrigerant that has an ODP value different to zero from this list of refrigerants. ODP = 0,038.

4.1 Climate and environmentally friendly refrigerants

As briefly suggested before, natural refrigerants are the only refrigerants that can be considered climate and environmentally friendly. These refrigerants have an ultra-low GWP, even below one (1), as seen in [Table 1](#), and therefore they are climate friendly since they pose the lowest of contributions to the radiative forcing phenomena responsible of the global warming effect. Beyond the global warming scope, these are substances that are naturally occurring in the environment and their industrial use, manufacturing, and later use in human activities, present no known danger to the health of any ecosystem or living beings. However, they need to be handled by trained and certified technicians. This publication considers sustainability as a property which describes that solar cooling technologies must be climate and environmentally friendly, in this amongst refrigerants, only natural refrigerants would be sustainable.

CO₂ is used as a refrigerant, and it is highly available and very cheap. However, it is toxic in high concentrations, odourless and can displace air (causing asphyxiation risks). It is currently an interesting alternative for freezing, refrigeration and air-conditioning systems but has higher investment costs than conventional systems due to the high pressures at which these installations work. It can be used as a replacement e.g. for R134a or R404A and other HFCs or HCFCs in ultra-low, low, and medium temperature refrigeration applications.

As for ammonia (R-717/NH₃), it carries the risk of being toxic and flammable, which again increases the initial investment cost by requiring facilities to implement additional safety features. NH₃ is also non compatible with copper materials. It is used in low and medium temperature refrigeration, in which ammonia presents excellent thermodynamic properties.

HC (hydrocarbons) refrigerants R290 (propane), R170 (ethane), R600a (iso-butane), and R1270 (propylene) are not toxic but flammable and must be handled in a safe and responsible manner. All can be used in domestic and commercial or even industrial refrigeration, with excellent thermodynamic properties and energy performance for refrigeration and air-conditioning purposes.

- Propane is normally used as an alternative to various refrigerants (R22, R410A, R404A, R134a, R32, etc.) and can be found both in refrigeration and air-conditioning applications.
- Isobutane is used as a replacement for R134a in a variety of high temperature refrigeration applications. Its major applications are domestic and light commercial refrigeration units.
- Ethane is generally used in very low temperature industrial refrigeration applications.
- Propylene is usually used as an alternative e.g. to R22, R410A, R32, etc. in low and medium temperature refrigeration and air-conditioning applications.

Flammability risks are much lower when little installations and volumes are concerned. Refrigerants with a higher flammability are therefore easier to implement in domestic and commercial refrigeration applications (such as R600a) or in split ACs (R290). However, HC are also used in larger applications e.g. chillers (R290) with up to hundreds of kgs of charge. EN, ISO, IEC and national standards are available to mitigate the risk of fire or explosion in most types of applications.

5 Technologies

This publication has presented the context of sustainability within the RAC sector to highlight the relevance of solar cooling, and why it is important to already focus on highly efficient solutions with natural refrigerants. Natural refrigerants are the best solution to lower direct emissions. Indirect emissions, responsible for approximately 2/3 of emissions of the cooling sector in most countries, are caused by the energy consumption of electricity generated with fossil fuels. This results in a demand for renewable and sustainable energy sources. Nonetheless, the quantity of demanded energy needs to be reduced, irrespective of the source. Solar cooling technologies can also help promote sustainable cooling practices and reduce energy consumption.

The adoption of solar cooling technologies faces many challenges including the high initial investment cost for the solar panels and infrastructure (energy storage and maintenance), which can be very substantial. Most potential customers are farmers who do not have the necessary capital or liquidity to make such purchase. Alternative financial mechanisms are needed to bridge this challenge. There is also the need to raise awareness to tackle the existing knowledge disparities that perpetuate the use of conventional energy sources.

Another challenge is the variable nature of the energy output from most renewable sources. Not having an adequate design and planned energy storage could really harm the operation of any solar cooling technology, losing its competitive edge in the process. Sourcing of minerals required for solar panels and their adequate disposal is also a contested aspect of solar

energy engineering, with opposing views claiming that these processes are not sustainable and harmful for the environment. One last challenge would be shortage of skills and qualified technicians, particularly for these products since they require both HVAC and Solar Energy expertise.

However, strategies have been developed to overcome these challenges, and solar cooling technologies clearly also come with benefits. Solar cooling technologies in general are simply the most sustainable way to reduce emissions, when compared to conventional alternatives for the same applications, especially when coupled with natural refrigerants like propane. Despite the present lack of awareness, studies have shown that, even considering more expensive investment prices, there is a strong willingness to pay for solar cooling devices in the Global South, because of its clear environmental benefit. The sector can also create jobs, especially in the cold chain sector, which incidentally targets to empower women, since women are often responsible of post-harvest activities. Overall, the cold chain sector is expected to grow in the following years, and solar cooling technologies are expected to follow the trend as a solution for this sector. As mentioned in a previous chapter, solar cooling technologies can move forward various of the SDGs. For this reason, projects concerning the implementation of these technologies are eligible for many partnerships and funding opportunities in the context of sustainable development.³¹ There are various sustainable solar cooling types of technologies already available, which will be presented in the following.

³¹ Ukoba et al. (2024) Adaptation of solar energy in the Global south: Prospects, challenges and opportunities; Ibegbulam et al. (2022) Adoption of Solar PV in Developing Countries: Challenges and Opportunity; Morison, A. (2023) World may have crossed solar power "tipping point".

5.1 Types of solar cooling

Solar cooling can be classified into two types: electrical cooling systems and solar thermal systems. In electrical cooling systems, solar energy plays a passive role, since it does not interact directly in the creation of the cooling effect, it only provides a means to generate electricity for a conventional cooling technology. In solar thermal applications, thermal energy from the sun is directly used in the system to create a cooling effect.³² Thermal storage, commonly in the form of ice banks, are an alternative to electrical storage (batteries) and provide autonomy to the systems during the night or when the solar output is not sufficient. Thermal storage can be coupled in both types of systems.

5.1.1 Electrical cooling systems

In electrical solar cooling systems, two primary elements are combined: a photovoltaic (PV) system and an electric cooler or regular refrigeration system or device. The generated cooling output increases with the amount of sunlight that the PV system receives. These renewable energy conversion systems are particularly beneficial because it aligns with the increased cooling needs during peak solar radiation times throughout the day. Additionally, the necessity for cooling is more pronounced in warmer climates compared to cooler regions.

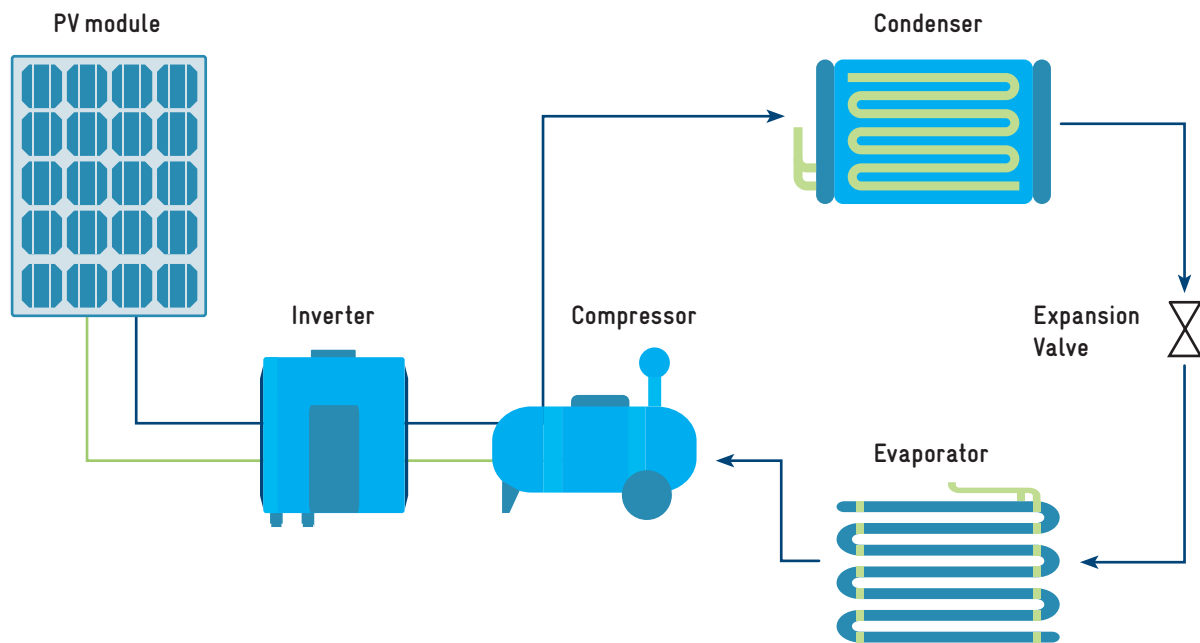


Figure 4: Diagram for a directly coupled refrigeration system.³³

³² Ajib, S. & Alahmer, A. (2019) Solar Cooling Technologies.
Elaozy, Y. & El Fadar, A. (2023) Solar and photovoltaics Energy utilization and sustainability.

³³ Albatayneh et al. (2021) Evaluation of Coupling PV and Air-conditioning vs. Solar Cooling Systems—Case Study from Jordan.

5.1.1.1 PV and batteries

Over the last decades, the price for PV panels has decreased significantly, making them a cost-effective alternative for powering refrigeration systems. Recently published reports and academic literature have suggested that the “tipping point” for PV panels has been crossed, meaning that this technology has become the most cost-efficient technology for electricity production and will undoubtedly become our main source of energy.³⁴ They provide a reliable source of electrical energy, however depending on solar radiation, only during the day. To be able to continue cooling during the night, an energy storage system is required. Batteries are the first option considered when addressing storage needs by these systems. However, they come with a high negative climate and environmental impact.

Around 100 research papers estimate the climate impact from Li-ion batteries manufacturing ranging from 39 kg CO₂e/kWh to 196 kg CO₂e/kWh. As an example, the embedded emissions from manufacturing one 40 kWh battery for an electric car equivalates the CO₂ emissions of a distance travelled of 11.800 km to 89.400 km, driven by a diesel car consuming 5 litres per 100 km (1.560 – 7.840 kg CO₂e/kWh).³⁵ The embedded emissions of the

manufactured batteries must be considered when designing environmentally friendly off-grid refrigeration systems. Moreover, most batteries need to be shipped from China and high CO₂e emissions occurring from transport emissions need also to be factored. Nevertheless, batteries remain an interesting option for energy storage during the night, and thanks to them, the installed solar panel surface can be reduced to a minimum.

Moreover, batteries used in solar cooling systems can be bulky and require periodic replacement, which increases the overall cost and maintenance needs. Therefore, battery replacement must be considered in the business model feasibility study and the total life cycle cost analysis. They are an expensive component and depending on the capacity installed they can account for a large portion of the initial investment. They are usually also large and heavy and cause additional transportation costs. Some batteries also require cooling because they cannot operate above certain temperatures. Moreover, batteries also come with environmental costs because in many countries, batteries cannot be properly recycled. Consequently, solutions with thermal storage, when possible, should be considered.

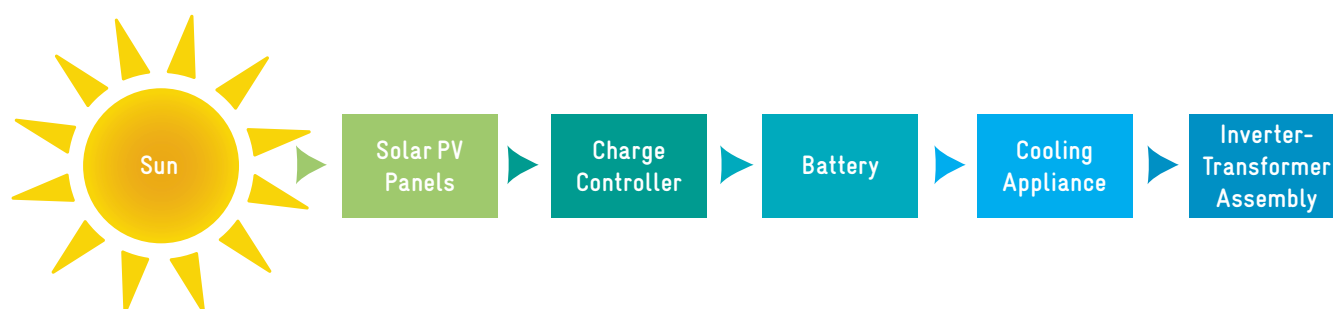


Figure 5: Diagram for a directly coupled refrigeration system. ³⁶

³⁴ Nijse et al. (2023) The momentum of the solar energy transition & Morrison, A. (2023) World may have crossed solar power ‘tipping point’.

³⁵ Melin, H. E. & Circular Energy Storage (2019) Analysis of the climate impact of lithium-ion batteries and how to measure it (By Transport & Environment).

³⁶ Own illustration.

5.1.2 Solar thermal

Different technologies and methods exist to capture the solar thermal energy to create a cooling effect, yet only a selected few will be presented in this publication due to their relevance. Sorption cooling systems, like vapor compression systems, rely on the basic refrigeration cycle involving the continuous evaporation and condensation of a refrigerant. Solar sorption chillers can be classified by whether they operate with absorption or with adsorption mechanisms.

Unlike the normal refrigeration cycle (vapor compression system), sorption systems do not use a mechanical compressor, instead sorption systems use a 'thermal compressor' driven by external heat, where the main component is a generator for absorption and a sorbent chamber for adsorption. The cooling effect is achieved through a refrigerant and sorbent pair, where the refrigerant evaporates to extract indoor heat, mixes with the sorbent, and then separates and condenses to reject the heat outside.³⁷

Sorption chillers can be driven by a stationary collector, including flat plate, evacuated tube, and PVT (photovoltaic thermal), or concentrating solar collectors such as parabolic dish, linear Fresnel and PTC (parabolic-trough collector).

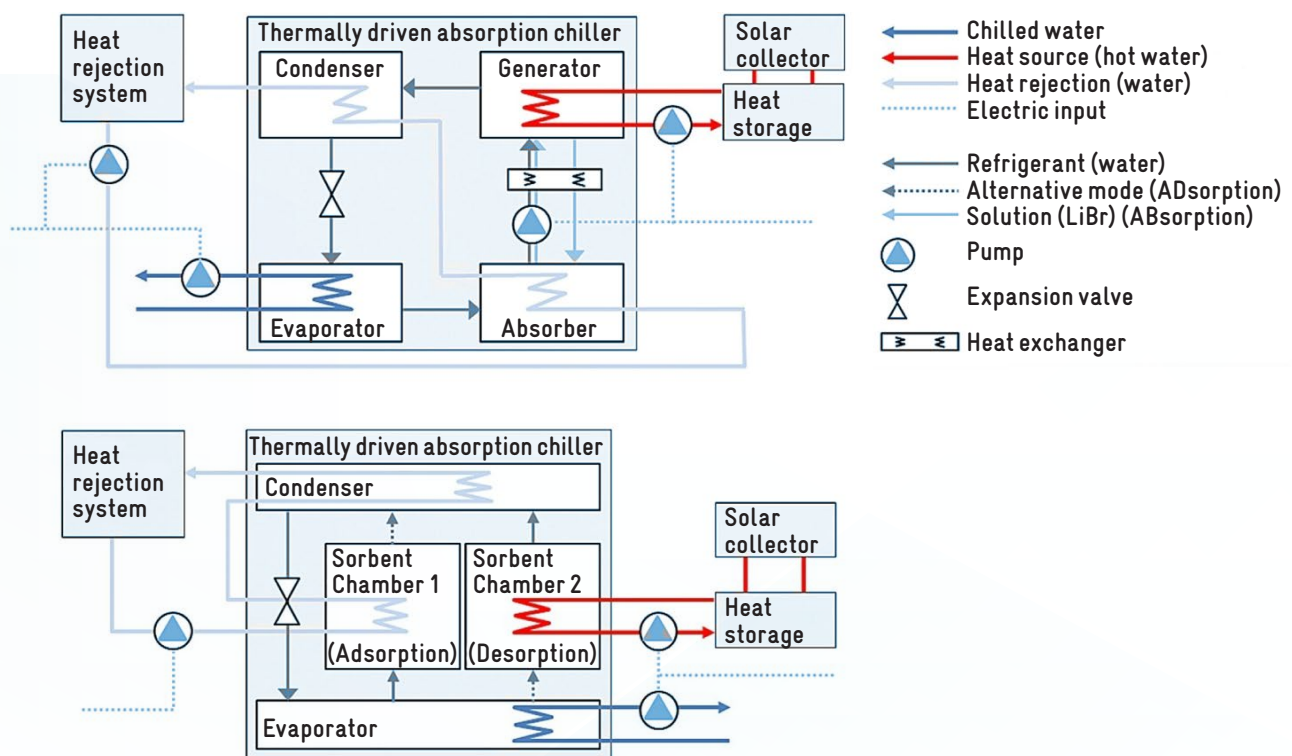


Figure 6: Basic schemes of the components of absorption and adsorption chillers with thermal energy captured from solar energy.³⁸

³⁷ Prieto et al. (2017) Solar coolfacades: Framework for the integration of solar cooling technologies in the building envelope

³⁸ Ibid.

Absorption chillers with thermal solar collectors represent a significant advancement in renewable cooling technologies. The core principle of absorption chillers involves the use of a refrigerant to absorb heat from a source, such as solar collectors that capture solar radiation and convert it into thermal energy, and then release it at a lower temperature to cool the desired space. This thermal energy is then used to drive the absorption chiller, making the cooling process both environmentally friendly and energy-efficient.

An absorption cooling system typically consists of a pair of fluids: a refrigerant and an absorbent. The refrigerant is absorbed by the absorbent at low temperatures due to the attractive forces between them and can be released as vapor when heated. Common fluid pairs in absorption systems include water as the refrigerant with lithium chloride (LiCl) or lithium bromide (LiBr) as the absorbent and ammonia (NH₃) as the refrigerant with water (H₂O), lithium nitrate (LiNO₃), or sodium thiocyanate (NaSCN) as the absorbent.³⁹

The refrigerant functions similarly to that in traditional vapor compression systems, extracting heat in the evaporator through evaporation and rejecting heat in the condenser through condensation. The thermal compressor in an absorption system includes a pump, generator, throttling element, and absorber. In the generator, the solution is heated by a solar collector or auxiliary heater until the refrigerant vapor is released, resulting in a concentrated solution. The released refrigerant vapor moves to the condenser, where it rejects heat and condenses. After condensation, the refrigerant passes through a throttling element (valve or capillary tube) to the evaporator. In the evaporator, due to lower partial pressure and temperature, and the strong attraction from the absorbent solution in the absorber, the refrigerant evaporates and is absorbed by the absorbent solution. This absorption process continues until the absorber solution becomes saturated with refrigerant vapor, forming a diluted solution. Certain technical challenges need to be addressed, such as the capacity of the chillers and the temperature glide⁴⁰ of the driving heat.⁴¹

The absorption process is exothermic, causing a continuous increase in the absorbent's temperature, which accelerates and reduces the amount of refrigerant absorbed as it approaches saturation. To enhance refrigerant absorption and cooling, the adsorbent material must be cooled during the process. The diluted solution returns to the absorber

through a throttling valve after being reactivated in the generator. The cycle's continuity and compression effect are maintained by the simultaneous actions of releasing refrigerant vapor in the generator, absorbing it in the absorber, and circulating the working pair solution via a pump and throttling valve. To improve the coefficient of performance, absorption cycles often include additional components, such as a heat exchanger between the absorber and generator for heat recovery between the weak and strong solutions.⁴²

Adsorption is a process that occurs on surfaces, where molecules, atoms, or ions from a gas, liquid, or dissolved solid attach themselves to a surface. This interaction happens at the boundary between two phases: the adsorptive (the substance that is being adsorbed) and the adsorbent (the material to which the adsorptive attaches). Unlike absorption, which involves the uptake of a substance throughout the entire volume of another material, adsorption is limited to the surface. Adsorption systems are less commonly used because of their lower efficiencies and intermittent operation. However, they have the advantage of not incorporating moving parts in their working cycle, which simplifies maintenance and ensures noiseless operation.

Materials considered for the adsorptive and adsorbent pair depend on the nature of the mechanism. Physical pairs include NH₃/activated carbon, ethanol/activated carbon, silica gel/water, and zeolite/water. By chemical adsorption it can be found NH₃/metal chloride, hydrogen/metal hydrides, and water/metal oxides. Lastly, there are also composite adsorption working pairs, including silica gel/water and chlorides, methanol/silica gel and chlorides, NH₃/chlorides, porous media, water/zeolite, and foam aluminium.

A typical adsorption system consists of an evaporator, an adsorber, a condenser, a throttle, a heater, and a cooler. The adsorber contains solid adsorbent material, while the evaporator holds the adsorbate material (refrigerant). Adsorption occurs when the solid adsorbent is cool and dry, creating a strong attraction to the adsorbate vapor generated in the evaporator. This process continues until the adsorbent reaches its maximum adsorbate capacity, known as the saturation limit. Since adsorption is exothermic, the adsorbent's temperature and surface vapor pressure increase, potentially halting adsorption before reaching saturation. To maintain effective adsorption, the adsorbent is cooled during the

39 Almasri et al. (2022) Thermal solar sorption cooling systems – A review of principle, technology, and applications.

40 Temperature glide refers to the difference in temperature between the input and output of a cooling system, such as an absorption chiller. It is more precisely a measure of the used heat at high temperature from the heat source. More glide, more efficiency.

41 Lahoud et al. (2021) A Review of single-effect solar absorption chillers and its perspective on Lebanese case.

42 Almasri et al. (2022) Thermal solar sorption cooling systems – A review of principle, technology, and applications.

process. Continuous cooling is achieved using two-bed adsorbers, with heat recovery between the beds to enhance cycle performance.⁴³

Sorption cooling technologies (absorption and adsorption) have the big advantage of not requiring electricity production for cold production, directly transforming the thermal sun energy (heat) into cold. Therefore, they do not need batteries or charge controllers for their usual operation and a very low maintenance is required.

This technology is very interesting and cost-effective when the ideal climate conditions are met (mostly Mediterranean conditions with high temperatures and a high sun irradiation availability all over the year). They are perfect for large scale industrial processes where a big amount of residual heat is available, to be combined with the heat generated via solar thermal.

The two chillers with solar thermal energy as input are both economical and eco-friendly, as they (i) utilize “free” energy from the sun to power the cooling effect, (ii) have minimal operational and maintenance expenses, and (iii) employ non-toxic working fluids. However, their lower Coefficient of Performance (COP) and higher initial investment compared to traditional cooling systems are significant drawbacks. Other type of systems are the desiccant and ejector systems, yet these technologies are still in the stages of research and development.

5.1.3 Thermal storage

Thermal storage technologies and applications offer a range of benefits over traditional lithium-ion batteries, including cost-effectiveness, safety, efficiency, versatility, and the ability to store energy for longer periods. These advantages make a compelling case in favour of these thermal storage alternatives, promising technologies for the future of energy storage and management. The most attractive advantage is its cost effectiveness, since applications are much cheaper and built within very low budgets, for the entirety of its lifetime. Thermal energy storage can find applications for both cooling and heating.

Materials are relatively cheap and easy to source, unlike lithium, cobalt, and nickel for lithium-ion batteries. Water and ice for cooling, or in other cases silica sand, graphite, or molten salt for mostly heating, are more readily available and their related processes to obtain them have a lower environmental impact. This configuration of materials makes the system easy to recycle at the end of its usable life. These materials are also considered safer, since lithium-ion batteries could potentially catch on fire, something very unlikely to happen with ice, water or sands, something to be considered in densely populated buildings.

Also related to the nature of the materials of thermal energy storage solutions, is the efficiency of these technologies. Whereas traditional lithium-ion batteries are usually changed after 10 years (in many cases also earlier), thermal energy storage technologies can last longer than that, since they can store energy more densely and convert it back to electricity with less energy loss. It does not reduce its performance over time, and the components do not need to be replaced after 10 years if durable materials are used; almost no maintenance is required.

From a system wide lens, thermal storage can reduce peak demand from the energy grid during times of great demand, for example whether by generating the ice or using it directly for cooling, contributing to grid efficiency and sustainability. They are a suitable complement for the evermore presence of renewable technologies in energy production. However, if high refrigeration capacity is needed during the night, cold storage might not be enough to meet the cooling demand, or the system would require an excessive over-sizing of solar PV cells, resulting in an unacceptable impact on the environment and costs.

Batteries and thermal storage can also be combined. A detailed study for each project and location must be conducted to ensure reaching the best compromise between using too much battery power and oversizing PV panels to store enough ice overnight. Thermal storage solutions can also be integrated into existing infrastructure with minimal changes, in both commercial and residential spaces, making thermal storage a versatile option for a wide range of applications.⁴⁴

⁴³ Ibid.

⁴⁴ Further readings: Chao, J. (2023) Turning up the heat: Thermal energy storage could play major role in decarbonizing buildings. Chung, E. (2024) These giant batteries store energy, but not as electricity; Flare Compare (2021) Evaluating the Pros and Cons of Using Thermal Energy Storage vs. Batteries.

⁴⁵ Knodt, M. & Kimani, R. (2020) Taking Cold Chains Off-Grid: How solar powered cold rooms could Dramatically Reduce food waste in Sub-Saharan Africa – Cool Coalition.

⁴⁶ ISAAC Solar Ice Maker | Energy Concepts.

5.2 Solar cooling: refrigeration

Solar cooling technology can play a significant role in establishing cold chains, especially in developing countries, by offering a sustainable and environmentally friendly alternative to traditional refrigeration methods. Solar-powered refrigeration is one such innovative solution that can also significantly reduce the reliance on fossil fuels and GHGs. By harnessing solar energy, it is expected to reduce food losses and improve market access, which can in turn encourage agricultural production and increase food security. This approach not only helps in reducing hunger but also contributes to the decoupling of cold chains from their worst climate impacts.⁴⁵

5.2.1 Solar ice makers

A first step to establish a functioning cooling chain (e.g. for fish) is to construct cooling boxes that can be filled with ice. For it to be a solar cooling solution, ice needs to be produced with solar ice makers (SIM). Furthermore, ice can serve as a thermal energy storage for solar refrigerators or cold rooms to provide energy in times of no or little solar radiation. This way, battery storage can be designed significantly smaller or may not be needed at all.

Solar ice makers can be distinguished into two types. Large ice makers for industries provide large ice quantities for refrigeration purposes. They utilize the solar energy captured to generate liquid ammonia during the day, which is then cooled by a thermosiphon at night to produce ice, which makes it a solar thermal technology.

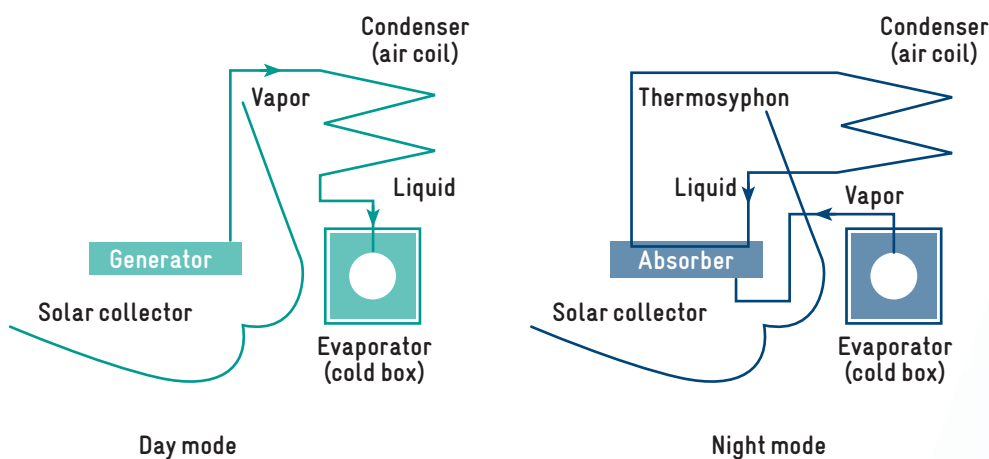


Figure 7: Operational diagram of large solar ice makers with liquid ammonia.⁴⁶



Portable or independent solar ice makers, typically used in off-grid solutions, use solar panels to charge a battery, which

powers a compressor and a fan to freeze water into ice, an example of electrical solar cooling.





Best Practice Example 1: Stationary Solar Ice Maker in Sulamu village, Kupang, Indonesia



The Solar Ice Maker (SIM) is the result of a multi-year technology collaboration (2017-2020) with the private sectors that includes technology development, demonstration, and establishment of local manufacturing in Indonesia. SIM is an environmentally friendly energy solution to stimulate economic growth in Indonesia's remote and disadvantaged regions by integrating a solar PV technology to powering an ice making machine; providing an ice block supply for the fishermen community with the capacity to produce one ton of ice per day as designed. Following the successful testing of the first prototype at a factory (AIREF) in 2018, GIZ, supported by Institut für Luft- und Kältetechnik Dresden (ILK), developed the technology and with the help of partners deployed this technology in Sulamu village, Kupang, East Nusa Tenggara, started in 2020 and fully operated in late May 2022. This machine now supports ice production in the community, mainly needed and used for cooling fish. As there is no access to electricity in this region, the

solar-powered ice maker brings a great advantage, as it only depends on solar radiation, which is abundant in this area.

The solar-powered ice maker is equipped with solar panels that can generate up to 25-kilowatt peak (kWp) and can produce up to one ton of ice blocks per day and up to 245 tonnes of ice blocks per year. The fishery sector plays an important role in the coastal regions of Indonesia, especially in the coastal area of Kupang, and until now the cooling of fish products could only be ensured inadequately due to the lack of electricity. Therefore, this solar-powered ice maker can improve the community's economy through the fisheries sector and empower the local fishermen in this area.⁴⁷ After successful piloting the first SIM in Indonesia, GIZ and its partners constructed another SIM. GIZ supported also the local assembly of the cooling units and respective capacity building measures.

⁴⁷ IKI (2023) Supporting local fisheries with solar energy; IKI (2021) Solar ice machines for fresh fish; GIZ (2021a) Ice from solar energy for sustainable fishing. GIZ (2020) Indonesia: Ice from solar energy.



Best Practice Example 2: Container solar Ice Maker in Indonesia



The small-scale handline yellowfin tuna fishers of Kawa Village, Seram Bagian Barat, Maluku Province, form the backbone of the local economy. Their sustainable one-by-one fishing methods, targeting large tuna with environmentally friendly techniques, are a cornerstone of Indonesia's artisanal fishing sector. However, they often face challenges in preserving the quality and freshness of their catch due to the lack of reliable cooling technology, particularly ice-making facilities, stemming from limited access to the electricity grid. This challenge has led to high post-harvest losses and reduced incomes. To address these issues and build on the success of the solar ice maker (SIM) developed and deployed in Kupang by GIZ Indonesia in 2022—which produces one (1) ton of ice per day using solar energy—Yayasan IPNLF Indonesia (YII), in partnership with the GIZ Energy Program, has implemented the second solar ice maker with a daily ice capacity of 1.2 tons, in Kawa, West Seram (see *Pictures above*). This unit has been operational since early October 2024 with an optimised container-based design. The SIM is a pioneering solution designed to operate entirely

off-grid, harnessing solar energy to produce ice sustainably and cost-effectively. Funded by the UNDP Ocean Innovation Challenge, this project aims to provide a sustainable ice production solution for local fishing communities. The solar ice maker has been procured by the YII under the UNDP award and was manufactured by AIREF, an Indonesian company specialising in cooling and refrigeration. The Marine and Fisheries Agency of Maluku Province, along with PT Aneka Sumber Tata Bahari (PT. ASTB), have provided support throughout. The local fishing communities, who are integral to the success of this project, will be the ultimate beneficiaries of this innovative solution. This initiative specifically targets small-scale handline yellowfin tuna fishermen, whose livelihoods depend on maintaining the freshness and quality of their catch. Furthermore, by integrating renewable energy, the project aligns with Indonesia's broader national goals of reducing carbon emissions and promoting sustainable economic growth, particularly in remote coastal communities.⁴⁸ For more technical details see *Figure 8* and *Table 2*.

48 IPNLF (n.d.) Factsheet and Catalogue of the Solar Ice Maker (SIM) facility.

5.2.2 Walk-in solar cold rooms

Cold rooms are crucial in the early steps of the cold chain, playing a pivotal role in preserving the health, safety, quality, and nutritional value of food. By providing precooling and cold room storage, these facilities can significantly reduce postharvest losses, thereby improving food security, increasing income for marginalized farmers, and reducing price fluctuations by better balancing supply and demand.⁵⁰

Solar cold rooms operate with the traditional vapor-compression refrigeration system, also known simply as refrigeration cycle. Solar cold rooms require then a refrigerant and insulation selection that matches the principles of Green Cooling, meaning natural substances for refrigerants and insulation foam, since they are the substance type that offers the least environmental and climate impact. The PV array and coupled battery system or thermal storage alternative must offer autonomy and self-reliance in areas with frequent power interruptions or no prevalent grid at all. Inverters are required, unless direct cooling systems are used, since the electricity in PV panels is generated in direct current (DC).

Modular and scalable approaches are crucial to provide feasible and affordable solutions for local businesses and industries promoting a local consumption. However, there is no all-in-one solution. Perishable goods come along with specific requirements for temperature, air humidity and air composition. Moreover, the given quantities of the stored goods as well as the required logistics need to be considered in the design process. The more exact temperature and amount of a certain product are determined, the more energy-efficient the technological components can be sized and balanced with each other.

In cold rooms, the desired cooling effect is applied on the air inside the room by transmitting the given heat in the room itself to the refrigerant. This extracted heat subsequently is released to the ambient air outside the cold room. Therefore, the cooling effect can be described as the pumping of heat from the inside to the outside air.



Guidelines

⁵⁰ IIFIR & Efficiency for Access (2023) Walk-in Cold Rooms, a Practitioner's Technical Guide.

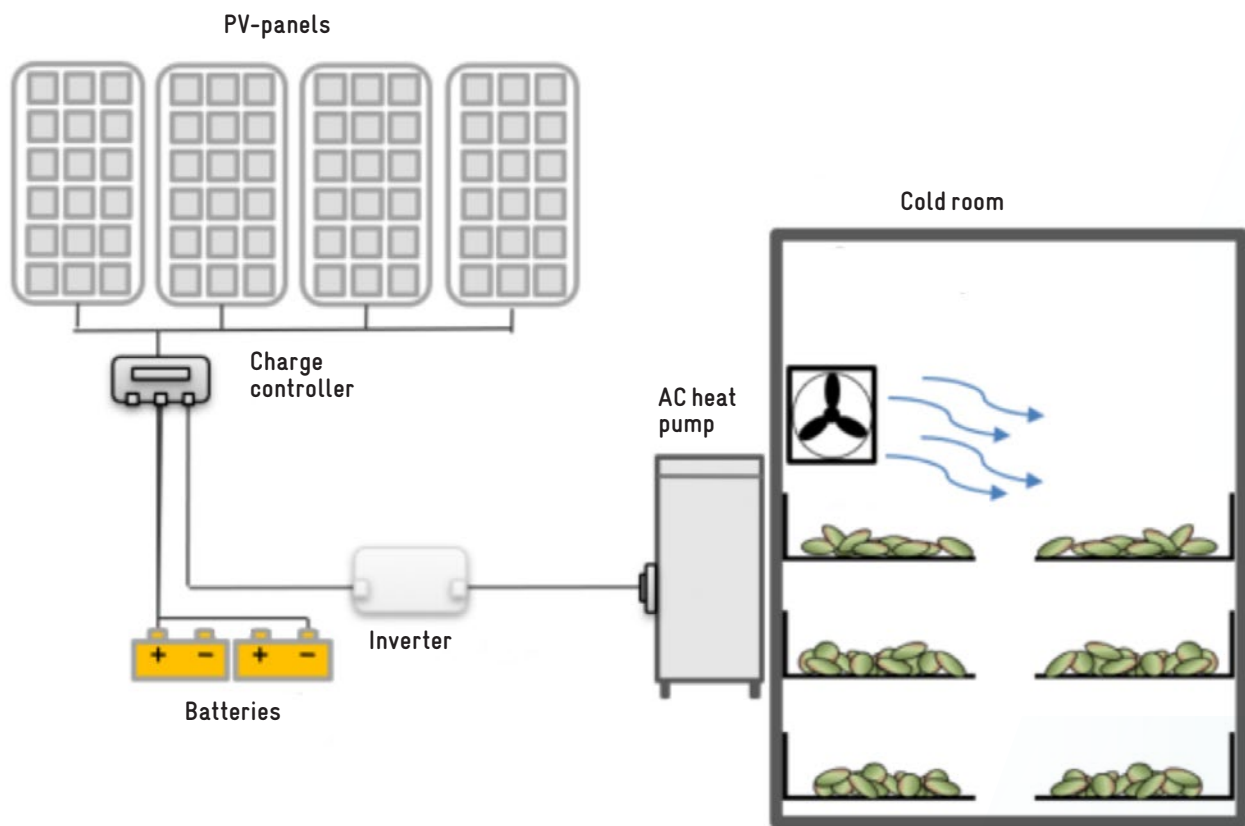


Figure 9: Conventional solar cooling system.⁵¹

The advantage of this common approach is its simplicity as well as the common availability and therefore low costs of the built-in components.

Problematic is the initial peak current of AC-230V-components, that are designed to be connected to the grid. Therefore, the inverter must be able to transmit this high current, which results in high costs. An additional financial disadvantage inheres in the large batteries that are necessary to store sufficient power to bridge hours of low or no sunlight.

The refrigeration system of a cold room can be different in each case, depending on the size, temperature requirements, insulation, and place of installation. The selection could either be an AC-230V split system or a monobloc system (Picture 9). When multiple cold rooms are considered, a central refrigeration AC-230V-system can also be implemented.



⁵¹ Solar Cooling Engineering (n.d.) Solar Cooling Engineering | Your technical partner for sustainable cooling.

A solar cold room can be configured using batteries to bridge the lack of sunlight overnight as main energy storage strategy. However, economic challenges as well as environmental disadvantages, prompt the alternative of thermal storage, normally in form of ice or chilled water.

Other alternative configurations exist where the cooling effect in the cold room is provided by virtue of chilled water or thermal plates with ice (Figure 10 and 11). This method simplifies design, and the refrigeration cycle happens before the cold room, it is the process that chills the water or produces the ice. In these cases, the ice bank works as well as a thermal storage, providing autonomy usually in a range of 15 to 30 hours.

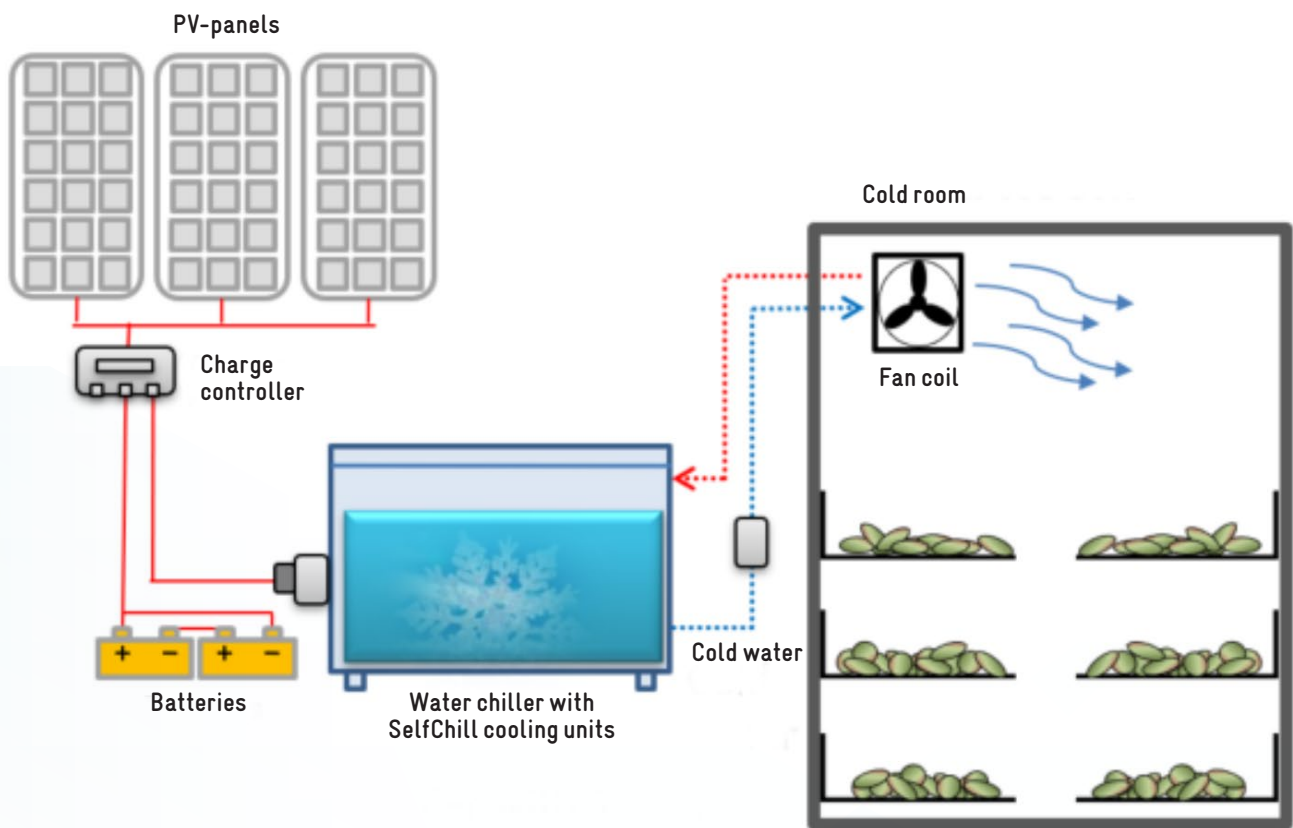


Figure 10: SelfChill solar cooling system without direct drive.⁵²

The most common type of thermal storage in solar cold rooms is an ice bank (Picture 10), that freezes water with excess energy to provide a cooling effect through ice in times of insufficient power supply. In other cases, the ice bank is used to chill water which will later be used to cool the

surrounding of the cold room. Both cases allow a significant downsizing of the batteries, which in this case are needed only to power peripheral devices like the pump and fan coil. However, it introduces the challenge of transmitting the cooling effect of the ice to the air inside the cold room.

⁵² Solar Cooling Engineering (n.d.) Solar Cooling Engineering | Your technical partner for sustainable cooling.



WALK-IN COLD ROOMS, A PRACTITIONER'S TECHNICAL GUIDE

Design and Operation of Walk-In Cold Rooms for Precooling
and Storage of Fresh Produce in Hot Climates, in Off-Grid
and Unreliable Grid Situations



DECEMBER 2023



INSTITUT INTERNATIONAL DU FROID
INTERNATIONAL INSTITUTE OF REFRIGERATION





Best Practice Example 3: ColdHubs Nigeria



ColdHubs Nigeria is an initiative that addresses the significant issue of food loss in Nigeria by providing off-grid cold rooms powered by solar energy. These solar-powered cold rooms are designed to extend the shelf life of perishable goods from two days to 21 days, significantly reducing post-harvest loss by 80 percent. The innovative “plug and play” cold rooms are equipped with stainless steel floors, 12 cm (4 inches) thick insulated panels (with hydrocarbon blowing agents), and solar panels on the roof, enabling them to operate without the need for backup generators or sunlight. The refrigeration unit (monoblock) within these rooms utilizes R290, a natural refrigerant with one of the lowest climate impacts among refrigerants. The solar-powered cold rooms are a clean and sustainable solution that lowers operating costs and has the potential to significantly impact the agricultural sector in Nigeria and beyond.

ColdHubs’ approach was designed by small-scale farmers for small-scale farmers, ensuring that the solutions are tailored to the needs of the very poorest farmers. This is facilitated

through a “pay-as-you-store” model, which makes access to cold storage affordable for farmers who might otherwise be unable to afford the high costs of traditional cooling systems. “Pay-as-you-go” financial mechanisms have been established as an excellent alternative to mitigate the effects of high initial costs. The initiative also places a strong emphasis on job creation, with many roles within the operation being filled by women.

The first ColdHub solar cold room using a R290 monoblock and cyclopentane insulation panels were installed in Nigeria (1st in entire Africa) around 10 years ago. The project was supported by GIZ and designed by ILK. The demonstration project was funded by the German Federal Ministry for Economic Cooperation and Development (BMZ) and ColdHubs. Currently ColdHubs is operating an estimated number of close to 100 cold rooms in Nigeria and other countries are copying the approach. Although ColdHubs is using mainly batteries, they are now also using thermal storage systems.

Best Practice Example 4:

Water chilled cooling units in Kenya and Togo



The SelfChill series is designed and manufactured by Solar Cooling Engineering (SCE) and are solar-powered water chillers that are engineered to be self-contained and highly efficient. These units are designed to provide reliable cooling for a wide range of applications, from residential to commercial use, without the need for external power sources.

In response to the cooling challenges faced by smallholder farmers in Kenya and Togo, particularly in the agricultural sector, innovative solutions like SelfChill water chilled cold rooms are emerging as promising alternatives. These technologies offer a sustainable and cost-effective way to preserve products and significantly reduce post-harvest losses due to high ambient temperatures. By leveraging solar energy, the cold rooms provide a reliable cooling solution that is accessible to farmers without the need for electricity grid access. The technology not only addresses the immediate needs of the agricultural sector but also aligns with broader sustainability goals, making it a viable option for small-scale farmers and fishermen alike.

The core element of cooling systems is the Water Chiller. It consists of an insulated box that accommodates a variable number of cooling units that are using the natural

refrigerant R600a, as well as in- and outlet piping that allows the circulation of water (*Picture 13*).

To initiate the cooling process the box needs to be filled with fresh water, that subsequently is cooled down at the surface of the cooling units. Consequently, a thermal stratification is established, starting with 2°C at the bottom of the box. This chilled water is then pumped to a fan coil inside the cold room. Since the water is colder than the air inside the cold room, the fan coil allows the air to transmit some of its heat to the cold water. The result is a cooling effect inside the cold room and a raised temperature of the circulated water.

To close the circuit, the heated, but still cold water is pumped back to the water chiller (*Figure 10*). Consequently, the water chiller needs to offer at least as much cooling capacity as demanded by the cold room. If, however, it produces a cooling effect that exceeds the heat extracted from the cold room, ice will be created, surrounding the cooling units. This has the effect, that returning water will be chilled by the ice, even when the cooling unit is turned off already due to a lack of solar radiation.



One cooling unit can create up to 30 kg of ice in one day, per water chiller while the cooling unit is inactive. Nevertheless, pump and fan coil need to be powered (in the direct drive version in Figure 11). This is realized through a battery that utilizes a variable DC Voltage of the PV-panel. A charge controller is needed to create a 12 V DC Voltage that supplies energy to the battery at times of excess sunlight. The battery then powers the fan coil and pump at times of insufficient sunlight. The fact that the DC Voltage produced by the

PV-panel is variable, due to factors like sun exposure and ambient temperature, combined with the fact that the cooling units can utilize a variable DC Voltage between 10-40 V (contrary to pumps, fan coils and batteries) prompts the usage of a direct drive approach for the cooling unit. This implies a reduction of heat losses on the side of the inverter and therefore a higher overall system efficiency that results in lower investment costs for PV-panels.

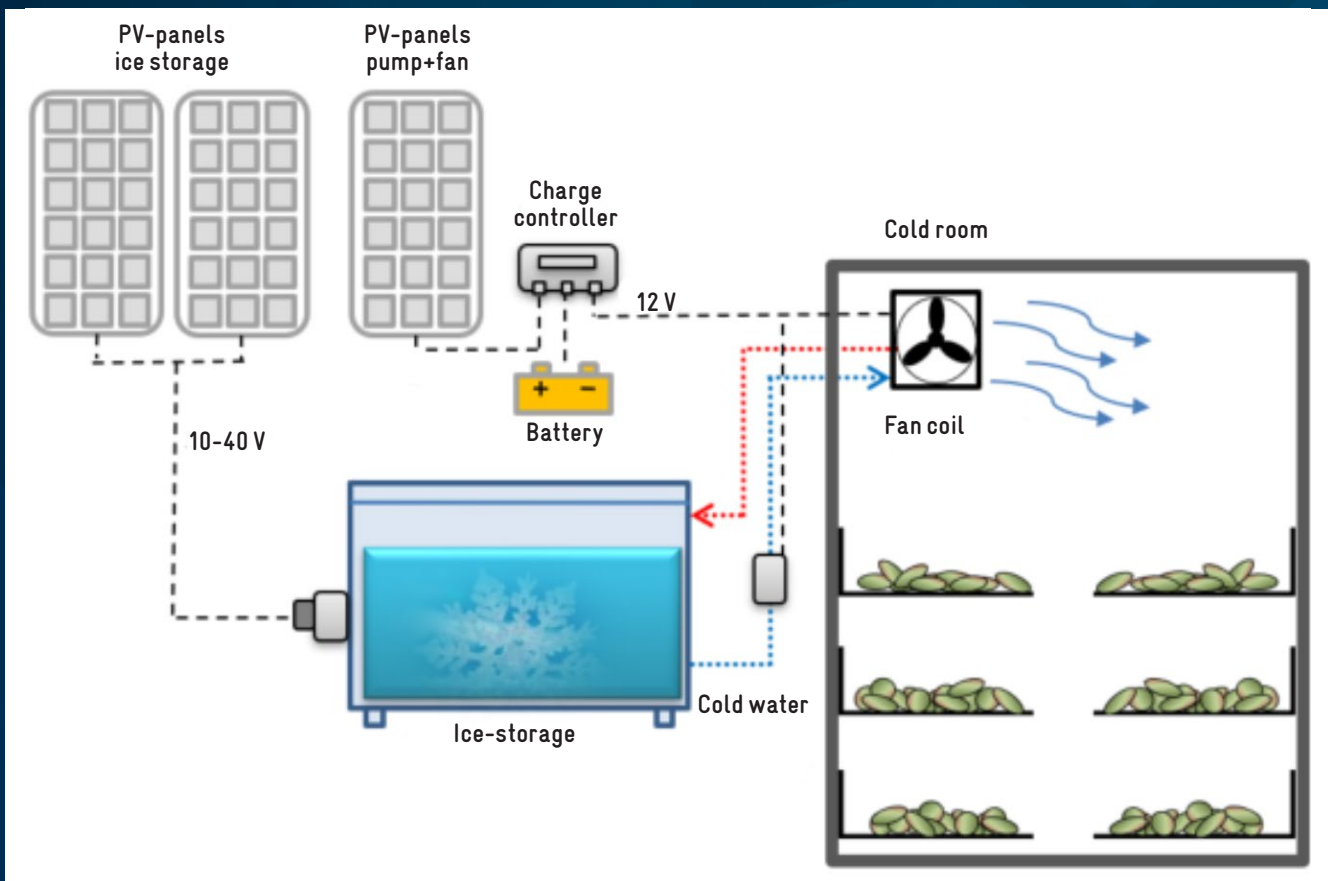


Figure 11: SelfChill solar direct-drive cooling system.⁵³

According to SCE, the highest system efficiency can be realized through a variant that combines the thermal storage (ice bank) with batteries and therefore forgoes the advantages of the direct-drive approach. For the examples

of Kenya and Togo, 12 SelfChill units were used for the cold room in the direct drive configuration. Both projects were implemented by GIZ.

⁵³ Solar Cooling Engineering (n.d.) Solar Cooling Engineering | Your technical partner for sustainable cooling.

The SelfChill approach of utilizing DC Voltage implies a usability for standalone operations at sites off the grid only. Therefore, the modular system must be designed appropriately. Sites that do have a connection to the grid and just need to bridge power cuts can consider an AC-DC hybrid approach.

The modularity of the panels and the solar cooling unit unlocks the possibility for tailor-made solutions. As shown in this case, the cold room used 12 cooling units. Different configurations and solutions enable AC operation (*Figure 10*), small scale applications (refrigerators, milk can cooler, and air-conditioning) and medium scale (cold rooms, milk tanks, and ice makers).

Parameter	Description
Technology	SelfChill-Approach by SCE with direct drive and ice bank
Use	Fruits & Vegetables
Cold Cell (Dimensions L x W x H)	3,3 x 3,3 x 2,2 m (21.5 m ³)
Cooling Capacity	12 x 200 W = 2400 W (2.4 kW)
Refrigerant and charge	R600a (12 x 35g = 420g)
GWP 100 years / 20 years (IPCC 6AR)	0.02 / 0.06
Voltage range	10 – 40 V direct drive
Ice Storage	600 kg, which represents 700 W of cooling power (72 hours of autonomy)
PV Capacity (cooling units – direct connection, ice storage)	5 kWp (East – West orientation)
PV Capacity (water pump and heat exchanger, fan coil)	400 Wp
Battery capacity (only for water pump and heat exchanger)	160 Ah
12 V Water Pump	22 W
Heat Exchanger (fan coil)	29 W energy consumption (1.2 kW cooling power)
Ambient Temperature / Min. achievable Cold Room Temperature	25 °C / 4 °C 35 °C / 6 °C 45 °C / 8 °C

Table 3: Main Parameters and characteristics of water chiller used in Togo.





Figure 12: Fish cold store: "Environmentally friendly cold storage for fish – an example from Kenya"⁵⁵

Best Practice Example 5: Solar Fish Cold Room in Kenya



Solar cold rooms are a significant innovation in the agricultural sector, particularly for Kenya, which relies heavily on agriculture, accounting for approximately 20% of its GDP.⁵⁴ This sector is predominantly supported by smallholder farmers in rural areas, who encounter numerous challenges, such as restricted access to electricity. These farmers also lack effective cooling solutions for their produce, resulting in substantial post-harvest losses due to elevated ambient temperatures. Similar issues plague the fishing industry, where small-scale fishermen find it difficult to produce ice for cooling their catches, and sourcing ice from other regions is both difficult and costly. The dairy industry faces a similar predicament, with most products originating from small farmers who are unable to access cooling technologies, thereby hindering the preservation of milk quality and the reduction of bacterial growth.

A cold storage room for fish has been constructed in Mfangano Island in Homa Bay County in Lake Victoria. The fish cold room is a pilot project in cooperation with a Kenyan private investor through co-investment. The cold store has state-of-the-art insulation, highly efficient refrigeration (monoblock) and ice-making (ice flakes) appliances that use the natural refrigerant R290 and is equipped with a PV system to reduce electricity grid dependency.

The concept was discussed with local fish farmers around Lake Victoria to identify first an economic quantity of fish to be caught daily and agreeing on the appropriate cooling capacity of the cold store, which is approximately 5 tonnes of fish. The routine harvesting and storage time is set to two to three days and then the fish is transported to the market in Nairobi. The design and performance of the cold room include refrigerating and storing the fish near zero degrees, requiring an ice machine, and using locally sourced plastic baskets. The cold store has a processing area for embedding the fish in ice flakes and a refrigeration unit.

⁵⁴ Statista (2024) Share of economic sectors in the GDP in Kenya 2022.

⁵⁵ GIZ (2019b) Environmentally friendly cold storage for fish – an example from Kenya.

The final detailed design of the cold room included metal-coated sandwich panels, with polyurethane raw materials as insulation material. Installation and commissioning faced challenges due to the large-sized panels, lack of local staff experience, and the remote island location. Despite these obstacles, the cooling systems have worked well from the

start for close to 10 years now, supported by service technicians trained. The project was supported by GIZ Green Cooling Initiative (GCI) and was funded by the German Federal Ministry for the Environment (now BMUV) and the local partner.

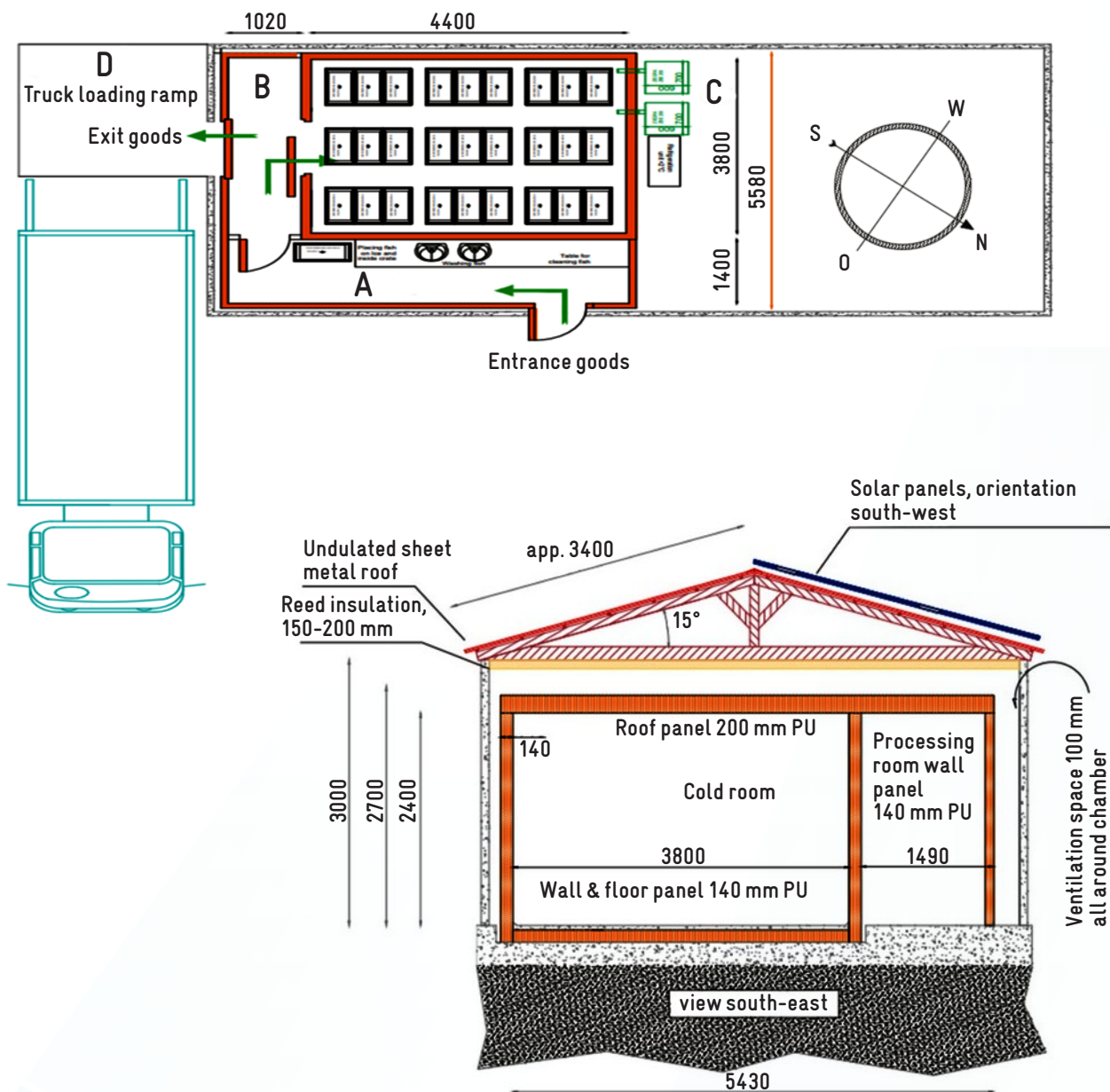


Figure 13: Layout drawings of the solar fish cold room in Mfangano Island ⁵⁶

⁵⁶ GIZ (2021b) Construction of a fish cold store in Kenya.

The cold room shown above has the following features:

- Washing and cleaning area insulated with 70mm panels and roof 200mm. No insulation on the floor (A).
- Anteroom in front of the cold store, same insulation as the washing and cleaning area with an entrance door and an exit door for loading the goods onto a truck (B).
- Area where the refrigeration unit is placed, on the roof and a possible place for an ice maker (C).
- Truck bed and possible additional space for an ice machine (D).

From this experience, the following considerations for the adequate implementation of a fish cold room were derived:

- **Cleaning the fish:** The fish needs to be cleaned properly and cleaning with water from the ponds where the fish is harvested is not an option because the water is not always clean, it is warm outside, and the fish needs to be cooled as soon as possible. When the fish is cleaned next to the pond, it is put in baskets, taken to the cold store, unpacked, and put on ice. This extra handling is not conducive to the quality of the fish.
- **Size of the cold store:** The plan is to sell the fish 2-3 days after harvest in large quantities for transport to the bigger cities, like Nairobi. Therefore, the size of the cold store was designed for 5 metric ton truckloads, which is the estimated quantity that can be sold at one time.
- **Freezing the fish:** The fish is not intended to be frozen. Should this be necessary in the future, an additional cold store can be placed next to or behind the existing one. The additional entrance would then be through the existing cold store.
- **Anteroom:** The decision for an anteroom is the optimal solution from a thermal point of view and is therefore implemented.
- **Delivery:** The fish should not be transported from the cold store through the cleaning and washing area, so a separate exit was provided for delivery to the trucks.

Parameter	Best Practice Example Cold Room
Technology	Separate ice machine and battery
Product to chill	Fish
Expected product amount	1000 kg (fish catch of 2-3 days)
Volume	40.1 m ³ plus Anteroom of 9.30 m ³
Dimensions (L x W x H)	4.4 x 3.8 x 2.4 m
Cold room temperature	0°C
Cooling System	Monoblock
Total cooling capacity	1.9 kW (< 5 kW)
Refrigerant	R290 (propane)
Refrigerant charge	118 g (ice maker) and 150 g (monoblock)
GWP 100 years/ GWP 20 years (IPCC AR6)	0.02 / 0.072
Power supply	100% PV
Total peak power consumption	2.6 kW
PV module type	260 W, 1665 x 991 mm, 15° tilt angle
Number of PV modules	10-12 (on roof with southwest orientation)
Total PV peak power	2.6 – 3.12 kW (calculated)
Energy storage	Electrical
Battery type	Deep cycle 12V
Ice bank type	Ice maker
Ice bank power	0.8 kW
Ice bank capacity	230 kg ice per day / 19.2 kWh (calculated)
Total autonomy period	10 hours (calculated)
Inverter	Off grid – two phases

Table 4: Main parameters and characteristics of the solar fish cold room in Kenya.

Key learning aspects from the project include the importance of careful preparation of construction work to reduce the build-up time of the cold room, ensuring a qualified installation team and electrician, and having enough tools and accessories on site to avoid delays. Training staff on logistical aspects, such as organizing how to fill a cold room without keeping the doors open for long periods, is crucial. The process of placing fish in baskets with layers of ice is relatively new but essential.





Best Practice Example 6: Solar-powered cold rooms in Ethiopia



In Ethiopia, a significant portion of the population relies on agriculture for their income. However, the sector's potential, especially in horticulture, is hindered by up to 25% due to post-harvest losses. Smallholder farmers struggle with these losses due to a lack of access to suitable cooling technologies, especially in areas with limited grid electricity. To address this, the GIZ project Green People's Energy introduced solar cooling technology through a pilot project in collaboration with two BMZ-funded initiatives: Sustainable Rural Value Chain (SRVC) and Building an Avocado and Sesame Value Chain in Ethiopia (develoPPP). This project aimed to test solar-powered cooling systems in rural horticultural cooperatives.

The pilot project featured six solar PV-powered cooling containers (Picture 15 and 16) from Frigos Indus, utilizing innovative thermal energy storage technology to minimize battery costs and environmental impacts. These containers can generate up to 4.55 kW of solar energy per container, used for cooling goods during the day and freezing water for

night-time cooling, thereby providing thermal storage as in the other solutions presented in this section. The system requires only a small battery for air circulation and control units, operating between 4 and 15 degrees Celsius. The cooling system operates with R290 as refrigerant.

The installed refrigerated containers have benefited over 1,400 farmers directly and indirectly. Farmers anticipate higher prices for their products due to improved product quality as well as increased income from reduced post-harvest losses and enhanced bargaining power. The project's almost battery-free solar cooling technology is particularly suitable for rural off-grid areas, reducing initial and operational investment and environmental impacts.⁵⁷

The installation of these cold rooms was followed by a training to capacitate the users on the monitoring, operation, and troubleshooting. Regular maintenance and inspections are required every six months.

⁵⁷ Further readings: Energypedia (n.d.) Increasing Crop Yields through Solar Cooling in Rural Ethiopia; Soete, A. (2023) Pioneering green cooling in rural Ethiopia – Green People's Energy for Africa. GIZ (2024) Increasing income and creating jobs in the agricultural sector. Accessed May 6, 2024; GIZ (2024) Organic sesame and avocado oil in Ethiopia.

Parameter	Given Case Study
Technology	Highly efficient refrigerated container working as a cold room with an ice bank for thermal storage.
Use	Fruits & Vegetables
Amount	Up to 4 tonnes
Volume	17.2 m ³ (20" Container)
Dimensions (L x W x H)	3.9 x 2.1 x 2.1 m
Cold Room Temperature	4–15 °C
Total Cooling Capacity	2.23 kW
Refrigerant	R290
GWP 100 year / 20 years (IPCC AR6)	0.02 / 0.072
Cooling Capacity separate IM	25 kWh
Thermal Storage / Ice Bank Type	Ice around tubes in water tank through special Bock compressor
Ice Bank Capacity	Scalable (2 m ³ tank = 25 kWh cooling energy)
Insulation	100 mm thick frigorific panels
Total Peak Power Consumption	4.4 kW
PV Modul Type	400 W monocrystalline
Number of PV Modules	12
Total PV Peak Power	4.8 kW
Energy Storage	Electrical and thermal
Battery Type	Cobalt free lithium iron phosphate (LFP)
Battery Capacity	5.12 kWh
Total Autonomy period	12 hours
Inverter	Hybrid

Table 5: Main parameters and characteristics of the Cold Room in Ethiopia.





Best Practice Example 7: Large solar PV powered warehouse-scale walk-in cold room

The “Much Cooler” Off-Grid Europe GmbH cooling solution provides turnkey warehouse-scale walk-in cold rooms solutions. The hall has a dimension of 20 x 30 meters and can also be flexible designed and can be 5-10 meters longer or shorter. The warehouse-scale cooling solution is based on a steel mounting structure for solar panels and is 100% powered by solar PV and integrated with a battery energy storage system (BESS). The Off-Grid Europe GmbH is currently still designing a thermal ice-storage that will be available in future. The refrigeration system is using ammonia (NH₃) as refrigerant (*see Table 7*), which is usually used for larger cooling capacities, and which is also very efficient in the tropics. The condensation water of the cooling system can be used

for solar panel cleaning. The robust cooling system all in one unit / self-standing unit, offers variable temperatures (6-14 °Celsius) for different agricultural good (*see Table 6*) that can be adjustable to different seasons.

The solution comes with a management system to support monitoring and control temperature, RH, fan speeds, inverters and batteries data, energy consumption. Farmer/ cooperative database (Name, location, historical data of warehouse use in terms of kg, space required for store, energy consumption). Rental agreement farmers (duration, volume, price / m³). Barcode based ticketing system for stored produce. Payment options as Pay-As-You-Go (PAYGo).⁵⁸

Products	Temperature	Humidity	CO ₂ PPP (parts per million)
Table potatoes	4 – 6 °C	92%	7000 ppm
Chips potatoes	7 – 12 °C	92%	2750 ppm
French fries potatoes	5 – 8 °C	92%	3000 ppm
Seed potatoes	2 – 4 °C	85%	5000 ppm
Onions	28 °C	65%	<1000 ppm
Carrots	0 – 1 °C	95-98%	<1000 ppm
Cabbage	0 – 1 °C	90-95%	<1000 ppm
R290	R290	R290	R290
0.02 / 0.072	0.02 / 0.072	0.02 / 0.072	0.02 / 0.072

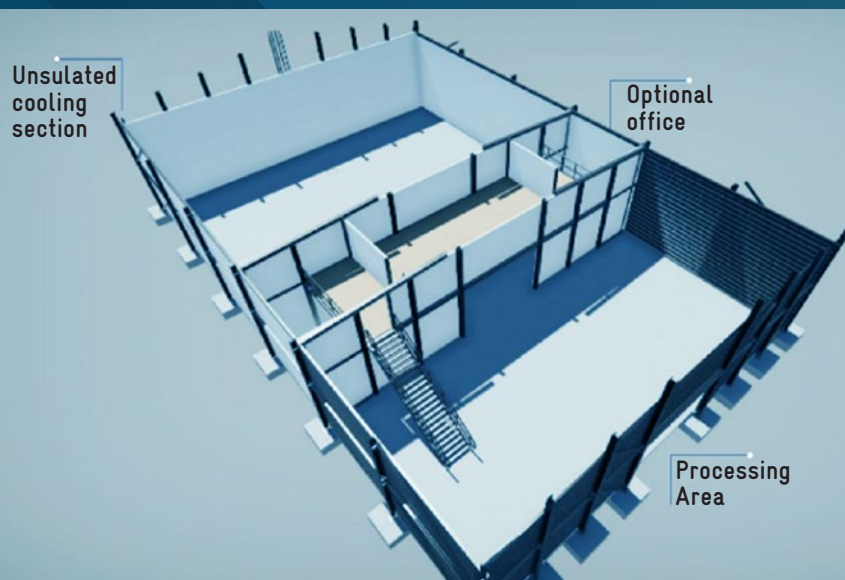
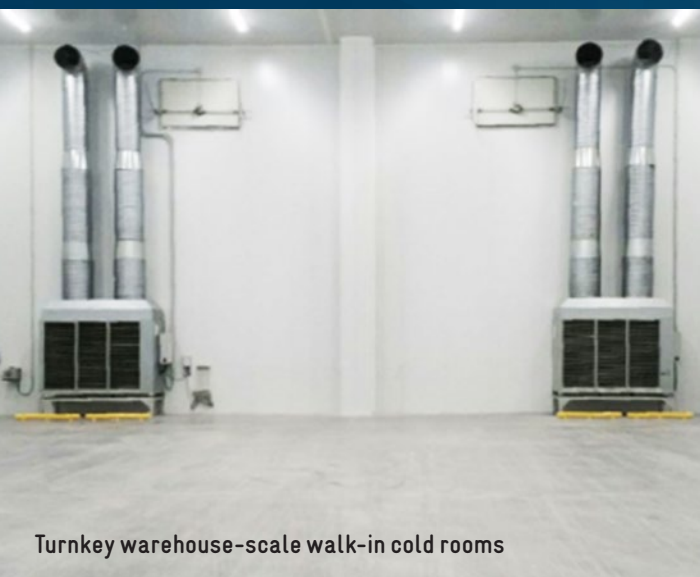
Table 6: Agriculture products and required temperature, humidity CO₂ PPP.⁵⁹

⁵⁸ Off-Grid Europe GmbH (2023) Much Cooler and Power Point presentation.

⁵⁹ Ibid. (own illustration)

Parameter	Given Case Study
Storage capacity	Conventional Alternative
Operation temperature	300t to 5000t vegetables and fruit (scalable by modular approach beyond 5000t)
Ambient external temperature	1 °C to + 35 °C (34 °F to +95 °F)
Humidity	-10 °C to +50 °C (14 °F to +122 °F)
Maximum installation altitude	5 % – 90 %
Volume	2000m above sea level
Dimensions (L x W x H)	50m ³ or larger (scalable)
Cold room temperature	6-14°C storage temperature
Cooling capacity	38 kW (scalable)
Refrigerant and charge	Ammonia (NH ₃)
GWP 100 / 20 (IPCC AR6)	0 / 0
Insulation	PU sandwich panels
Total PV peak power	50 – 300 kWp
Inverter	50 kVA – 500 kVA
Battery type	Ohms Box Battery Energy Storage Systems (BESS)
Battery capacity	60 kWh – 1.5 MWh
Thermal storage	Under development
Inverter	50 kVA – 500 kVA

Table 7: Main parameters and characteristics of the PV powered warehouse-scale walk-in cold room



5.2.3 Solar milk cooling

Solar cooling technology is being used in innovative ways beyond traditional building and cold chain applications, such as milk cooling. In the dairy industry, solar cooling is a more sustainable and cost-effective alternative to traditional milk cooling methods, as it significantly reduces reliance on electricity and lowers carbon footprint.⁶⁰ In numerous countries, milk production is predominantly carried out by small and medium-sized dairy farms, each with a daily output of less than 200 litres. Typically, this milk is transported to collection facilities without any cooling measures. Furthermore, inadequate hygiene and cleaning practices, along with cattle health issues, are the primary causes of significant bacterial growth during the short-term storage of milk on the farm and during transportation.⁶¹ Solar technology in general can even be coupled to provide both pasteurization and cooling of the milk. This was done in a study by combining a parabolic solar collector for the pasteurization process and a solar adsorption chiller with a flat solar collector for the cooling of up to 150 litres of milk.⁶²

Milk has a temperature of approximately 37°C immediately after milking and can spoil within three to six hours if not cooled to at least 20°C. Spoilage can be minimized by maintaining good hygienic practices and storing milk at lower temperatures. To prevent bacterial growth and ensure compliance with national standards in the corresponding countries raw cow milk quality, milk should be stored at low temperatures, ideally 4°C but at least in the range of 15 – 20°C for rapid consumption.⁶³

Cooling milk extends its storage life and maintains its quality during transportation. Typically, milk is stored at 4°C for up to 48 hours. However, in rural areas, this cooling process is often limited or not implemented due to the high energy costs associated with conventional electric grids and stand-alone diesel generators. This situation presents an opportunity to introduce sustainable energy solutions based on renewable sources. Photovoltaic systems, which are increasingly accessible in rural areas of many African countries, offer a viable energy source option.⁶⁴

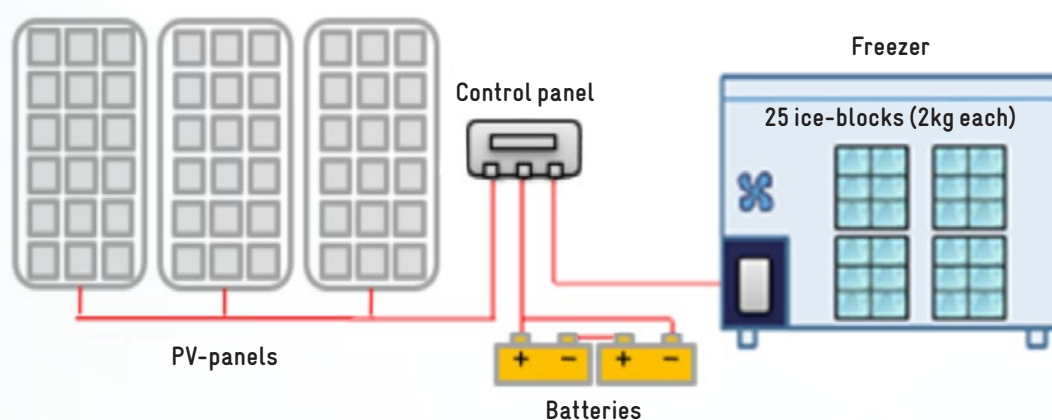


Figure 14: Production of ice blocks – smart solar freezer.⁶⁵

Solar milk cooling is still an application found in a stage of development, research, and testing. Solar technologies offer many possibilities of implementation as well. For these reasons, not one configuration of solar milk cooling has been established as a standard. GIZ collaborated in two projects with the Institute of Agricultural Engineering of the University of Hohenheim in Tunisia and Kenya. The solar milk cooling system to be showcased is then specific to this design.

The milk cooling system involves two steps: first, ice blocks are produced using a smart solar freezer paired with a control panel that optimizes solar energy usage for daily ice production (Figure 14). Second, the milk is cooled in insulated milk cans. The ice blocks are placed in an ice compartment, which is then inserted into the milk can once it is filled with milk (Figure 15).

60 Sain et al. (2020) Solar energy utilisation in dairy and food processing industries – current applications and future scope.

61 Energypedia (n.d.) Solar Milk Cooling with Insulated Milk Cans.

62 Sur et al. (2020) Milk storage system for remote areas using solar thermal energy and adsorption cooling.

63 Salvatierra-Rojas et al. (2018) Improving Milk Value Chains Through Solar Milk Cooling.

64+65 Ibid.

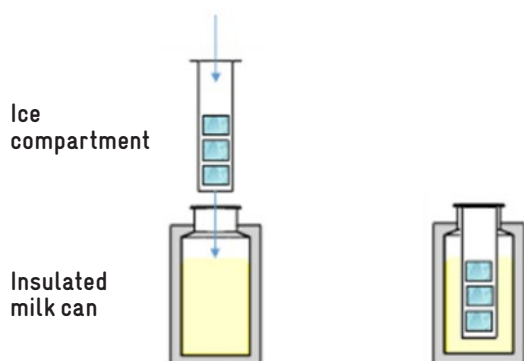


Figure 15: Milk cooling in the insulated milk can with the produced ice blocks.⁶⁶

Best Practice Example 8: Solar powered milk cooling solution in Tunisia



In central Tunisia's Sidi Bouzid region, which contributes about one-sixth of the national milk production, most milk comes from small and medium-sized dairy farms with fewer than ten cows and a daily output below 200 litres. This milk is produced on the farm and transported to collection facilities without cooling, leading to significant bacterial growth during short-term storage and transportation.

Under the region's climatic conditions, milk can exceed the maximum bacterial count set by Tunisian food safety laws within two to five hours. During the hottest periods, poor quality is the main reason for milk rejection at collection centres. Additionally, due to low production volumes, evening milk collection is not available year-round, causing further on-farm losses. No cooling methods were currently applied during the initial stages of the dairy value chain at the start of the project in 2016.

The GIZ project installed ten solar milk cooling systems in seven farms. Milk is usually collected twice a day in Tunisia, in the morning and in the evening. The data collection considered this and compared the results of the milk transported

in the insulated tanks as in *Figure 15*, compared to usual milk collected with no cooling device, in both collection times. Milk transported in the insulated cans was clearly preserved in both collection times, while milk transported without cooling exceeded the bacterial count limits set by the regulation in Tunisia in the morning and in the evening.⁶⁷

The solar milk cooling systems were well received, and many advantages were identified. Farmers using the system can maintain the quality of milk from their farms to the dairy plant, as insulated stainless steel milk cans help reduce spoilage by keeping temperatures below 20°C. Additionally, the cooling system provides collectors with more time to transport the milk without the risk of spoilage, even when transport times are extended. This allows for changes in milk collection methods, as the milk cans are commonly used for transport. These benefits lead to improved milk quality and reduced energy consumption at the collection centres. The strengthening of the cold chain and the consequent increased output of preserved milk ensures the payment to the farmers at the end of the month.⁶⁸

⁶⁶ Ibid

⁶⁷ GIZ (2024) Organic sesame and avocado oil in Ethiopia.

⁶⁸ Salvatierra-Rojas et al. (2018) Improving Milk Value Chains Through Solar Milk Cooling



Best Practice Example 9: Solar milk cooling in Kenya

The project in Kenya grew upon the lessons learned in Tunisia. In rural Kenya, small-scale farmers are the primary producers of milk, as larger dairy plants typically do not collect milk from these areas due to insufficient supply volumes. To address this, cooperative systems were established as a form of business organization. These cooperatives are responsible for arranging the transport of milk from farms to the market.

In the region approached for the projects, farms generally have one to three dairy cows and provide 1 to 10 litres of milk per day to their cooperative. Milking occurs twice daily, in the morning and afternoon. Milk handling involves three stages: the farm, the satellite (a collection point near the cooperative), and the cooperative itself (which usually serves as a selling point). Farmers typically walk five to 60 minutes to transport their milk to satellites. At this stage, milk is bulked in a 50-litre milk can and transported to the cooperative within one to two hours by motorbike. However, the afternoon milk rarely reaches the cooperative due to lower volumes and late collection time. This milk is either sold locally around the farm or collected on motorbikes to be sold by the roadside or at local markets. Another strategy farmers use to preserve milk quality is submerging the milk containers in a water stream to lower the temperature and delay spoilage. This practice is not advisable for large volumes of milk as consistent cooling cannot be guaranteed. Pasteurization, if it happens, occurs only in the cooperative, but this contingent to whether there is enough volume of milk or not. It happens that the volume is not enough, and the administrators of the cooperative decide not to pasteurize. Three different versions of the approach tested in Tunisia were implemented in Kenya. Their description is on the following *table 8*:

The implementation of the different versions was consecutive. One of the lessons learned from the first version was the predominance and familiarity of the farmers with the food grade plastic containers. They are common in the area and have lower prices in the market when compared to the stainless-steel cans used when the approach was first designed and developed. The amount of ice was also iterated according to the different size and shape of the plastic containers.

Version I considered the same successful design used in Tunisia, and it included modified plastic cans that were able to hold the ice compartment with the ice block. Each modified milk can was individually tested against a 20-litre aluminium milk can, which served as the control unit. Comparisons were made to assess the performance of cooled versus uncooled milk during transport. During these evaluations, farmers received training on the correct use of the technology.

During transport from the satellite to the cooperative, the milk temperature was approximately 25°C, while the ambient temperature was 30°C. The cooling performance of the modified milk cans met expectations, reducing, and maintaining the milk temperature below 20°C throughout the three-hour transport period between the cooperative and the selling points. In contrast, the temperature of the milk in the aluminium milk can increased to match the ambient temperature, highlighting the significance of modifying milk cans for transporting small volumes of milk.

System	Stages	Modified milk cans details			
		Units	Material/Capacity	Capacity of milk per unit (l)	Capacity of ice per unit (kg)
Version I	Cooperative	2	Stainless steel 40 litres	30	8
			Food grade plastic 40 litres		
Version II	Farm	8	Food grade plastic 10 litres	7.5	2
Version III	Satellite	2	Food grade plastic 40 litres	30	8

Table 8: Description of the solar milk cooling systems installed in Kenya ⁶⁹

⁶⁹ Ibid.

Time of the day	Stages	Temperature (°C)		
		Ambient	Cooled Milk	Uncooled Milk
6:50	Farm	21	20	32
8:00	Satellite	22	15	29
10:30	Cooperative	28	17	27

Table 9: Temperature records of the Version II system ⁷⁰

Version II (*see also table 9*) considered modifying another type of plastic container commonly used in the area for the transport of milk. This commercial plastic milk container or can, known as the Mazzi can, was modified to work with the solar milk cooling system, requiring the system to produce smaller ice blocks. This is testament of the flexibility and adaptability of the system designed. The Mazzi can have a 10-litre milk capacity, but when adapted to carry 2 kg of ice, its milk volume is reduced to 7.5 litres. This Version II can cool 60 litres of milk using eight insulated Mazzi cans.

Since this version was installed in a farm, it offered the opportunity to record the temperature of the milk during the whole process. Ambient temperature, along with the temperature of cooled (Mazzi can) and a can with uncooled milk, was recorded. Thermocouples were either exposed to the ambient environment or placed inside the Mazzi can, with and without insulation, for approximately ten minutes to measure temperatures. The results indicated that the temperature of uncooled milk was nearing ambient levels, whereas the cooled milk maintained values below 20°C.

The improved cooling offered by the modified Mazzi can is evident. The microbial load was also tested at each stage, and it was demonstrated that the microbial growth was effectively limited by the modified Mazzi can, when compared to the growth of a regular Mazzi can.

Version III, installed at the satellite stage, fall back to the plastic container used in the first version. Previous evaluations indicated a preference for modified plastic milk cans over modified stainless-steel ones. Consequently, two insulated plastic milk cans were tested.

For the satellite operation, the test observed the recollection of different smaller contributions of milk by different farmers at different times, until filling the 40 litres can, which would then be transported to the cooperative, but that transport was outside of the scope of the test. The temperature of the milk began to gradually decrease as it was collected in the modified milk can at various intervals, since farmers did not all bring their milk to the satellite simultaneously, causing interruptions in the cooling process. Transport commenced at 9:24 a.m. with the milk at 15°C, and during transport, the temperature further dropped to 13°C, effectively keeping the temperature even under the allowable range of 15 – 20°C.

The project demonstrated to be a fruitful experience for all parties involved. The integration of the solar milk cooling system with existing milk handling processes was fluid and quickly adapted. Farmers, as key participants in the value chain, actively engaged with the technology and contributed to various adaptations during the installation of three solar milk cooling systems. They successfully adopted the technology and acknowledged the significant role cooperatives can play as an efficient milk collection alternative.

⁷⁰ Ibid.



Best Practice Example 10: Solar milk cooling in Ethiopia



In Ethiopia, dairy cooperatives play a vital role in the dairy sector, which the national government is actively supporting and developing. However, many cooperatives are in off-grid areas where lack of access to cooling leads to high milk losses and compromised milk quality. To address this, the GIZ SEFFA EnDev project has piloted a solar-powered milk cooling system at the Denkaka Dairy Cooperative near Bishoftu town. This system enables evening milk collection by keeping it cold overnight. It also includes a mobile phone charging service. The solar cooling system requires minimal energy, making it highly cost-effective. Additionally, the cooperative has the potential to expand services, like mobile charging, at the milk collection center offering new income opportunities and valuable benefits to the local community.

Additional measures supported by the project include trainings for cooperative farmers and stakeholders on good governance, financial management, business operation, good dairy farming practice, as well as the solar milk cooling technology.

The piloted technology is a solar-powered ice storage milk cooling system developed by Selfchill. It uses R600a as refrigerant. The system harnesses solar PV power to produce ice on evaporator plates, which is used to cool water. The chilled water is pumped into a bath containing stainless steel milk cans. The system can cool 160 litres of milk and maintain it at 4°C for at least 14 to 18 hours. It is designed to cool milk to 4°C in less than 4 hours, primarily storing milk collected during night-time.

The system includes a control mechanism to manage surplus power for mobile charging without compromising the milk cooling process. Additionally, it has remote monitoring capabilities to log system data such as cooler temperature, energy production, power consumption patterns, and any faults. It also allows for real-time tracking of the system's performance.

5.2.4 Solar refrigerators and freezers

There are various manufacturers for solar refrigerators and freezers that are using natural refrigerants (mainly R600a) and natural blowing agents (e.g. cyclopentane). They are also available in many countries of the Global South. However, many still also use HFC refrigerants (mainly R134a) or even contain ozone and climate harmful blowing agents

e.g. R141b. Most equipment contains still harmful batteries. However, some manufacturers are using Solar Direct Drive technologies with thermal storage. It is recommended to procure only units containing ultra-low GWP refrigerants and natural blowing agents, ideally with thermal storage and without batteries.





Examples of SolarChill devices⁷²

Best Practice Example 11: SolarChill in Eswatini



The first African manufacturer that offered solar refrigerators or freezers that used natural refrigerants was Palfridge (The Fridge Factory) from Eswatini. Under the SolarChill project solar refrigerators/freezers for commercial or private use, optimized for tropical and subtropical climates were developed and manufactured in Eswatini. GIZ Proklima's involvement was financed through the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

within the International Climate Initiative. The project's success lied in its ability to provide a sustainable solution for cooling in regions where access to electricity is limited, thereby addressing a critical need for refrigeration, and preserving life-saving vaccines and medications. Palfridge optimized a SolarChill devices for commercial or private use. The fridge Factory currently offers two different R600a 12 Volt solar models one with 107 and one with 199 litres.⁷¹

5.2.5 Solar Direct Drive (SDD) coolers/freezers for medicine or vaccine

Solar Direct Drive (SDD) vaccine refrigerators/freezers need to comply with strong World Health Organisation (WHO) temperature criteria. They need to sustain the temperatures between +2°C to +8°C for up to 72 hours without external power supply. Some SDD vaccine refrigerators/ freezers also contain a freezer for ice packs for field vaccinations. In January 2025 the Performance, Quality and Safety (PQS) catalogue of the WHO contained 44 solar units, of which 43 contained the ultra-low GWP refrigerants R-600a or R290 and one (1) unit did not contain any refrigerant.⁷³

Some manufactures use PU foam that has been produced e.g. with HC cyclopentane a natural ultra-low blowing agent. Other units within the PQS devices catalogue contain HFO blowing agents, which break down to PFAS and TFA and are harmful to the environment. It is recommended to procure only units containing natural ultra-low GWP refrigerants and natural blowing agents.

⁷¹ The Fridge Factory (2024) Product Catalogue September 2024, p. 19.

⁷² SolarChill (n.D.) GEF SolarChill project.

⁷³ WHO (2025) PQS devices catalogue. Product List E003: Refrigerators and freezers.



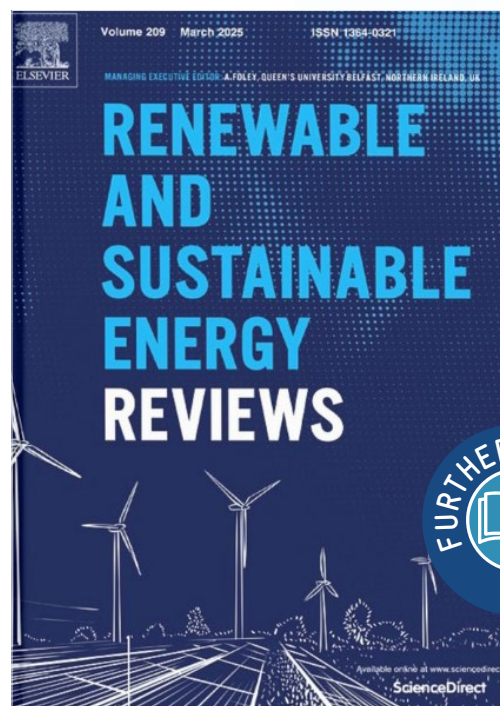
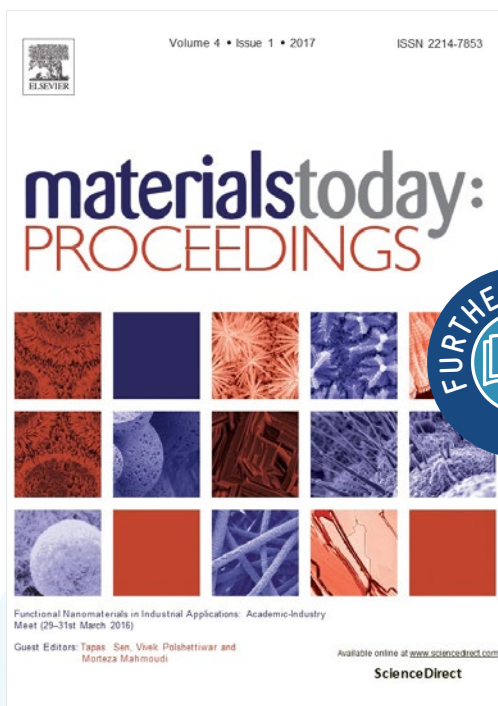
Solar-powered freezer
(© Shutterstock/creative republic).



5.2.6 Solar cooling for other purposes

Solar Energy can be not only a source of electricity and cooling, as shown in this publication so far, but also a source of heat for industrial purposes. And as in most heat industrial processes, there is a heat rejection process that can be converted into a cooling process to increase the efficiency of the installation, just as with chillers in hotels and commercial buildings where it is usual to use the heat sinks as a source of heated and cooled water. Solar energy can be implemented in this way in many industries, providing both the required heat for the industrial process and the cooling for a secondary or subsequent stage. Some examples are:

- Breweries can use solar energy to create heat for steam generation, malting process, stopping the germination of grains, and others, and cooled air for the climatization of the working places. Winery can use heat for similar process and also cooling for the wine cellar. Cold water can be used for bottle washing.
- Pharmaceutical processes require heat in a temperature range of 160-180°C, cooling is used for the warehouse complex.
- Manufacturing of machinery requires hot water, and both space heating and cooling.



5.3 Solar cooling: air-conditioning

The building sector, a major contributor to global energy consumption, presents itself as an opportunity for the adoption of solar cooling technologies. With the sector's energy consumption projected to increase in the coming years, the need for efficient and renewable cooling solutions is paramount. Solar cooling not only addresses the immediate challenge of reducing energy consumption and CO₂ emissions but also offers a long-term solution to the growing demand for cooling in residential and commercial spaces.⁷⁴

By using solar energy to power cooling systems, buildings can reduce their carbon footprint and contribute to a more sustainable future. Additionally, solar cooling can be combined with other energy-saving measures such as efficient algorithms and programming, optimized cooling and air-conditioning solutions, and the use of waste heat to further reduce energy consumption.

The commercial sector has various demands from cooling technology like climatization of spaces, chilled and hot water systems, refrigeration, among others, that can be supplied by chiller systems. Solar chillers are a subset of solar cooling technologies that utilize solar energy to drive the cooling process, significantly reducing the reliance on conventional electricity sources. These systems are particularly relevant for commercial applications, where the demand for cooling is substantial and the potential for solar energy is high. Systems with conventional refrigeration cycles and PV are also available for buildings, but mostly for the purpose of air-conditioning.

For residential buildings there are options available in both types of solar cooling, electrical and thermal. In this case these systems also show the opportunity to be combined with techniques of passive cooling, with the goal of providing complete climatization in hot weather locations in the most sustainable way possible.

Generally, there are two main types of technologies for solar air-conditioning:

- PV-powered (electrical) air-conditioning systems and solar thermal air-conditioning systems.
- In PV-powered air-conditioning systems, the electricity generated by the PV modules drives the electric compression system.

5.3.1 Solar absorption air-conditioning chillers

In solar thermal air-conditioning hot water from solar collectors is used to drive absorption or adsorption chillers (the operation of these systems is explained in the [Section 5.1.2](#)). These chillers require very little electricity for operation, compared to conventional chillers, directly transforming the thermal sun energy (heat) into cold. Therefore, they do not need batteries and require little maintenance. However, solar thermal systems are only cost-effective for larger cooling systems above 10kW capacity, because solar PV systems are cheaper.

74 Sârbu, I., & Sebarchievici, C. (2017) Introduction.



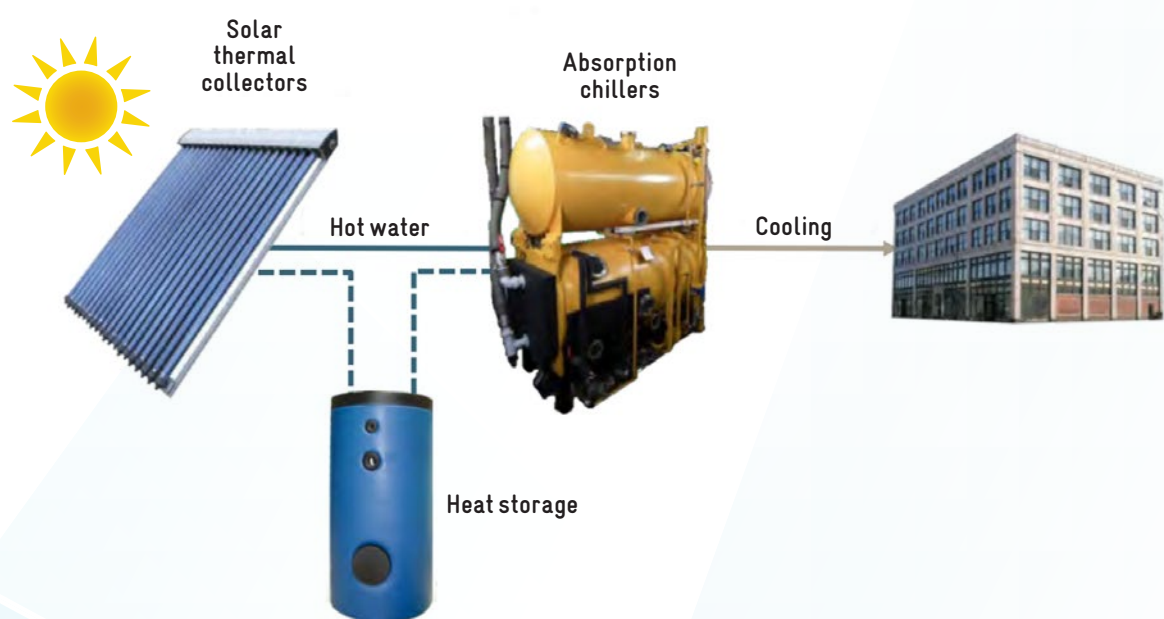


Figure 16: Absorption chiller powered by solar thermal collectors ⁷⁵

⁷⁵ GIZ (2018a) Solar Cooling for Industry and Commerce Experiences gained in Jordan.



Best Practice Example 12:

Absorption cooling for industry and commerce in Jordan

Jordan faces a rapidly growing demand for air-conditioning. Currently, the region relies on chillers with low efficiencies, refrigerants that harm the ozone layer or climate, and systems with high leakage rates. Cooling commercial buildings in Jordan contributes approximately 600,000 tonnes of CO₂ equivalent annually, comparable to the emissions from 120,000 passenger vehicles per year. However, Jordan has excellent conditions for solar cooling, a high cooling demand overlapping with high solar radiation and a small proportion of indirect radiation. In addition, electricity prices have been rising and it is mostly imported. About every second commercial building in Jordan uses a chiller system for cooling.⁷⁶

The project aimed to facilitate technology transfer through demonstration projects for solar cooling in buildings. The operation and maintenance team collaborated closely with Technical University of Berlin (TU Berlin), the provider of the absorption chiller, and Millennium Energy Industries, the local engineering firm responsible for setting up the cooling system and integrating it into the solar thermal field.

At four different project sites, thermal solar collectors have been combined with air-cooled absorption chillers. In absorption chiller systems, the thermal refrigeration cycle is driven by heat, such as industrial excess heat or solar thermal energy. As heat is removed from the indoor air through desiccant evaporative cooling, the refrigerant vapor is absorbed into another liquid. Using hot water generated by the solar thermal collectors, the refrigerant and absorber mixture is heated until the refrigerant evaporates out of the fluid. Subsequently, the refrigerant is pumped through a condenser, and the heat is released to the outside air (air-cooled). Thermal storage such as hot-water tanks or ice storage enable partial decoupling of energy production from cooling needs.⁷⁷

Lithium bromide and water serve as refrigerants in the different project sites. These systems not only cool buildings in an environmentally friendly way but can also function as heat pumps, reducing electricity costs for air-conditioning and heating costs in winter. The pilot projects

demonstrate that carbon-neutral building cooling with natural refrigerants is feasible even in regions with high ambient temperatures.

Technical University of Berlin has enhanced the systems to meet essential requirements for widespread use: the cooling process now starts at 55°C instead of the previous 75°C, the compact design reduces material usage by 40%, and significant improvements have been made to streamline system technology while maintaining efficiency close to the theoretical maximum.

All four demonstration projects in Jordan showed excellent results in terms of energy efficiency, i.e. 30 % higher efficiency compared to conventional systems, as well as lower operation and maintenance costs. Cooling systems with solar thermal collectors have high upfront costs and are typically more expensive than PV-supported systems, but they have a potential for commercial and industrial scale applications with large roof areas exposed to solar irradiation.

Recommendations for cooling systems in Jordan vary based on the roof area and exposure to solar irradiation. For buildings with a small roof area exposed to solar irradiation, a PV-supported with hydrocarbon as refrigerant compression chiller is recommended. In contrast, buildings with a large roof area exposed to solar irradiation should consider an absorption chiller with solar thermal collectors. For roofs with a high amount of shading, a conventional compression chiller with hydrocarbon as refrigerant is advisable.

Up-scaling is necessary as approximately every second commercial building in Jordan uses a chiller system, with around 5% (150 units) being broken and replaced annually⁷⁸, and these numbers are rising. Solar/geothermal hybrid cooling systems have been implemented in Oman, indicating a need for higher capacities, such as the development of 500 kW solar absorption chillers. Although costs are decreasing, further projects are required to reduce technology costs. Additionally, product packages are needed, and local production of the technology might be a viable option in the future.⁷⁹

⁷⁶ p.57 ibld.

⁷⁷ p.57 ibld.

⁷⁸ p.57 ibld.

⁷⁹ p.57 ibld.

	German Jordan University (GJU)	Petra Guest House (PGH)	Royal Culture Center (RCC)	Irbid Chamber of Commerce (ICC)
Solar System	Solar heat for heating & district heating water / Absorption Chiller Compound Parabolic Collectors			
	150 CPC, 480 m ²	114 CPC, 388 m ²	132 CPC, 449 m ²	41 CPC, 140 m ²
Heat Storage	4 x 3.5 m ³ for heating hydraulically decoupled	4 x 3 m ³ for heating/cooling hydraulically coupled	3 x 3 m ³ for heating hydraulically coupled	1 x 3 m ³ for heating hydraulically coupled
Chiller(s)	TUB absorption chiller – type Bumblebee			TUB absorption chiller – type Bee
	½ direct air-cooled compression chillers			
Reject Heat Device	Dry cooler – GEA V-bank type			
Operating temperatures	6.7 – 9°C to 14°C			
Operating hours	8 to 16	24h/7d	8 to 24	8 to 16
Cooling Capacity	160 kW			50 kW
Refrigerant and charge	Lithium bromide/water			Lithium bromide/water
GWP	0			0

Table 10: Summary table of the four solar absorption chillers implemented.



5.3.2 Solar compression air-conditioning chillers

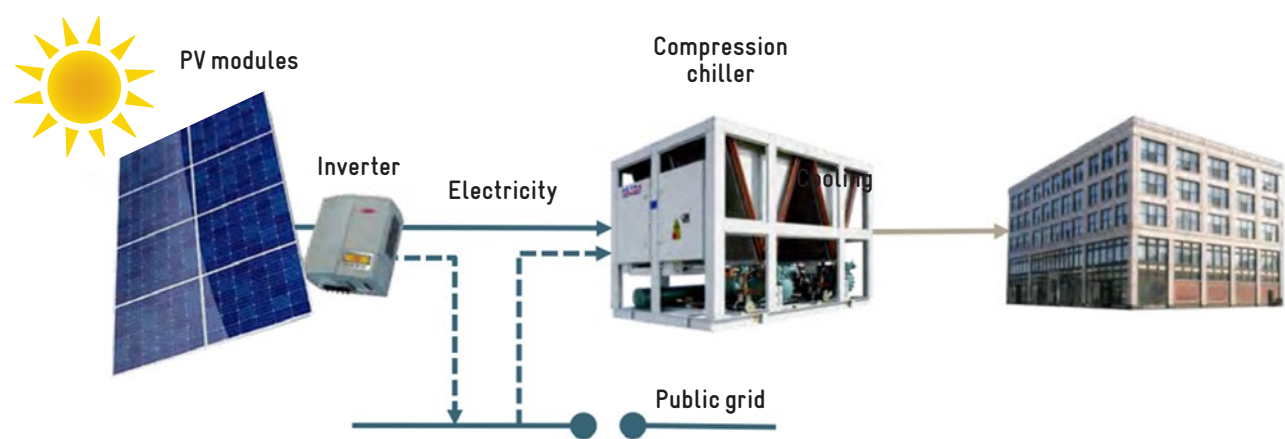


Figure 17: Compression chiller powered by hybrid solar PV or public grid ⁸⁰

80 Ibid.







Best Practice Example 13: Air-conditioning chiller powered mainly by PV in Ghana



For larger buildings or multiple rooms, indirect cooling via a chilled water loop can be used to extract the heat from the building. Under the GIZ project Sustainable Energy for Climate Protection (SustainE4Climate) at the Energy Commission of Ghana the first climate and environmentally friendly Air-Conditioning (AC) chiller has been installed in entire Africa. The project has been funded by BMZ. The project has been implemented by GIZ in cooperation with the Ministry of Energy and the Energy Commission of Ghana.

The climate and environmentally friendly chiller was installed at the nearly Zero Emission Building (nZEB) in Accra and has a cooling capacity of 115 kW and that uses the natural refrigerant R290. R290 also provides great thermodynamic properties in term of energy efficiency even in tropical climate zones such as Ghana. The entire building and its chiller are mainly (88%) powered by the

50 kWp PV system that is installed at the roof of the nZEB, reducing the indirect emissions to a minimum, thus creating a pioneer for sustainable construction. Once net metering is implemented the building will be an exporter of energy into the grid. The nZEB has 50% less environmental impact, compared to similar buildings constructed with traditional materials. This model building demonstrates how office buildings can be designed to be more energy-efficient and environmentally responsible. The objective was to minimise energy consumption and produce majority of the building's energy needs through on-site solar PV.

The design and installation of the R290 chiller has been supported by GIZ Proklima and HEAT. Installation and commissioning have been supported by international experts jointly with a local company. Capacity building (training) of local technicians and operators have been conducted to ensure a sustainable and efficient operation in future.

According to the RAC inventory⁸¹ and roadmap⁸², cumulated emissions from the RAC sector from now to 2050 will reach 338 Mt CO₂eq. The mitigation potential based on introduced best available technology (BAT) amounts to 79 Mt CO₂eq by 2050, to which R290 chillers contribute. Under the Kigali amendment HFC chillers will need to be phased out in future and Ghana has clear NDC targets for the RAC sector.⁸³

Chillers, that combine energy efficiency and natural refrigerants can reduce the total emissions by 40% in industrialised countries and by up to 60% in the Global South, not considering renewable energy sources.



Parameter	Given Case Study
Technology	Central Air-Conditioning (AC) chiller (GEG 850S HC HT2 STE Frido Indus)
Use	To cool a large office building
Gross Floor Area	920sqm (2 conference rooms (65&70-seater), offices, meeting room, staff kitchenettes, washrooms)
Cooling Capacity	115 kW
Refrigerant and charge	R290 (2 x 4 kg = 8 kg)
GWP 100 years / 20 years (IPCC 6AR)	0.02 / 0.072
Weight	2500 kg
Voltage / Hz	400 Volt 3 Phase / 50 Hz
Max Power Consumption	50 kW
Power Consumption	35.6 kW
Electrical Load per year	63MWh (88% - 56.1MWh) of the building's energy produced through PV
PV Modul Type	JKM540M-7TL4-V
Number of PV Modules	84
Total PV Peak Power	50 kWp
Inverter	SUN2000-50KTL-M0
Energy Management System	To monitor and control energy use during operation

Table 11: Air-conditioning chiller powered mainly by solar PV system in Accra, Ghana

81 GIZ (2018b) Ghana's GHG Inventory and Technology Gap Analysis for the Refrigeration and Air-conditioning Sector.

82 Environmental Protection Agency (2022) Ghana Refrigeration and Air-conditioning (RAC) roadmap.

83 UNFCCC (2021) Updated Nationally Determined Contribution under the Paris Agreement.

5.3.3 Solar PV and split air-conditioners

For smaller Air-Condition (AC) systems typically single-split ACs are used, which have a cooling capacity of up to 7 kW (24.000 BTU/h) and account for 70% of all ACs used for space cooling. A single-split AC consists of an indoor unit and an outdoor unit. The indoor unit is mounted on the wall inside the air-conditioned room. It includes an evaporator and a fan. The outdoor unit is installed outside, and it contains a compressor, condenser, fan, and expansion device. The indoor and the outdoor units are connected by refrigerant piping and electrical cables.

Green ACs need to fulfil two fundamental criteria: high energy efficiency and use of climate-friendly refrigerants. High energy efficiency in split ACs can be achieved using variable speed (also called inverter) compressors, which can be run in part load to reach or maintain the desired temperature. Two thirds of emissions from split ACs are caused by fossil fuel-based electricity consumption, and one third

is due to refrigerant leakage. Typical refrigerants used in split ACs are R22 (GWP of 1.960), R32 (GWP of 771) and R410A (GWP of 2.256). R290 (GWP of 0.02)⁸⁴ is currently the only climate-friendly refrigerant used in split-type ACs. HFOs are also a considered new alternative for AC split systems by some sectors of the industry, but it is important to remember their degradation into TFA, a PFAS type substance, as explained in Chapter 4, and therefore cannot be considered environmentally friendly.

Solar panels coupled with air-conditioning systems can be installed completely off-grid or in a hybrid mode, functioning at times with electricity provided by the grid when the solar irradiation or the storage system cannot supply the necessary energy to function. Figure 18 shows the relevant components of a solar-powered split AC system in off-grid and hybrid modes.



Solar cooling for the specific case of air-conditioning in buildings is thoroughly analysed in another GIZ publication.

⁸⁴ Clarke et al. (2022) Energy Systems. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

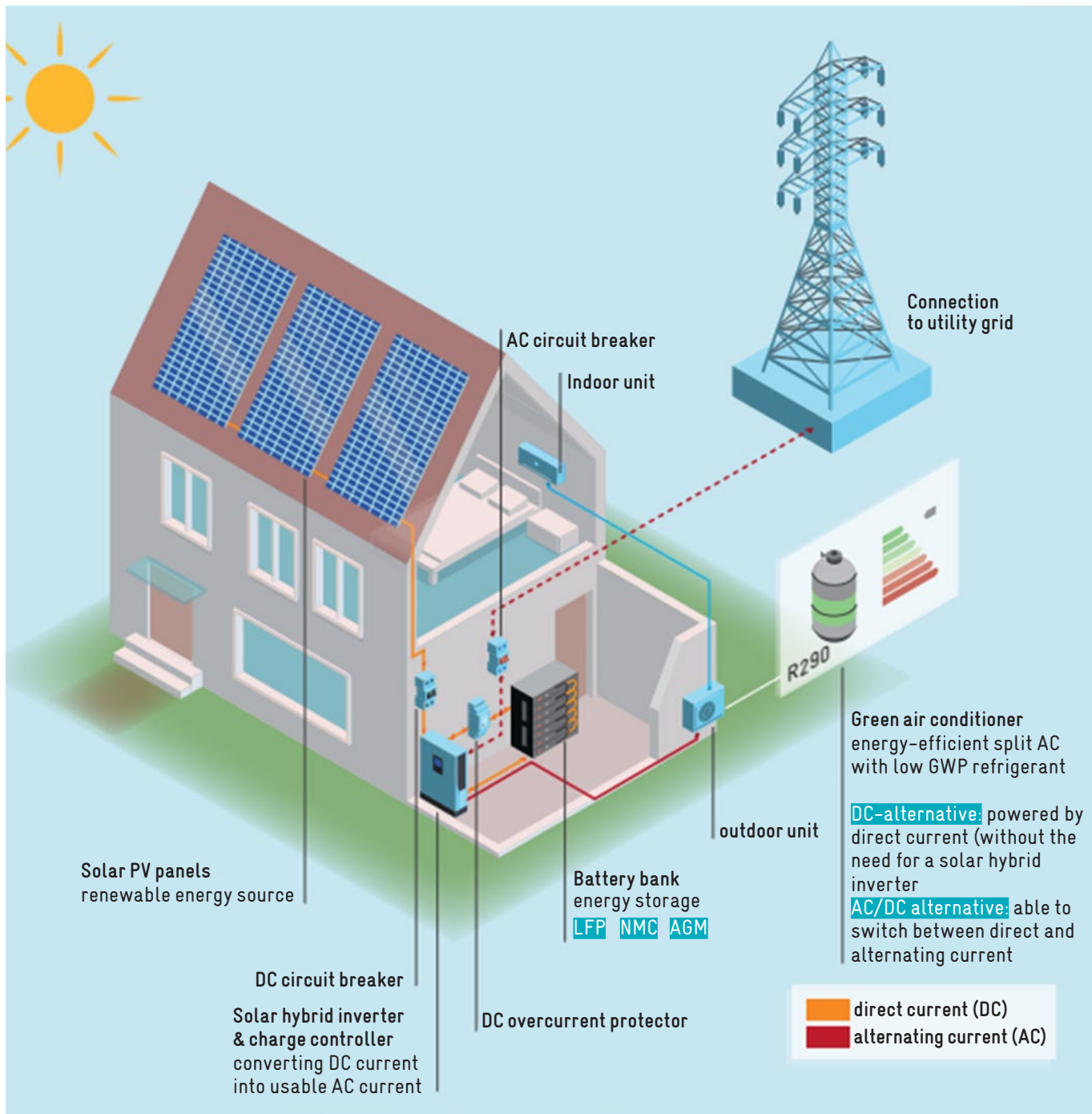


Figure 18: Components of a PV-powered split AC ⁸⁵

Best Practice Example 14: Green split AC powered by individual PV system



SelfChill developed pre-configured sets of a PV-powered R290 split AC for three different applications: on-grid, off-grid day, and off-grid night. The sets contain all necessary

components such as PV panels, inverter, circuit breaker, batteries, AC unit, and optional grid connection. The sets are suitable for rooms of an area between 17 and 30 m².

Data	On-grid	Off-grid day	Off-grid night
Power Source	220-240V-40-63 Hz, 1 Ph	220-240V-40-63 Hz, 1 Ph	220-240V- 40-63 Hz, 1 Ph
PV Capacity	2.3 kWp	3.0 kWp	3.8 kWp
PV Voltage	38.6 V	38.6 V	38.6 V
PV Current	9.1 A	9.1 A	9.1 A
Battery capacity	n.a.	4 x 125 Ah AGM 12 V	4 x 240 Ah AGM 12 V
Autonomy	n.a.	4 h	8 h
Inverter Power	5 kW	5 kW	5 kW
Inverter Voltage	48 VDC	48 VDC	48 VDC
Inverter Charging Current	80 A	80 A	80 A
Cooling Capacity	12000 Btu/h	12000 Btu/h	12000 Btu/h
Heating Capacity	13000 Btu/h	13000 Btu/h	13000 Btu/h
Max. electrical power	3.50 kW	3.50 kW	3.50 kW
Seasonal Efficiency Ratio (SEER)	8.50 Btu/hW	8.50 Btu/hW	8.50 Btu/hW
Efficiency Ratio for Cooling at 20°C	16.43 Btu/hW	16.43 Btu/hW	16.43 Btu/hW
Efficiency Ratio for Cooling at 25°C	10.36 Btu/hW	10.36 Btu/hW	10.36 Btu/hW
Efficiency Ratio for Cooling at 30°C	5.91 Btu/hW	5.91 Btu/hW	5.91 Btu/hW
Efficiency Ratio for Cooling at 35°C	3.63 Btu/hW	3.63 Btu/hW	3.63 Btu/hW
Refrigerant and charge	R290 (380g)	R290 (380g)	R290 (380g)
GWP 100 / GWP 20 (6AR)	0.02 / 0.072	0.02 / 0.072	0.02 / 0.072
Sound Power Level	50-58 dB(A)	50-58 dB(A)	50-58 dB(A)

Table 12: Technical specifications for SelfChill PV-powered split AC kits



Best Practice Example 15: Green ACs powered by centralized PV system in Uganda



The GIZ Uganda Country Office has taken a significant step towards environmental sustainability by replacing old ACs with the German eco-friendly “Blue Angel” ecolabel certified and highly efficient technology. Eighteen efficient ACs, with an A+++ energy efficiency rating, that use natural refrigerant (R290) have been successfully installed. They replaced old inefficient fixed speed AC units that utilised the synthetic refrigerants R22 or R410A, which are ozone depleting, climate harmful and pollutive refrigerants that break down to per- and polyfluoroalkyl substances (PFAS) and Trifluoroacetic Acid (TFA) impact.

The change of ACs happened in cooperation with the GIZ Green Cooling Initiative project that supported the procurement, organised the training, supervised the installation and is monitoring the energy and cost savings as well as the CO₂ mitigation. By opting for R290 ACs, GIZ Uganda is making a significant contribution to reducing its carbon footprint and actively supporting sustainable and green initiatives.

The GIZ office installed a 40 kWp PV system on their premises to produce clean energy, which is supplying the ACs, the electric charging station for the GIZ electric car as well as other electricity demand for lights and computers of the country office. The remaining office’s energy demand is supplied by the grid which includes a large proportion of renewable sources.

GIZ’s internal sustainability strategy aims that by 2025, 60 % of all ACs in GIZ country and project offices globally use the refrigerant R290 and are highly energy efficient. Apart from contributing towards this target, the project fully fulfilled the following GIZ sustainability indicators: climate mitigation and mobility, sustainable procurement, resource efficiency regarding energy efficiency and cost efficiency, as well as the use of sustainable consumables and equipment. Consequently, the GIZ country office in Uganda is nearly CO₂ neutral. As a result, the project has been awarded by the GIZ Sustainability Award 2023.



5.4 Insulation materials

When discussing energy efficiency, the conversation tends to gravitate towards the compressor, the presence or not of an inverter for the compressor operation, other electrical components, and the circuit of the refrigerant. Insulation can be overlooked, and many solutions have been deemed as standard in different sectors. Yet it is important to aim for better insulation, favouring foams with natural refrigerants or considering novel approaches with different materials which in many times happen to be organic and readily available without that much processing as foamed refrigerant.

Traditional commercial insulation materials normally contain air or other blowing agents in the form of little bubbles to reduce their thermal resistance. Some of these blowing agents can still contain molecules classified as Ozone Depleting Substances (ODS) and also have a high GWP, like HCFC_{141b} (GWP 860; ODP 0.11). These substances are slowly released to the atmosphere over time, as the trapping material loses its initial mechanical properties, contributing to global warming and damaging the ozone layer. Moreover, most countries do not have foam destruction facilities and therefore, at the end of life (EoL) these emissions are released into the atmosphere. In many developing countries insulation foam containing the blowing agent R141b even some new cooling appliances. As an example, the insulation foam of one standard small cold/freezer room (14 m³) includes 6.3 kg of the blowing agent R141b, meaning an equivalent to around 4.9 tons of CO₂ as well as 0.693 g ODP. There are climate-friendly alternatives, which use ultra-low to zero GWP blowing agents such as hydrocarbons (e.g., pentane, isopentane, cyclopentane), water-blown or liquid CO₂. Their environmental impact is very low to almost zero⁸⁶. Cyclopentane (C₅H₁₀) is the most used blowing agent for insulation panels, which has a GWP of 11. Many foam producers have already converted or will convert in near future. Some newer generation insulation panels can also contain hydrofluoroolefin (HFO) blowing agents, with an ultra-low GWP, but are harmful to the environment due to PFAS and TFA.⁸⁷ Consequently, it is highly recommended to only purchase panels/foams that contain insulation material that is blown with

natural blowing agents (like HC). Other local and natural insulation materials can be used depending on the application, budget and cooling demand, see e.g., the study on local insulation materials available in Zambia.⁸⁸ For all the above reasons, insulation panels containing ozone, climate or environmentally harmful blowing agents (HCFCs, HFCs, HFOs) should be avoided and it is strongly recommended that only insulation materials with natural blowing agents, e.g., cyclopentane (C₅H₁₀), are purchased. Other natural insulation materials might also be a solution but should be carefully evaluated according to technical requirements.

Insulation is the combination of materials with the right selection of properties and dimensions with the aim to slow down heat transfer between a climatized space and the environment. Heat transfer can happen via three mechanisms, always looking to establish a thermal balance, moving from high temperature to low temperature until both spaces and/or materials have the same heat quality (reflected as same temperature). Conduction happens in solids, as heat is transferred by neighbouring atoms and molecules as energy and vibration. Convection is the main mechanism of transfer in liquids and gases, combining both the effects of conduction and fluid flow. Radiation is the third type of mechanism, and it does not need a medium to happen (as in the vacuum in space). Radiation is the emission of electromagnetic radiation, where photons carry energy which then can be absorbed, reflected, or transmitted by another body.

The design of a cooling application needs to consider both the insulating material and the configuration of the climatized space. The insulating material is characterized by its conduction coefficient, but the U-value is obtained when considering the interaction of the material with all three heat transfer mechanisms, thickness, and the coating material (wall). The reciprocal value of U, R-value per inch of thickness, is usually the value to look for when selecting an insulating material. The selection of the coating material is contingent to the strength of the bond that it has to the different insulating materials.

86 GIZ (2010, 2012). Natural Foam Blowing Agents.

87 ATM0sphere (2023) Overview of PFAS refrigerants used in HVAC&R and relevance of refrigerants in the PFAS Restriction Intention. Everitt, N. (2023) PFAS ban affects most refrigerant blends.

88 GIZ (2019b) Feasibility Report: Insulation Materials and Solar Cooling in Zambia.

Type of Material	Description	Examples	Description
Organic	Typically derived from natural, renewable resources sourced from animals or plants. To enhance their bonding strength and fire resistance, these materials are often treated or combined with synthetic fibers. They are generally more eco-friendly compared to mineral or synthetic alternatives.	Timber	Timber's cellular structure contains small air pockets that trap heat, resulting in low thermal conductivity. Lightweight timber is the most effective insulator, as thermal conductivity rises with density. R-value generally ranges from 3.4 to 4 per inch.
		Cellulose	Considered one of the most eco-friendly types of insulation. Made from recycled materials such as cardboard, paper, and similar substances, and is available in loose form. Cellulose insulation has R-values ranging from 3.1 to 3.7 per inch of thickness. Has great resistance to fire.
Mineral	Composed of inorganic substances like stone, sand, or lime, which can be either synthetic or natural. These materials offer inherent fire protection, eliminating the need for additional treatments.	Mineral wool	Encompasses various types of insulation. It can refer to glass wool, which is fiberglass made from recycled glass; rock wool, which is insulation derived from basalt; or slag wool, which is produced from steel mill slag, which is the most common. R-value ranges from 2.8 – 3.5.
		Fiberglass	It is produced by weaving fine strands of glass into an insulating material. The primary drawback of fiberglass is the handling risk, since it generates glass powder and tiny glass shards. R-value can be found in the range of 2.35 – 2.45.
Synthetic	Cost-effective and resistant to rot. These materials are made from plastics that are processed into rigid foams. Despite being less sustainable than organic or mineral alternatives due to their petroleum base, synthetic insulation materials are notably durable and resilient.	Polystyrene	Thermoplastic foam available in two types: expanded (EPS) and extruded (XEPS). These types vary in performance ratings and cost, with XEPS being more expensive and less permeable to moisture. EPS has an R-value ranging from 5.00 to 5.90 and XEPS from 5.0 to 5.6.
		Polyurethane	Highly effective method of insulation. Polyurethane foams utilize refrigerant gases as a blowing agent. They are relatively lightweight, with test samples showing R-values ranging from 8 to 10 per inch of thickness. Additionally, this type of insulation is fire-resistant.

Table 13: Types and examples of insulating materials⁸⁹

It is important to note that when considering polyurethane, one of the most used solutions, natural refrigerant cyclopentane is the only solution that is sustainable and friendly to the environment, fitting the Green Cooling approach promoted by GIZ Proklima.

Other than insulation material of climatized space, the problem of external heat input, though frequent door openings, remains. Since these are indispensable for loading and unloading the cold room, logistical activities must be well planned and restricted to a minimum. Another factor to be considered is the heat input through freshly harvested produce and staff inside the cold room. Therefore, precooling the goods is recommended.



⁸⁹ GIZ (2022b) Feasibility Report: Insulation Materials and Solar Cooling in Zambia.

6 Guidance on procurement

For those intending to procure a solar cooling system, the following guidelines are paramount:

Genuinely sustainable, climate and environmentally friendly solar cooling technologies should adhere to the following criteria:

- Exclude any HCFC, HFC or HFC/HFO blends (F-gas free) refrigerants, as these substances possess a high Global Warming Potential (GWP) and consequently a substantial climate impact.
- Avoid insulation materials / panels containing HCFC or HFO blowing agents.
- Refrain from using refrigerants or blowing agents that include per- and polyfluoroalkyl substances (PFAS), also called “forever chemicals”, which most HFCs and HFOs contain. PFAS are notorious environmental contaminants linked to adverse ecological and human health effects.
- Do not employ refrigerants or blowing agents that degrade into Trifluoroacetic Acid (TFA), an ultra-short chain type of PFAS.
- Avoid the use of large batteries, as their production and transportation typically result in significant CO₂ emissions. Moreover, batteries are environmental detrimental, with lithium-ion batteries releasing PFAS, and most developing countries in the Global South lack sufficient recycling facilities. The necessity to replace batteries after several years incurs additional high investments costs and can pose a significant sustainability risk.

Consequently, for a solar cooling system to be truly sustainable and climate-friendly, the technology should be:

- **F-gas and PFAS free,**
- **utilize ultra-low GWP natural refrigerants (e.g. R290, R600a, CO₂ or NH₃) for cooling systems,**
- **use ultra-low GWP natural blowing agents for the insulation material/panels (e.g. cyclopentane),**
- **ideally incorporate thermal energy storage systems (e.g. ice banks).**

Donors and implementing agencies should exclusively fund sustainable solar cooling solutions. An exemplary initiative is the approved Post-Harvesting Solar-Cooling project in Kenya, commissioned by the Mitigation Action Facility, which aims to deploy 1,000 solar-powered cold stores utilizing natural refrigerants in rural and peri-urban areas.⁹⁰

Moreover, public procurement in many countries constitutes a large share of solar cooling equipment. Meanwhile Green Public Procurement (GPP) has immense potential to demonstrate and promote green solar cooling solutions. Despite the massive potential to reduce operational costs and GHG emissions, and its allegedly lighthouse function, public entities often encounter challenges in procuring state-of-the-art solar cooling technologies. Advancing GPP standards is the quintessential sustainable way forward (avoid and shift approach), and actions can be undertaken through the promotion of GPP for green solar cooling solutions, employing climate-friendly refrigerants and insulation materials as well as thermal storage.⁹¹



⁹⁰ Mitigation Action Facility (n.d.) Kenya – Post-Harvesting Solar-Cooling.

⁹¹ GIZ (2021c) Green Cooling in Public Procurement.

7 Conclusions

In numerous low and lower-middle-income countries, fragmented cold chains and limited access to reliable electricity pose substantial challenges. The wastage of horticultural produce is a significant concern in these regions, with substantial percentages of crops being lost due to inadequate storage and cooling facilities. Enhancing solar-powered cold chains can mitigate crop damage and spoilage, thereby reducing postharvest losses. Sustainable solar-powered cooling systems offer a decentralized solution that can operate independently of the grid, ensuring consistent cooling even in remote areas. This is particularly beneficial for communities where traditional energy infrastructure is either lacking or unreliable. Additionally, solar cooling solutions can yield economic benefits by enabling farmers to store their produce for extended periods, thereby avoiding distress selling and obtaining better market prices. This is particularly impactful for marginalized groups, such as women and smallholder farmers, who often lack access to traditional storage facilities.

The novelty of the systems, the off-grid possibilities of solar, modularity and scalability, in combination with affordable economical schemes, can considerably enhance the robustness, strength and the reliability of cold chains in rural settings across the world. This approach not only reduces emissions but also promotes the progress of various SDGs.

Solar cooling, in conjunction with Green Cooling, is an excellent approach to avoid emissions from two primary sources of a cooling device during its operation: emissions from refrigerants (direct) and emission from energy consumption (indirect). This publication reviews the principal sustainable solar cooling technologies currently in use, emphasizing the use of ice banks as a thermal storage option. The publication showcases various sustainable, climate and environmentally friendly solar cooling technologies for different types of applications, as well as various best practice examples.

This publication contends that sustainable, climate and environmentally friendly solar cooling technologies should adhere to the following criteria:

- Exclude any HCFC, HFC or HFO (F-gas free) refrigerants, as these substances possess a high Global Warming Potential (GWP) and consequently a substantial climate impact.
- Avoid insulation materials / panels containing HCFC or HFO blowing agents.
- Refrain from using refrigerants or blowing agents that include per- and polyfluoroalkyl substances (PFAS), also called “forever chemicals”, which most HFCs and HFOs contain. PFAS are notorious environmental contaminants linked to adverse ecological and human health effects.
- Do not employ refrigerants or blowing agents that degrade into Trifluoroacetic Acid (TFA), an ultra-short chain type of PFAS.
- Avoid the use of large batteries, as their production and transportation typically result in significant CO₂ emissions. Moreover, batteries are environmental detrimental, with lithium-ion batteries releasing PFAS, and most developing countries in the Global South lack sufficient recycling facilities. The necessity to replace batteries after several years incurs additional high investments costs and can pose a significant sustainability risk.

Consequently, sustainable, climate and environmentally friendly solar cooling systems should be F-gas and PFAS free, and use only ultra-low GWP natural refrigerants (e.g. R290, R600a, CO₂ or NH₃) for their cooling systems and ultra-low GWP natural blowing agents (e.g. cyclopentane) for the insulation material/panels. Moreover, the use of thermal energy storage systems, such as ice banks, is highly recommended.

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