Environmentally and climate-friendly solar-powered walk-in cold rooms

Technical guidelines

PROKLIMA NATURALLY COOL

green cooling initiative

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Registered Offices
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Address
Dag-Hammarskjöld-Weg 1-5
65760 Eschborn, Germany
T: +49 6196 79-0

E: info@giz.de
I: www.giz.de/proklima, www.green-cooling-initiative.org

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Responsible:
Philipp Denzinger (GIZ Proklima)
Dr. Rokia Goldmann (GIZ WE4F)

Authors:
Alfonso Valle Rey (GIZ WE4F)
Philipp Denzinger (GIZ Proklima)

Acknowledgement for Review:
Kilian Blumenthal, Zelalem Girma, Vanessa Knies, Till Serafimov, Lara Teutsch, Anja Werntges (GIZ),
Victor Torres Toledo (Solar Cooling Engineering)

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On behalf of:
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Table of contents

Tables

Abbreviations

AGM	Absorbent Glass Mat
Ah	Ampere hours
BMU	German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
BMZ	German Federal Ministry for Economic Cooperation and Development
C-Si	Carbon-Silicon
Cd-Te	Cadmium-Tellurium
CE	Conformité Européenne (European health & safety product label)
CEC	California Energy Commission
CIGS	Copper Indium Gallium Selenium
CO_2	Carbon dioxide
CO_2eq.	Carbon dioxide equivalents
CPV	Concentrator Photovoltaic
EoL	End of Life
FLA	Flooded Lead Acid
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
GWP	Global Warming Potential
HCs	Hydrocarbons
HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofluorocarbons
HFOs	Hydrofluoroolefins
HPMPs	HCFC Phase-out Management Plans
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
kWh	kilo Watt hours
LFP	Lithium Iron Phosphate
MP	Montreal Protocol
MPPT	Maximum Power Point Tracking
NH_3	Ammonia
NMC	Nickel Manganese Cobalt
NOCT	Normal Operating Cell Temperature
ODP	Ozone Depletion Potential
ODS	Ozone Depleting Substances
Pmax	Temperature coefficient (solar panels)
PV	Photovoltaic
PE	Protective Earth
SDGs	Sustainable Development Goals
TFAs	Trifluoroacetic Acids
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
VRFB	Vanadium Redox Flow Batteries
WEEE	EU Waste of Electrical and Electronic Equipment policy
WE4F	Water and Energy for Food

Background and purpose of these guidelines

As needs for food conservation, thermal comfort or safe medicines access grow, the numbers of solar powered walk-in cold rooms increase every year. Many people and organisations believe that by constructing a solar walk-in cold room, they are green, environmentally and climate-friendly. However, many technologies are still having quite some negative environmental and climate impacts, which often eliminates the positive side of using solar energy to run the system. Cooling technologies currently constitute about 10% of global energy consumption [1] and a significant share of global GHG emissions. Refrigerants of the cooling system and blowing agents of the insulation materials often used are harmful to the ozone layer and/or have a high global warming potential and therefore have a negative impact on the climate. In addition, solar walk-in cold rooms often use batteries that have high embedded CO_2 emissions from manufacturing and transport and negatively affect the environment at the end of life.

Within the policy framework of the UNFCCC (Paris Agreement) and the Kigali Amendment under the Montreal Protocol and for the achievement of the Sustainable Development Goals (SDGs) 2, 7, 9, 12 and 13 solar cooling solutions will constitute a major pillar of action.

The following technical guidelines aim to provide a general overview on the most important related aspects to minimize the environmental and climate impacts and contribute to sustainability of solar walk-in cold rooms.

Picture 1: Polycrystalline solar panels, © Kilian Blumenthal, GIZ

1 Energy source: technologies

Solar cooling has become much cheaper in the last decades. Several studies report that off-grid solar photovoltaic (PV) systems are already cost-effective for a lifetime basis and savings compared to traditional diesel generators can go up to 60-65% [2,3,4,5]. PV cooling systems are easily scalable and especially suitable for places with high irradiation values (3 kWh/m2 or higher) over the year.

Solar sorption cooling technologies 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 and a very low maintenance is required [6]. This technology is cost-effective at large scales, when ideal climate conditions are met (mostly Mediterranean conditions with high temperatures and a high sun irradiation availability all over the year). These systems are suitable for large scale industrial processes where a big amount of residual heat is available, to be combined with the heat generated via solar thermal [7,8]. Before the reduction of PV cell prices, small scale absorption chillers also seemed like a very promising option for small off-grid refrigeration appliances. However, PV off-grid system prices leave now very little space for this kind of technology [2]. Only a few companies offer very small-sized cold boxes for food and vaccines preservation [32].

Given the high energy consumption of refrigeration systems, a low cost and above all a reliable and constant source of energy is needed. Fossil fuels are subject to constant price fluctuations, and their access is not always guaranteed. In addition, the reliability of diesel generators does not compare to that of a photovoltaic system.

Grid power could be a solution, but again access is not universal, some rural areas still do not have access to the grid and when they do, reliability is not assured. Prices are also highly variable from country to country. For all these reasons, off-grid solar systems are one of the safest alternatives. Among the various solar technologies, photovoltaic is currently the most cost-effective, and the one recommended within this guideline [2,3,4,5].

1.1 Photovoltaic cells and inverter technologies

When choosing Photovoltaic (PV) panels, quality and uniformity must be considered. They can provide electricity with a good performance rate for more than 25 years, so it might make sense to invest in high quality more lasting PV cells. Uniformity between panels is key to achieve the maximum performance. One single panel being slightly different in terms of performance due to poor quality standards or to a manufacturing defect, will reduce the performance of the rest of the panels. Higher quality standards reduce these differences between panels.

Mono and polycrystalline PV panels complying with the technical specifications and certifications set out in **Annex 1** are recommended.

With regards to the inverter, it is worth mentioning that there are systems that use DC compressors and can therefore be directly connected to the solar panels. These compressors are generally less popular than AC compressors and therefore there is a smaller supply on the market, usually of small to medium power. In this case, an inverter is not necessary, making the initial investment smaller, having less environmental impact and potentially less of a source of technical problems. In this case, it is also recommended to instal an Maximum Power Point Tracking (MPPT).

When choosing an AC system where an inverter is needed, Sine Wave inverters with European Efficiency or California Energy Commission (CEC) efficiency higher than 93% and at least IP65 protection are recommended. It should have a safety certification provided by an independent testing laboratory.

As it is much more cost effective and sustainable, it is recommended that the MPPT is also included in the inverter. In addition, it is also important to consider any further expansions that the system will require, like for example multistring inverters allowing solar modules to be installed at different tilt angles and directions (one set-up per string).

One may also want to consider hybrid inverters that allow for connecting the system to the national grid (in case it arrives in the area of system deployment) or generator (in case the solar irradiation is low). If the cooling system gets connected to the grid, the off-grid solar-PV system can still be used as a back-up in case of power outages / power fluctuations.w

It is equally important that the inverter has the following protections: overcharge protection, deep discharge protection, short-circuit protection of load and module, reverse polarity protection via internal fuses, overtemperature and overload protection, audible alarm, PE connection.

Further recommended requirements for the **inverter** are summarised in **Annex 1.**

Picture 2: Batteries from a PV solar system, © Kilian Blumenthal, GIZ

2 Batteries and thermal storage

PV systems provide a continuous source of electrical energy (depending on solar radiation) throughout the day. To provide cooling at night, an energy storage system is required.

2.1 Battery-based energy storage

As it is required to store a large amount of energy, batteries are currently still the most widely considered option. They are however very polluting: for example, around 100 research papers estimate climate impact from Li-ion batteries manufacturing ranging from 39 kg CO_2eq./kWh to 196 kg CO_2eq./kWh. Based on these numbers, calculating the embedded emissions from just manufacturing a 1000Ah battery from a 21m³ walk-in cold room would mean the same CO_2 emissions to a range between 2,950 km and 22,350 km driven by a diesel car consuming 5 litres per 100 km [10]. This does not only happen with Li-ion batteries, and end-of-life pollution is not yet considered.

Two main types of batteries are commercialized for solar off-grid applications: lead-acid batteries and Li-ion batteries. Within lead-acid batteries, flooded lead acid (FLA), absorbent glass mat (AGM) and gel batteries are found.

There is no better type of battery for different uses. Different technologies will perform better (technically or economically) in specific situations. As an example, flooded lead-acid batteries would be mostly recommended as a backup power storage, for power outages or failures. For demand charge applications, lithium batteries are better not only because they last longer (more cycles), but also because they can be discharged up to almost 100% (deep cycling) without dramatically reducing their lifespan. FLA batteries could also be used for the same applications, but they will require maintenance (water-filling every 1 to 3 months), they should not be discharged lower than 50% (would reduce their lifespan) and still in the best conditions they will not last half as long as Li-ion batteries.

Within lead-acid batteries, AGM and gel batteries solve some problems of FLA, supporting deep cycling, lasting a little longer and having no maintenance.

Gel batteries perform very well in very hot environments and are more suitable than AGM for deep cycling and for longer and lower current cycles. However, these batteries are very delicate during charging and a charger that is not properly adjusted or is not suitable for the battery can damage the battery prematurely.

AGM batteries, on the other hand, are cheaper than gel and last slightly longer, they are also the most impact and vibrations resistant and can charge and discharge quicker. AGM batteries are better for applications where high discharge currents are needed. Despite working worse than gel in hot environments, AGM batteries still perform well under 32°C [34, 35].

In view of the above, for solar off-grid cooling systems, AGM batteries are recommended due to their good enough deep cycling capacity, affordability and resistance (compared to gel). Even though Li-ion batteries are generally much more difficult to recycle and are at least twice as expensive they are still a good alternative to AGM batteries, as they last longer than AGM and are good in deep cycling.

Table 1. Comparison of battery characteristics relevant for end-of-life management strategies [24, 34, 35, 36].

Type	Approx. purchasing price (120Ah battery)	Expected lifetime (years)	Recycl-ability	Complexi-bility of recycling	Profitability of recycling	Toxicity potential	Safety risk in use-phase
Lithium-ion	high (≈ 750 USD)	10-15	medium	high	very low	medium	low
Lead-acid: Gel	low (≈ 200 USD)	Up to 6	very high	medium	high	very high	medium
Lead-acid: AGM	Low (≈ 175 USD)	Up to 6	very high	low-medium	high	very high	medium
Lead-acid: flooded	very low (≈ 110 USD)	3-5	very high	low-medium	high	very high	medium/ high

2.2 Thermal energy storage

Thermal storage (or here: ice storage) refers to storing excess energy that is captured during the day in a thermal form, e.g., by cooling down a medium. Excess electricity can be used during the day to create ice that will allow cooling at night, presenting big advantages over traditional batteries. It can be built within a low budget and at the end of its life, it will be easy to recycle and will result in a low pollution footprint. It will not reduce its performance over time, and it will not need to be replaced after 10 years if durable materials are used. It also requires almost no maintenance. It is recommended that the cooling unit that produces the ice contains an ultra-low GWP refrigerant (normally R-290 or in some applications also R-600a). The refrigerant used for the thermal storage system can be water, salt-water or glycol-water based, all being good options compared to batteries. Ethylene glycol has been shown to have little environmental impact [11]. It is important to mention that ethylene glycol is not food safe and therefore should not be in contact with stored food or ice generated [42]. The use of propylene glycol is therefore recommended if a glycol-based system is chosen, having similar environmental impacts to ethylene glycol [18]. However, water or saltwater are the preferred options compared to glycol because of their wide availability and proved environmental safety in the event of a leakage. When a thermal storage is used, the refrigerant circulates to a heat exchanger, where air is cooled down and transported (e.g. by a fan) to the product.

An intelligent control system is crucial to control batteries and/or thermal storage. The compressor speed (cooling power) together with pumps, fans and/or other elements varies depending on several conditions such as ambient temperature, cold room temperature, battery voltage, irradiation, etc. It is recommended that such a system is installed and optimized to achieve the desired temperatures while consuming the least amount of energy.

Cold thermal storage will always be able to meet the cooling demand for temperatures above freezing. However, a system with only a thermal storage can easily lead to an oversized PV-array and also oversized compressors to produce enough ice during the day. Small batteries (despite being not so "green") in combination with thermal storage is usually the most economical option, depending on the prices of the different components.

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.

It is highly recommended to include thermal storage at least in addition to batteries, if they cannot be avoided. However, the optimal sizing of this thermal storage and of the batteries must be calculated on a case-by-case basis.

Annex 3 provides further guidance on technical specifications for batteries and thermal storage systems.

Picture 3: R600a compressors and ice storage solar cold room, © SelfChill Innovation Center, Germany

Picture 4: R290 Monoblock, © Mariana Cerdas Gutierrez, GIZ

3 Cooling system and refrigerants

Many solar cooling technologies still are usually equipped with refrigeration units using conventionally hydrofluorocarbons (HFC) refrigerants with high Global Warming Potential (GWP) values (see table below). The Global Warming Potential metric measures each greenhouse gas's ability to trap heat in the atmosphere compared to CO_2 [38]. For example, one solar walk-in cold room equipped with a small cooling unit containing only 0.5 kg of the refrigerant R404A, would be equivalent to 3604 kg of CO_2 over a period of 20 years in the atmosphere, if this gas was released. 1kg of R134a would be as harmful as 4144 kg of CO_2 over a period of 20 years.

However, natural refrigerants with ultra-low or even zero GWP are also available for all types of cooling solutions. CO_2 (R744) and Ammonia (R717) have a GWP of 1 and 0, respectively. However, they are mainly used in large-scale installations. Therefore, we will focus on refrigerants that are currently used in small off-grid solutions.

Hydrocarbon refrigerants like R600a (iso-butane) or R290 (propane) are natural refrigerants with an ultra-low GWP (0.072 over a period 20 years for propane). R600a or R290 are used in conventional domestic and commercial refrigeration at a large scale globally. They have excellent thermodynamic properties, which results in high energy efficiency even at high ambient temperatures. However, they are flammable and must be handled with care by trained technicians. Flammability risks are much lower when the application is smaller and consequently only contains little volumes (charge) of refrigerants. If the application is installed outside the risk of flammability is very low to almost zero. There are many monobloc or split cooling systems available in different sizes that use R290 as a refrigerant (see table 2). For a standard small or medium size refrigerated room, low quantities of refrigerant are required (as little as 150 g – equivalent to the average charge of a large domestic refrigerator). Depending on the application, additionally some refrigerant is required for the ice storage system.

Hydrofluoroolefins (HFOs) like R1234yf also have ultra-low GWP and are suitable for replacing some HFCs. However, some studies suggest that the degradation products of HFOs, trifluoroacetic acids (TFAs), can have a negative effect on the environment, organism, ground water and human health [14]. Others argue they have a neglectable impact [15]. Being unknown what environmental impact TFAs will have in 100 years, it is preferrable to avoid its use if possible.

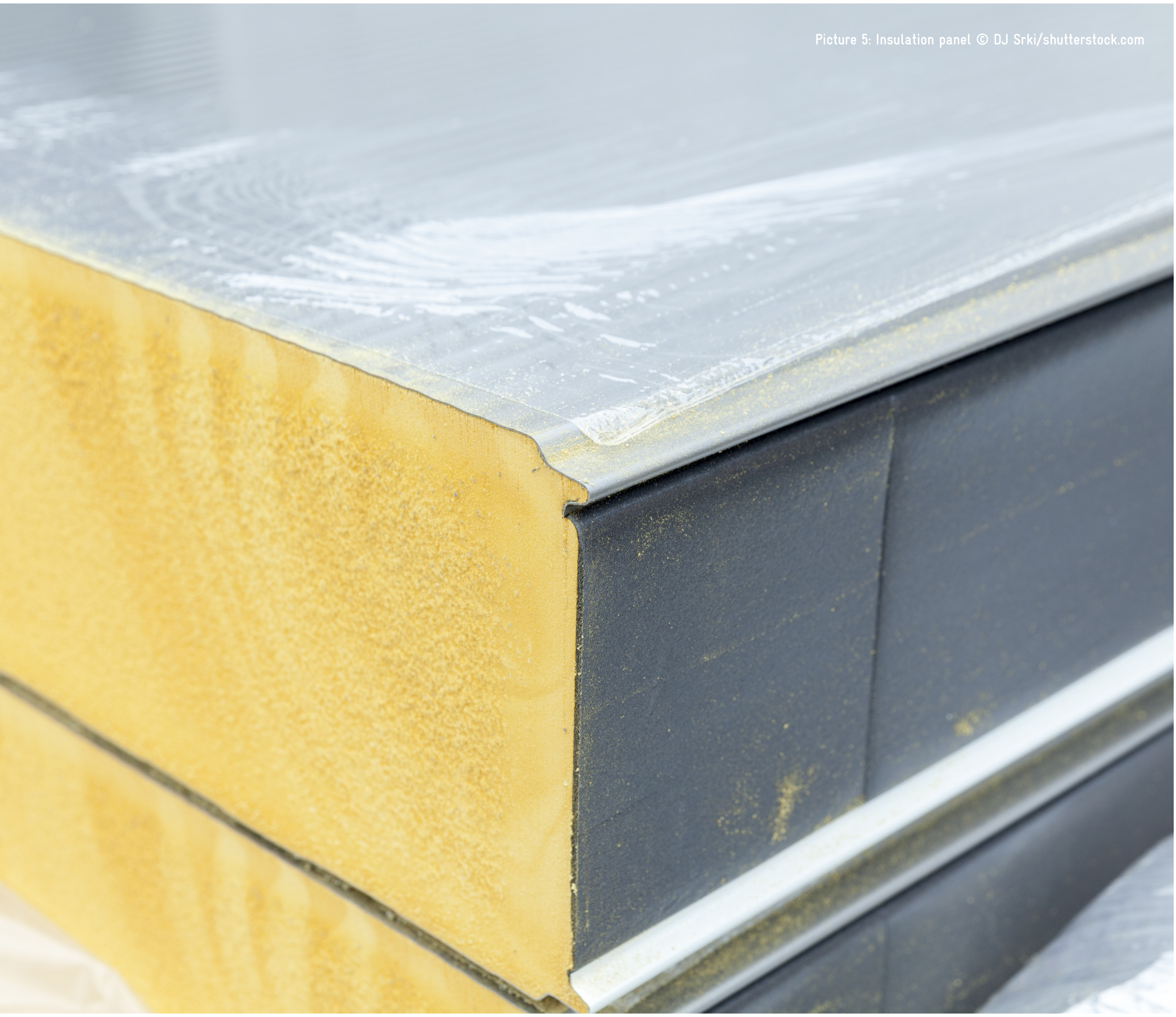
In addition to cold storage needs, lower temperatures are also required for the preservation of fish or meat. However, high installed power and many batteries are required to power freezing chambers. A more accessible and easier to implement alternative is the production of ice for the preservation of these types of products. Ice production machines are more adaptable for off-grid solutions and require less power.

R404A is very popular for ice making machines, but it has a GWP of 7208 CO_2eq. over 20 years. R410A or R507A are also used in ice machines, but their GWP values remain high. Currently, different companies use R290 as a refrigerant for ice-cooling machines powered by PV [40, 41]. We strongly recommend the use of R290 for ice production in off-grid solar systems. However, some companies also use R600a for smaller ice production capacities powered by PV.

Annex 3 provides guidance on technical specifications for cooling systems.

Table 2 GWP values for relevant conventional and climate-friendly refrigerants for solar cooling technologies. IPCC AR6, 2022 [39].

Refrigerant	Type	GWP equivalent 20 years (IPCC 6th AR) [39] 1kg = kgs CO_2eq.	GWP equivalent 100 years (IPCC 6th AR) [39] 1kg = kgs CO_2eq.	ODP
R22	HCFC	5690	1960	0.005
R404A	HFC	7208	4728	0
R410A	HFC (blend)	4715	2256	0
R452A	HFC	4273	2292	0
R449A	HFC/HFO (blend)	3321	1435	0
R134a	HFC	4144	1526	0
R717	NH3	0	0	0
R744	CO_2	1	1	0
R290	HC	0.072	0.02	0
R600a	HC	0.022	0.006	0



Picture 5: Insulation panel © DJ Srki/shutterstock.com

4 Insulation panels

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 HCFC141b (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 is still produced and sold and therefore even some new walk-in cold rooms can potentially still contain R141b. Besides this, R141b is probably still used in the USA for some appliances and insulation material of cold rooms. 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 CO_2 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 CO_2. Their environmental impact is very low to almost zero [17]. Cyclopentane (C5H10) is the most commonly 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 e.g., R1234ze, with an ultra-low GWP, but because of the possible impacts from HFOs previously commented, this guide recommends purchasing foams containing insulation material blown with natural blowing agents (like HC), more likely to have no negative impact at all.

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 [37].

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 (GWP<12), e.g., cyclopentane (C5H10), are purchased. Other natural insulation materials might also be a solution but should be carefully evaluated according to technical requirements.

Picture 6: Insulation Panel, © Depositphotos/marsan

Picture 7: Technicians training, © Jefferson Costa, GIZ

5 Operation, maintenance and spare parts

5.1 Operation and maintenance

Environmentally and climate-friendly technologies should not be implemented without first considering the sustainability of the project itself. For a successful implementation, the availability of a local expertise capable of maintaining the system in optimal conditions throughout the life of the project is vital.

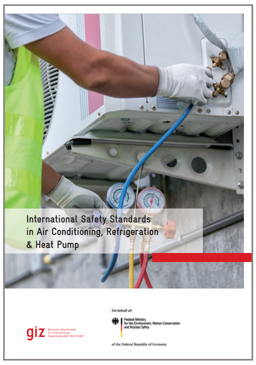
To ensure the availability of technical staff, in the field, especially in developing countries, capacity development measures and trainings should be facilitated.

As a general recommendation, only trained technicians (and companies) should install, service and repair the solar system, to ensure the best possible performance and avoid safety hazards or minimize environmental and climate impact.

When it comes to the cooling systems, also only qualified and certified RAC (Refrigeration and Air Conditioning) technicians (and companies) shall perform the installation, maintenance, repair and de-commissioning of cooling units containing refrigerants, according to international best practice standards. In many countries there are already domestic and commercial refrigerators and freezers that use hydrocarbons (R600a and R290) and RAC technicians know how to service and repair them. These refrigerants have peculiarities that require specific handling know-how. Under the national HCFC Phase-out Management Plans (HPMPs) of the Montreal Protocol, many trainers and technicians have already received trainings on hydrocarbons. Nevertheless, additional trainings according to international best practice and standards are highly recommended and should be planned when promoting solar walk-in cold room technologies.

Apart from proper maintenance procedures and trained technicians, the correct operation of the walk-in cold room is essential. Again, we recommend that only trained operators operate the cold room.

We strongly recommend developing operational and maintenance plans with well-defined maintenance frequencies for each of the components and technologies used. In addition, we also recommend that there is a financial plan for operational and maintenance costs incurred.



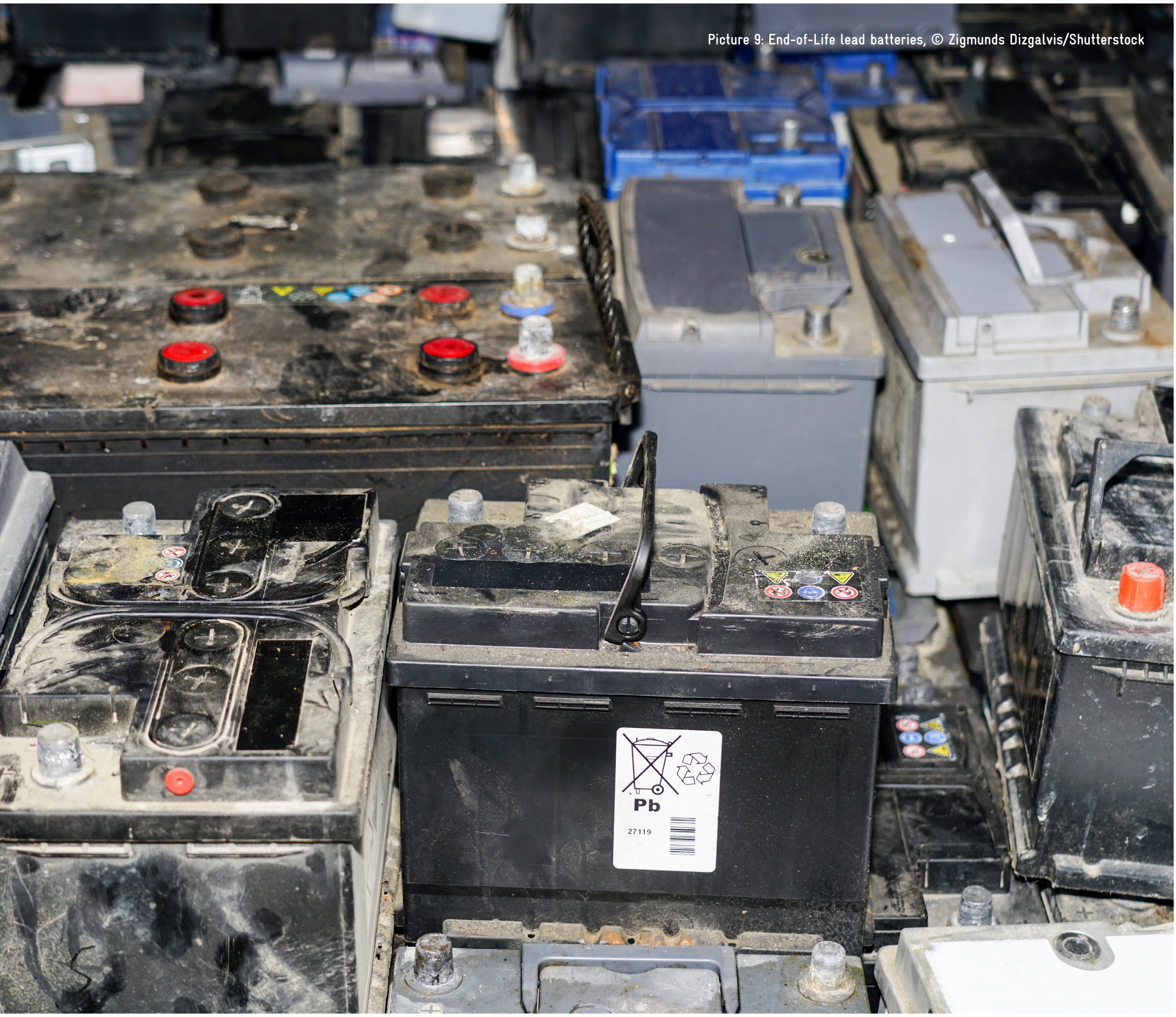
Further information on the safe installation, maintenance and decommissioning can be found in the "Good Practice in Refrigeration" guideline and the "Guidelines for the safe use of hydrocarbon refrigerants", published by GIZ Proklima.

5.2 Spare parts

Spare parts are essential to ensure continuous operation and sustainability. If there are no local retailers of the system that also provide after-sales service and repair (ensuring a continuous supply of spare parts), it is strongly recommended that all required spare parts are ordered with the initial purchase of the system.

It is also advised to build systems with as many locally available materials as possible. They will be easier to repair when breakdowns occur and therefore, they will be more sustainable.

Picture 8: Manifold used for evacuating natural refrigerants, © Gianfranco Vivi, GIZ



Picture 9: End-of-Life lead batteries, © Zigmunds Dizgalvis/Shutterstock

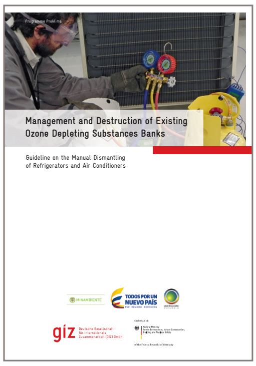
7 Management and recycling of end-of-life

A full assessment of the impacts of disposal and recycling of system components should be carried out at the beginning of the project to minimize climate and environmental impacts.

Insulation materials and refrigeration system:

Many faulty or abandoned cold stores contain blowing agents that are very harmful to the environment. The recovery and destruction of these materials is very important to prevent them from being released into the environment. At the end of the useful life, even if the insulation materials in our project do not contain these blowing agents, they should also be recycled in an appropriate manner.

Regarding refrigeration machines, refrigerant gases must be recovered and reused or destroyed. All other machine components should also be managed in the best possible way.



Further reading: Management and Destruction of Existing Ozone Depleting Substances Banks. GIZ Proklima, 2017 [31].

End-of-life (EoL) solar panels can become an important source of hazardous waste in the next decades. Some policies like the EU Waste of Electrical and Electronic Equipment (WEEE) are slowly starting to get implemented, forcing manufacturers to assume the costs of collecting and recycling for solar panels. At this moment however, there is a lack of dedicated solar panels recycling plants. Further policies need to be developed worldwide.

Different types of solar PV cells exist, c-Si solar cell dominating 80% of the market globally and followed by thin film solar cells or CdTe – CIGS technologies (made from materials such as cadmium, telluride and copper indium gallium selenide). Third generation PV panels (dye sensitized, CPV, organic hybrids) are predicted to reach 44% of the market's share by 2030 [20]. Recycling processes are different for every technology, due to the different materials.

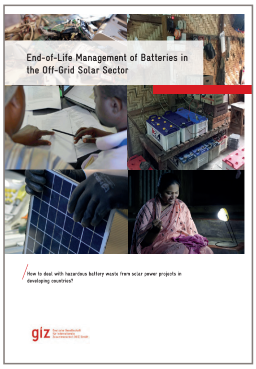
Currently, two types of PV recycling technologies are commercially available, and others are under research (one company from the USA, specialized in thin film solar panels and a German company, recycling c-Si solar panels). Unfortunately, these processes generate big quantities of toxic gases, noise emissions, organic melted waste (difficult to treat) and consume high amounts of energy. Less polluting technologies still need to be developed for future panels [20]. A life cycle environmental analysis suggests that PV cells recycling can decrease human toxicity and freshwater ecotoxicity by 78% and that it can be cost-effective compared to not managing these wastes [21].

Batteries used in PV systems are composed of very different chemical components (lithium-ion, lead-acid, nickel cadmium, salt water, flow batteries, etc.) [22]. As an example, using secondary recycled lead can reduce associated CO_2 emissions up to 99% compared to producing a new lead-acid battery [23]. Batteries produced with recycled chemical components should be prioritized, if possible.

Neither Li-ion batteries, nor lead-acid batteries are clearly superior in terms of end-of-life management as they both have very negative environmental impacts. Li-ion batteries are however the fastest growing technology, and they can last around three times longer than lead-acid batteries. Choosing the best and most environmentally friendly option is complicated and depends completely on the context of the project and the area concerned. Further recommendations on battery selection can be found in the End-of-Life Management of Batteries in the Off-Grid Solar Sector Report from the GIZ (2018), in chapter 5.1, page 26 [24].

A study published in 2020, however, determined vanadium redox flow (VRFB) as the technology having by far a lower environmental impact (100% recyclable, with a lifespan exceeding 20 years but more expensive than lithium-ion batteries and with a very low energy density). VRFB batteries are also extremely safe, non-flammable, non-toxic and have a high tolerance for high temperatures operation [25]. VRFB batteries reduce CO_2 emissions up to 78% compared to lithium batteries [26]. IRENA estimates the cost reduction potential for VRFB technology to be as high as 66%, reaching a lower price than Li-ion batteries [27]. Availability and cost of vanadium to face great storage demand is the main limitation for VRFB [28]. It is currently an attractive technology for grid-scale applications where both high-power and high-energy services are being provided by the same storage system (big installations) [29].

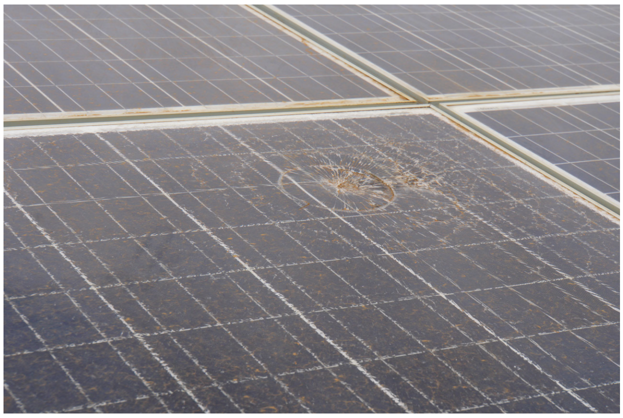
As a big opportunity for the near future, a big quantity of used electric car batteries will be available (normally no longer useful after losing more than 80% of their original capacity). These batteries can be then used for solar systems until the end of their life (at about 60% of their original capacity). They can cost <60% less than a new battery and be a more cost-effective solution for solar off-grid systems [30]. Furthermore, solid state batteries might become a reality in the medium to long term, increasing their lifespan and potentially reducing environmental impacts.



Further reading: End-of-Life Management of Batteries in the Off-Grid Solar Sector. GIZ, 2018 [24].

Other electrical components:

There are no specific recommendations for the other electrical equipment (wiring, switchboard, inverter, etc.). At the end of their useful life, they should be properly recycled or disposed, according to international best practices, to minimise their environmental impact.



Picture 10: End-of-Life solar panel, © Kilian Blumenthal, GIZ

Picture 11: SelfChill solar cold room, © Strathmore Energy Research Center, Kenya

8 Conclusions

In summary of the above information, the following recommendations are made:

- **Solar PV systems** are currently the most environmentally and climate-friendly, accessible and safer choice for the implementation of off-grid small to medium scale refrigeration systems, even though their initial investment is higher than that of traditional diesel generators.

- **Mono and polycrystalline PV panels** are the best technology currently available on the market. Special attention must be paid to their quality of construction, homogeneity and performance at high temperatures, ensured by the corresponding certifications and guarantees.

- If a **DC compressor** is chosen, the inverter can be dispensed with. With or without an inverter, we recommend the installation of an MPPT to increase the efficiency of the solar system. Regarding the inverter, a multistring inverter, IP65 protection and a European or CEC efficiency greater than 93% are recommended.

- Where climatic conditions and project characteristics permit, it is recommended to **dispense with batteries** and to store energy in the form of **thermal storage.** It is recommended that the cooling unit that produces the ice contains an ultra-low GWP natural refrigerant (normally R290 (propane) or in some applications also R-600a (iso-butane)). Among the coolants used for thermal storage, water, salt water or propylene glycol-based systems are recommended from an environmental point of view. However, salt water or water-based systems should be prioritized because of their wide availability.

- If climatic or project conditions do not allow for sufficient energy storage with thermal storage, it is generally recommended to opt for **lead-acid AGM batteries,** due to their good price-quality-durability and recyclability (compared to Li-ion, FLA or gel).

- In terms of **refrigerants,** hydrocarbon refrigerants with an ultra-low GWP such as R600a or R290 are recommended. R290 is also suitable for freezing applications. Generally, refrigerants with a GWP higher than 10 or/and with ODP potential should be avoided if environmentally friendly refrigerants are available.

- **Insulation panels** can also contain very harmful blowing agents like R141b. Materials containing blowing agents with a GWP higher than 12 should be avoided, and natural blowing agents should be prioritized.

- **Spare parts** are essential for the sustainability of the project. A long-lasting business model will generate less environmental impact. The supply of these spare parts should ideally be ensured by local technical services. If not, provision should be made for the purchase of necessary spare parts in the future at the start of the project.

- **Maintenance** is also essential for the sustainability of the project and to avoid potentially environmentally damaging breakdowns. This should be ensured through education and capacity development measures to promote the availability of qualified local technicians. A trained technician shall follow the recommended maintenance periods for each of the system components.

- Finally, a study should be carried out prior to the start of the project on the treatment of the different components at the End-of-Life. All of them should be properly **reused, recycled or disposed,** in accordance with best available techniques.

Examples of solar walk-in cold room companies

The following companies are presented as examples of cooling solutions that are considered sustainable and use natural refrigerants. We would like to point out that many other companies are currently following the same path and that these are not the only options available.

Table 3: List of exemplary environmentally friendly solar cooling companies.

Name	Walk-in cold room with PV and batteries	Walk-in cold room with PV and ice storage	Ice production
Cryosolar	X	X	
Ecofrost - Ecozen | Ecozensolutions		X	
Frigo Indus Tunisia	X	X	
SelfChill - Solar Cooling Engineering	X	X	X
Solar-Cooling-Technologies	X	X	X

Relevant further reading on solar cooling

Promoting Food Security and Safety via Cold Chains - Technology options, cooling needs and energy requirements. (GIZ (2016). giz_2016_Food_Security_Cold_Chains.pdf

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Management and Destruction of Existing Ozone Depleting Substances Bank. GIZ Proklima (2017). giz2017-en-weee.pdf

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Annex

Annex 1: Specifications for solar panels

It is recommended to procure high quality mono and polycrystalline PV panels:

- Panels should be certified for wind load up to 2400 Pa, framed with an anodized aluminium profile and have a maximum NOCT of 45±3°C.
- Panels offering certifications (IEC-61215, IEC-61730, IEC-17025, IEC-60891, IEC-60904, IEC-61345, IEC-61701, IEC-61721 and EN-50380) and the longest product warranty times (minimum 10 years) are recommended. Most efficient technologies are currently mono and polycrystalline, and both can be equally performant.
- CE declaration of conformity of the manufacturer should also be provided.
- The junction box at the back of the modules should be weatherproof (at least IP 65 and DIN DVE 0126-5 standards). Cabling between modules should comply with EN-50521.
- Panel racks that allow for mounting the panels on the roof-top of the container (reduces shading, saves space) and at an angle that is ideal for the area of deployment, as that varies depending on how close to the equator it is.
- The efficiency value of panels is not a key aspect to worry about when enough roof surface is available, since it only means how much power per panel surface is produced.
- The last important specification to consider is the temperature coefficient or Pmax. Solar panels perform worse over 25°C, and in a hot sunny day they can easily get over 50°C. The Pmax represents how much efficiency in % is lost for each degree over 25°C. A maximum temperature coefficient of 0.5% is recommended [9].

Regarding the inverter, the following characteristics are recommended:

- At least 5 years warranty
- Overcharge protection, deep discharge protection, short-circuit protection of load and module, reverse polarity protection via internal fuses, overtemperature and overload protection, audible alarm, PE connection.
- MPPT included
- Multistring (able to manage multiple strings of panels with different orientations).
- European Efficiency or California Energy Commission (CEC) efficiency higher than 93%.
- At least IP65 protection.
- Safety certification provided by an independent testing laboratory (e.g. UL, ETL, CSA, etc.).
- If possible, it should comply with the following standards: EN-IEC 60335-1, EN-IEC 60335-2-29, EN-IEC 62109-1, EN 55014-1, EN 55014-2, EN-IEC 61000-3-2, IEC 61000-6-1, IEC 61000-6-2, IEC 61000-6-3, CE.

Annex 2: Specifications for batteries or ice storage systems

When choosing AGM batteries:

- Best AGM battery manufacturers offer up to 3 years warranty on their products. A minimum of 2 years warranty is recommended, although the batteries should be able to last at least 5 or 6 years under optimal conditions.
- Conformity to IEC 60896-21/22 and IEC 61427 is recommended.
- Energy efficiency > 80%.
- Ampere-hour efficiency > 90%.
- Self-discharge less than 3%/month at 20°C.
- Each battery is labelled with at least the following data: Manufacturer, type, model number, nominal voltage in V, nominal capacity in Ah, month and year of commissioning.
- Each cell must have a factory serial number.
- Fully insulated, corrosion-free lead terminal.
- At least 1500 cycles @50% DoD, 20°. Related to this, it is recommended to buy batteries larger than the power needs of the system so that with each cycle they are not discharged by more than 50%. This will considerably extend their lifetime.

When choosing Li-ion batteries:

- Good Li-ion batteries have product warranties for 5 years or more. Only batteries having more than 5 years warranty should be bought.
- Within Li-Ion: NMC (manganese cobalt oxide) and LFP (lithium iron phosphate). LFP can charge and discharge two times quicker than NMC, which makes them better for off-grid solar systems (a high charging speed is important during hours of high solar radiation) [19].
- IEC 62133-2:2017 and IEC 62133 requirements are recommended.
- Each battery is labelled with at least the following data: Manufacturer, type, model number, nominal voltage in V, nominal capacity in Ah, month and year of commissioning.
- Each cell must have a factory serial number.

When choosing thermal storage systems (preferred option depending on the required conditions):

- The cooling unit that produces the ice should contain an ultra-low GWP natural refrigerant (normally R-290 (propane) or in some applications also R-600a (iso-butane)).
- Among the coolants used for thermal storage, water, salt water or propylene glycol-based systems are recommended from an environmental point of view. However, salt water or water-based systems should be prioritized because of their wide availability.

Annex 3: Specifications for cooling systems

It is recommended that solar walk-in cold rooms should use cooling systems (monoblocks or split systems) that use ultra-low GWP refrigerants such as R290 (propane) or in some cases also R600a (iso-butane). Moreover, if ice machines are used, also ultra-low GWP refrigerants mainly R290 is the preferred refrigerant. As previously stated, HFOs are not recommended due to concerns about possible environmental effects.

Below are some examples of manufactures of monoblocs. Most of them also offer split systems. However, it must be stated that there are also other manufacturers that offer monoblocks and that there are many other manufacturers of split-systems. Depending on the type of application, standard monoblock units have the advantage that they can be easily set up because installation is quite simple, risks are limited and leakages occur rarely because no bracing of refrigeration pipes is required. Moreover, most standard monoblock units are also cheaper than split systems.

Table 4: Examples of climate-friendly mono-blocks with ultra-low GWP refrigerants for cold/freeze rooms.

Manufacturer	Ref.	Temp. range °C	Cooling cap. in kw (50Hz)	Size in m3	Energy Consumption in kW
Frigadon [43]	R290	+4 to +2	0.6 - 2.4	3 - 105 (+4°C)	0.85 - 2.15
		+4 to +2	0.6 - 14.8	5 - 430 (+4°C)	0.3 - 12
		-20 to -22	0.8 - 13.3	12 - 534 (-20°C)	2.1 - 18.6
Intarcon [44]	R290	+10 to 0	0.7 - 2.1 (+5°C)	7 - 43 (+5°C)	0.4 - 1.31
		+10 to -5	0.8 - 2.8 (+5°C)	6 - 28 (+5°C)	0.30 - 1.34
		+10 to -5	6.5 – 51.5 (+5°C)	No information	2.5 – 17.8
		-15 to -25	0.4 – 1.1 (-20°C)	2 - 8 (-20°C)	0.26 - 0.96
		-15 to -25	0.4 – 1.2 (-20°C)	2 - 14 (-20°C)	0.38 – 0.97
		-20 to -35	5 – 29.7 (-20°C)	No information	3.5 - 20.1
Intarcon [45]	R170	-60 to -80	0.4 - 0.65 (-80°C)	3 (-80°C)	0.65
Rivacold [46]	R290	+5 to -5	1.2 - 3.1 (+5°C)	10 - 38 (+5°C)	No information provided
			1.0 - 4.4 (+5°C)	12.6 - 81.6 (+5°C)	
		-15 to -25	0.8 - 2.8 (-20°C)	5.2 - 20.3 (-20°C)	
			0.6 - 2.5 (-20°C)	8.2 - 55.5	
Techno-B [47]	R290	+5 to -5	1.1 - 3.7 (+5°C)	10 - 42 (+5°C)	0.68 - 2.05
		-15 to -25	0.8 - 2.1 (-20°C)	15 - 25 (-20°C)	0.82 - 2.1
Technoblock [48]	R290	+10 to -5	0.9 - 4.6 (+5°C)	13 - 92(+5°C)	No information provided
		-15 to -25	1.2 - 2.5 (-20°C)	4.3 - 28 (-20°C)	
Zanotti (Daikin) [49]	R744 (CO_2)	+10 to -5	1.7 - 12.8	40 - 200	No information provided
		-16 to -25	0.8 - 4.8	17 – 72	
Zanotti (Daikin) [49]	R290	+10 to -5	1.4 - 2.4	10 - 25 (+5°C)	0.94 – 1.61
		+10 to -5	1.4 - 6.3	9.1 – 81 (+5°C)	0.94 – 4-66
		-15 to -25	0.8	3.4 -4-4 (-20°C)	1.26
		-15 to -25	0.8 – 2.4	2.7 – 22 (-20°C)	1.26

1 For the 60Hz units the cooling capacity in kw is usually a little bit higher

2 Average ambient temperature used 32-35 °C, depending on ambient temperature and on the thickness of the insulation panels. However, the cold/freezer room size can be easily doubled or tripled if a 2nd or 3rd unit is installed.

Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered offices
Bonn and Eschborn

Friedrich-Ebert-Allee 32 + 36
53113 Bonn, Germany
T +49 228 44 60-0
F +49 228 44 60-17 66

Dag-Hammarskjöld-Weg 1 - 5
65760 Eschborn, Germany
T +49 61 96 79-0
F +49 61 96 79-11 15

E info@giz.de
I www.giz.de