Construction of a fish cold store in Kenya

Guidelines for the installation, design and calculation
of a highly efficient solar-powered cold store using natural refrigerants

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About this publication

This publication is a product of *GIZ Proklima*, a program of the 'Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH', which provides technical support to developing countries to implement the provisions of the Montreal Protocol and the Kigali Amendment on substances that deplete the ozone layer and affect the global climate. As part of *GIZ Proklima*, the *Green Cooling Initiative* (GCI) is working on behalf of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) under its International Climate Initiative (IKI) to promote ozone- and climate-friendly technologies. The overall objective of GCI is to minimize the environmental and climate impact of cooling systems used in the private and public sectors.

Against this backdrop, the Kenyan Ministry of Environment, Natural Resources and Regional Development and the Green Cooling Initiative launched a collaboration to promote sustainable cold storage solutions in the fisheries sector with an approach to climate-neutral cooling through the use of **energy-efficient** cold storage powered by **renewable solar electricity** and the use of cooling systems with **natural**, **low-GWP refrigerants**.

Kenya has one of the most active fisheries sectors in the region, consisting of freshwater (lakes, rivers and dams), coastal, marine and aquaculture fisheries. The total fisheries and aquaculture production in 2014 was about 193,000 tonnes (Ministry of Industrialization, Trade and Enterprise Development, 2020). Most of the fish were caught inland (predominantly in Lake Victoria). Freshwater aquaculture in Kenya has developed rapidly over the last decade, making Kenya one of the fastest-growing major producers in sub-Saharan Africa (FAO, 2015). Food conservation, including fish, plays an important role in increasing resilience to rising temperatures in Africa due to climate change. The project focus is the promotion of climate-friendly solutions for the domestic market for fresh fish as a contribution for sustainable and resilient food supply.

As part of the cooperation with GIZ, the Kenyan Ministry launched a tender for local operators to pilot Green Cooling cold storage in their operations. More than 10 companies were shortlisted and Lakeview Fishery, which operates a fish farm on Mfangano Island on Lake Victoria, was selected. The company received financial support from the Green Cooling Initiative and funds from the International Climate Initiative (IKI). The company also received technical support in planning and installing the cold store according to this guide's principles.

The aim of the project was to set up a pilot project to demonstrate the off-grid, energy-efficient use of high-efficiency refrigeration and ice-making equipment operated with natural refrigerants (R290) in a modular, well-insulated cold store. For grid independence, the cold store is equipped with a photovoltaic (PV) system and batteries. GIZ provided the initial technical design for the cold store. GIZ jointly trained the cold storage builders and provided training to replicate the implementation. The first cold store was successfully commissioned in 2016.

Within this framework, this practical guide was developed, which contains general and practical advice on the construction of environmentally friendly cold storage facilities. The guide also deals with the experiences in Kenya.

GIZ Proklima expresses its gratitude to the Kenyan Ministry of Environment, Natural Resources and Regional Development and Lakeview Fisheries for their collaboration and support for the successful implementation of the project.

In addition, the project team would like to express their gratitude to BASF for their cooperation, supply of raw materials and technical support in the procurement of environmentally friendly sandwich panels for the project.


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Introduction

This handbook is intended as a guide for the planning and building of a fish cold store in an environmentally and climate-friendly way, specifically adapted to the local conditions in Kenya. Fish resources often play an important role as a source of food for the rapidly growing population in developing countries. Small and large inland waters are often important fishing areas and provide a source of fresh fish. This fish is consumed locally or transported by road to marketplaces. In many African countries, including Kenya, there is a lack of facilities to properly store, transport and consume fish.

Developing countries are affected by strong population growth combined with rapid urbanisation, growing urban poverty, water scarcity, declining food production and decreasing resilience to climate change. These countries are often located in the hot, tropical equatorial regions where refrigeration and air conditioning (RAC) plays an important role in adapting to temperature increases caused by climate change. By combining energy efficiency improvements with the transition to natural refrigerants, the world could avoid cumulative GHG emissions of up to 210–460 Gt CO_2 eq over the next four decades. This is roughly equal to 4–8 years of total annual global GHG emissions, based on 2018 levels.[1]

Commercial refrigeration plays an important role in developing countries but is often not implemented sustainably. Yet climate-friendly and energy-efficient technologies have been shown to have several benefits: Improved energy efficiency brings economic benefits; improved refrigeration leads to increased food safety combined with less direct and indirect greenhouse gas emissions. All these factors contribute to a more sustainable environment and help mitigate climate change.

This guideline focuses on fish refrigeration, specifically the domestic fisheries sector in Kenya and the sustainable and resilient supply of fresh fish. There is a great need for refrigeration especially around Lake Victoria and Lake Turkana: the fisheries sector in Kenya contributes significantly to food security, foreign exchange generation and a protein supply for the local population. Lake Victoria is by far the most important source of fish in Kenya and represents a large share of the total fish supply from freshwater and seawater. The Lake Victoria area is by far the most densely populated area in Kenya and represents an important food/fresh fish supply for the whole of Kenya.

1 iea (2020). Cooling emissions and policy synthesis report.

Food preservation, including fish, plays an important role in increasing resilience to rising temperatures in Africa due to climate change.

The Green Cooling Initiative (GCI) aims to improve the fish cold chain through efficient and climate-friendly cooling systems. To this end, the GCI entered into a cooperation with a selected Kenyan fish farm operator, Lakeview Fisheries. The cooperation included the following points:

- Introduction of a solar-powered fish cold store with high-efficiency insulation
- Use of natural refrigerants (in this case propane R290) and high energy efficiency
- High degree of autonomy and self-reliances and suitable for the operation in areas with frequent power interruptions
- Modular and scalable approach
- Affordability and feasibility for local businesses
- Support mainly local industry for local consumption (not exported/imported fish)

This guide is intended to assist practitioners in planning and setting up cold stores with refrigeration systems based on natural refrigerants powered by photovoltaics (PV). It is based on the experience gained in the planning and implementation of the pilot demonstration cold store in Kenya. The experience gained from the demonstration project can be easily transferred to other locations.

The cold store is designed to preserve food sustainably and avoid GHG emissions by using renewable energy and natural refrigerants for cooling. The design of the cold store is energy optimised and features an advanced refrigeration system that uses refrigerants with zero ozone depletion potential (ODP) and negligible global warming potential (GWP). The combination of natural refrigerants with energy-efficient technologies is a key element in providing sustainable cooling and refrigeration and is in line with the EU F-Gas Regulation and the Kigali Amendment to the Montreal Protocol. The GCI summarises the combination of high energy efficiency, natural refrigerants and, in the best case, renewable energy sources as “Green Cooling”.

A cold store is not simply a room for refrigerating food, but a room specifically designed to provide the conditions for the safe storage of perishable goods, taking into account the specific requirements of the developing country. The design of the cold store starts with the purpose, i.e. which perishable goods are to be stored in it. The type of perishable goods determines the temperature requirements, which are regulated by both national and international laws.

This guideline provides practical solutions that can be consulted for the design and implementation of fish cold room solutions for the domesic markt. It provides an overview of the following topics:

- Aspects of the proper use of a cold store
- Logistical aspects of using a cold store
- Different construction methods of the cold store as such
- Thermodynamics of a cold store
- Building material (e.g. insulation, PV panels, etc.)
- Suitable refrigeration systems and natural refrigerants
- Correct positioning of the cooling unit.

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List of abbreviations

A	A	Amps
	AC	Alternating current
	Ah	Ampere hours
	AWG	American wire gauge
B	BOS	Balance of the system
C	Cp	Specific heat capacity (KJ/kg.K)
D	DC	Direct current
E	EPS	Expanded polystyrene
G	GCI	Initiative for green cooling
	GHG	Greenhouse gases
	GWP	Global warming potential
I	IEEE	Institute of Electrical and Electronics Engineers
	IGBT	Bipolar transistor with insulated gate
	Isc	Short-circuit current
	I-V	Current voltage
K	kWh	Kilo-Watt-Hour
L	λ	Thermal conductivity (W/mK)
	LEW	Licensed electrician
	LVD	Low-voltage isolator
M	MOSFET	Metal oxide semiconductor field effect transistor
	MPP	Maximum credit point
	MPPT	Maximum Power Point Tracking
O	O&M	Operation and maintenance
P	PIR	Polyisocyurenate
	PU	Polyurethane
	PV	Photovoltaics
Q	q	Heat (KW)
	Q	Thermal energy (KJ)
R	RAC	Refrigeration and Air Conditioning
S	STC	Standard test conditions
U	U	U-value (W)
V	V	Voltage
	Vdc	Volts direct current
W	W	Watt
	Wh	Watt hours
	Wp	Peak power Watt
X	XPS	Extruded polystyrene

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1 General design considerations

When designing a cold store, it is essential to consider important aspects already in the initial planning stages. Below you will find an overview of the most important aspects and how to avoid common mistakes.

1.1 Size and function of the cold room

An optimally designed cold room is calculated based on the intended quantity of food stored and the temperature range to be maintained. A room for frozen meat will not be suitable for storing fresh fish stored at 2-4°C, as opposed to meat with a storage temperature of -18°C. The refrigeration system designed for frozen meat with the same amount of food would be much larger than for fresh fish. To assess which cold storage is needed, it is important to distinguish between the cold storage enclosure and the refrigeration system. The differences are:

Cold store housing	Cooling system
Mainly insulated panels,	Balances the heat coming into the room from the immediate environment and products to achieve the desired internal temperature of the room,
The amount of insulation, the thickness of the panels determines the required cooling load for a particular product to be stored.	A typical refrigeration system is designed either for cooling food in the range of 2–10°C or with temperatures –18°C and lower.

A cold store is only designed to maintain the temperature and not to lower the temperature of a particular product. Before choosing a particular system, it is important to understand the proper function of a cold store. This practical guide provides the background explanation.

Before you decide on a cold storage system, there are various aspects to consider. Often, cold storage cooling systems are not properly sized, resulting in inefficient energy use. Correct sizing can therefore reduce both the costs associated with construction and the operating costs during operation.

A cold storage supplier must provide proper design calculations and the user must provide a realistic picture of the intended use of the cold storage. Understanding the products to be stored and the storage temperatures is crucial, as the temperature of the goods during storage plays an essential role.

1.2 Temperature levels

The temperature of the stored food is the average of the inside and outside temperature. Using an infrared temperature device that measures the outside temperature is therefore not sufficient. The temperature of the goods must be confirmed by measuring the core temperature inside the food with additional probes.

Freshly caught fish should be completely covered with ice before being stored in cold storage. This allows the fish to cool down to reach the desired storage temperature, the fish to maintain a constant temperature and ensures good quality.

When covering the fish with ice, it is important to:
- ensure that the ice has full contact to the fish
- prevent the fish from drying out when a cooling system is used
- ensure that the fish placed in a box is cooled evenly.

The user of the cold store must know the temperature conditions and how to cool the food down to the desired target temperature. This aspect is of great importance as it is a cost factor in addition to food preservation.

> **The cold chain requires goods to be kept within the required temperature range during transport. A weak element in the cold chain can jeopardise the complete proper transport.**

If the food is not at the correct target temperature before entering the cold room, it must be cooled down separately. If, as previously recommended, ice is not available for cooling down, the cooling process must be carried out in a separate chamber from the storage chamber. The cooling process is facilitated by not using cardboard boxes and goods wrapped in plastic, and by unpacking and placing the goods on a table in the cold room.

But it is not only the storage of fish that requires special care. To prevent food spoilage, the transport of frozen or refrigerated goods must also be carried out properly. It must be ensured that food arriving at and leaving the cold store, e.g. from the producer and for transport to the final or next consumer, is always kept within the correct temperature range. Ideally, the fish cold store itself can produce ice to both chill the fish down before storage and to cover it and keep it in the same temperature range in case of transport.

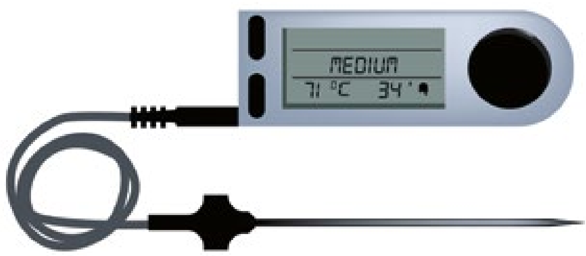
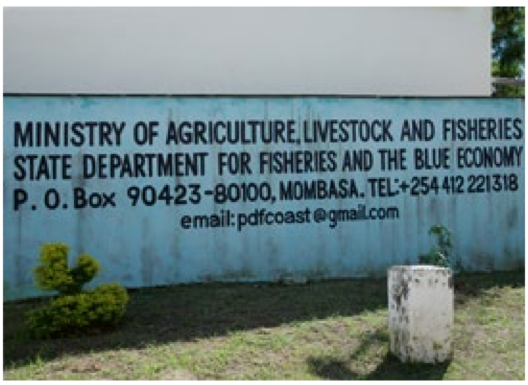


Figure 1: Temperature sensor for the food sample



1.3 Construction considerations and energy consumption

The energy required to maintain the temperature is entirely dependent on the goods stored in the cold store and the insulation of the cold store itself. Therefore, the design of the cold store insulation is another important element for the proper construction of the cold store.

Keeping food chilled or frozen is all about maintaining the optimum temperatures. Cold stores, refrigerators and freezers are used for this purpose. Some basic principles apply to all these technologies: A refrigeration unit cools down the inside of the insulated area and keeps the higher ambient temperature outside. To cool down the inside of an insulated space, a certain amount of energy is needed to drive the cooling unit.

A well-insulated room always reduces the energy required to maintain the temperature within the insulated area.

The energy balance required to maintain the temperature follows an arithmetic equation with the following required vectors:

- an external environment outside the cold room that is warmer
- a desired cooled down temperature inside the cold room
- energy required to maintain the temperature in the storage room and of the food or goods
- the refrigerated food or goods are assumed to be at the same temperature as the storage room
- energy is supplied from the outside of the cold room and it is necessary to balance this energy flow with the cooling unit.

$$Q_{environment} = Q_{refrigeration\ unit} \quad (1)$$

Assuming that the goods do not initially have the same temperature as in the cold store, additional energy is required to cool the goods from ambient temperature to cold store temperature:

$$Q_{environment} + Q_{goods\ temperature\ difference} = Q_{refrigeration\ unit} \quad (2)$$

Proper food preservation and energy saving requires that the cold chain is always secured. Goods entering the cold store should be as close as possible to the temperature in the cold store. In addition, the insulation of a cold store is crucial for its energy-efficient operation.

Equation *(1)* shows the energy entering the cold store. The rate of energy required over time depends on the degree of insulation of the cold store. More insulation means:

- less heat entering the cold store
- longer holdover time of the cold store
- smaller required refrigeration unit
- less energy is needed.

Good insulation in combination with an appropriately sized cold room consumes less energy for cooling. There are several considerations to make when deciding on a refrigeration unit. Below is a short list of "DOs and DON'Ts" to avoid the most common mistakes when planning a cold room and a cooling unit.

Table 1: Overview of the "DOs and DON'Ts" when selecting a cooling unit

Do	Don't
Make sure that the cold store is designed for a specific quantity and type of food.	Do not change the typology of food, temperature and quantities – as the refrigerator will then no longer work as efficiently as intended.
For optimal energy savings, calculate the heat load and optimise the size of the cooling unit.	Don't just buy any type of cooling unit without knowing the cooling capacity you need.
Calculate the right insulation properties, material and insulation. To further reduce operating costs, choose insulation one size thicker.	Do not buy insulation material without appropriate certification indicating performance. Calculate the type of insulation you need before buying the right material.
Determine a logistics plan for how much food is brought into the cold store each day. Estimate the temperature of the food brought in and estimate how often people enter the cold store.	Do not work without a detailed logistics plan and without correct costing.
Preferably, oversize the thickness of the insulation to minimise the energy required to keep the cold room cold and reduce the possibility of the cold room interior heating up. Note that the cost of a sandwich panel is largely determined by the sheets on it. Increasing the thickness of the foam is associated with a small increase in cost.	Do not buy a room with thin walls and insufficient insulation. This increases the operating costs of the refrigeration unit and makes a larger unit necessary. The running costs will quickly exceed the cost of a cold room with sufficiently insulated walls.
Observe good practice when using the cold room and storing foodstuffs.	Do not open the door too often. Keep the door closed. Do not put in food that is too hot or too moist.

2 Insulated panels

Foam insulation boards are the most commonly used solution for cold room insulation. The efficiency of the insulation material is usually measured in thermal conductivity in mW/m*K. For example, a corrugated steel roof has a thermal conductivity of about 50,000, a brick wall about 500, a surface insulated with wool about 50 and surfaces insulated with foam are in the range of 22-35mW/m*K.

The panels have a core of foam and an outer covering of metal or flexible covering materials, such as plastic or paper. Metal-covered panels usually have a steel sheet foamed or glued to the outside of the foam. Panels covered with flexible material may have a paper or plastic sheet. Other covering materials such as plasterboard or cement are not suitable for use in cold rooms because they are not sealed against moisture. Moisture penetration destroys them and makes the cold room unusable.

The two main types of foam used for insulation boards:

- Polyurethane foams:
  - PU – Polyurethane
  - PIR – Polyisocyurenate
- Polystyrene foams:
  - EPS – expanded polystyrene
  - XPS – extruded polystyrene

Other core insulation materials include "wool" core insulation materials, such as mineral wool, glass wool or rock wool. Due to their water absorption properties, "wool" boards are not suitable for wet cold rooms. Below you will find an overview of other alternative core insulation materials:

Woodchips: 40–45mW

Woodwool: 90mW

Sheepwool: 32–36mW

Plain grass: 42mW

Flax flower: 36–40mW

Hemp: 47mW

Reed: 48mW

Seagras: 37–43mW

Figure 2: Insulation materials, mW indicates thermal conductivity in mW/m.K. (source: HEAT, own research)

2.1 Selection of materials (cover material)

The choice of lid insulation material depends on the application for which it is used. On the one hand, it must be decided whether food or other goods are to be stored. On the other hand, a differentiation must be made between dry or wet storage.

Food storage

Food storage always entails strict and high hygiene standards, whether the food stored is packaged food or fresh food such as fish, meat or poultry. The covering material of the insulation must comply with certain regulations and the surface must be easy to clean and must not contain any hazardous substances, such as paint or certain additives that release harmful substances when they come into contact with the food.

Storage of other goods (non-food)

Non-food storage also requires cleaning, of course, but the cover material of the panels hygiene standards are different with insulating panels for food storage.

Dry or wet storage

Dry and wet storage can be reflected in the choice of materials for the covers. This depends on the location where the cold store is placed. Regions with high humidity require different materials than dry regions. Another decision that leads to different materials is the type of goods stored in the warehouse. For example, fish stored on ice will most likely increase humidity and lead to wet floors and walls. If moisture penetrates the panels, mould can develop.

2.1.1 Cover materials: Food and wet storage

With regard to the storage of food in humid environments or products that may cause moisture in the cold room, the main requirement for the cover material is that it can be cleaned to high hygienic standards. Therefore, the cover material must be non-porous and existing joints between adjacent panels must be sealed.

- Steel or plastic cladding is the best choice
- Excellent sealing of the gap between the panels is mandatory
- Certificates that the paint or plastic is suitable for the storage of foodstuffs should be provided
- Steel sheet is usually a usable material for panel covers.

Figure 3: Example of PU panel moulds

2.1.2 Cover materials: Non-food and dry storage

When storing non-food products in a dry environment or products that do not cause moisture inside the cold room, the requirements are not as strict as when storing food. The surfaces inside the cold store are less susceptible to contamination from moisture and mould is unlikely. The goods are usually stored in packaged form and are not intended for consumption.

- Steel or plastic, but also cement or plaster cladding is suitable for this type of cold store
- Good sealing of the gaps between the panels is important to maintain adequate thermal efficiency.

Additional requirements may depend on the goods being stored in the cold room. Goods that arrive as powder or create a dusty area, e.g. wheat, corn or grain, require panels with low flammability. Close cooperation with the local fire brigade and legal requirements must be taken into account when planning a cold store.

3 Insulation materials

Suitable core insulation materials are crucial for the proper functioning and energy efficiency of a cold store. Condensation can occur due to a temperature gradient, this moisture occurs on the outside or on the inside when relatively warm air is cooled down. Materials in which water collects are problematic as this can lead to bacterial growth or mould. Both can negatively affect the hygienic conditions of the cold room.

3.1 Foam insulation PU, EPS and XPS

PU (polyurethane), EPS (expanded polystyrene) and XPS (extruded polystyrene) are well-known and widely used insulation materials.

When making panels with PU, EPS and XPS, there are specific aspects that make some materials more suitable than others. The PU panels are the most suitable for building a cold store because the bond with the covering material is stronger. Other important aspects are the physical and thermal properties. The thermal properties determine the insulation values and the amount of conductive heat flow through the material. This is expressed by the U-value.

The U-value (W/m² K) is the overall heat transfer coefficient that describes how well a material or composite of materials conducts heat. It is calculated as the ratio between the thermal conductivity of the material (λ: thermal conductivity (W/m K)) and the thickness of the foam (m):

$$U = \frac{\lambda}{t} \qquad (3)$$

FLOOR SPACE INCREASE

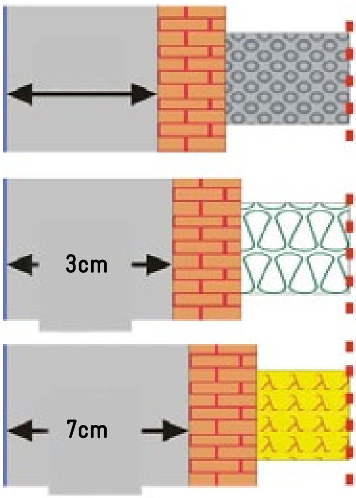


Figure 4: Insulation thickness difference for the same thermal efficiency (source: HEAT, own research)

Insulation material	PU	EPS	XPS
Thermal conductivity range l (W/m.K)	22–24	28–35	29–35
≈ U-value for 100mm panel*	0.22 / 0.24	0.28 / 0.35	0.29 / 0.35
Equivalent thickness	100	159–117	159–121
Mechanical strength	High	Medium	Less until properly glued

* the best insulation has the lowest value

Table 2: Foam properties

Using the thermal conductivity of the foam and the thickness of the insulation material (foam and coating) allows a calculation and comparison of the U-value *(Table 2)*.

The thermal transmittance of the insulation material affects the thickness chosen. For example, a PU board with a thickness of 100mm achieves the same U-value as an EPS board with a thickness of 159–117mm.

Insulating foams have the property of a closed cell structure. Therefore, water absorption is minimised. Typically, PU, EPS and XPS foams have values of less than 5% water absorption. Core insulation materials of the “wool” type have a high-water absorption capacity and when used, one side is always open for ventilation purposes. Core insulation materials of the “wool” type are not suitable for cold rooms. The slightest damage to the face material results in water absorption, which leads to reduced hygienic conditions and a reduction in thermal insulation. In view of all these properties, foam is the most suitable core insulation solution for cold stores.

3.2 Floor materials

There are two options that are most commonly used for cladding floor panels:

1. Cement covering reinforced with a steel mesh or tiles: A cement covering is poured as soon as all wall panels are in place. The disadvantage is that it has to dry for 2–3 weeks, otherwise it will crack in sub-zero temperatures.
2. Wood panelling as used in refrigerated vehicles: Wood panelling is done with 2–3cm thick plywood and is then coated with glass fibre. This is done to prevent moisture from penetrating the wood.

With both solutions, care must be taken to ensure that the corners between the wall and floor panels are properly filled.

3.3 Sealing the cold store

When building a cold store, it is important to reduce all possible leaks and achieve as much airtightness as possible. Proper sealing is important to improve thermal insulation and prevent dust and insects from entering the cold store. The joints of the panels for the roof and walls must be firmly glued together with their tongue and groove design, this ensures additional strength and provides a tight construction. This construction feature also ensures the correct alignment of the panels.

Larger panels offer fewer joints, which in turn reduces the possibility of leaks. Openings between panels reduce the overall performance of the cold room and reduce the energy efficiency of the design.

Sealing the gaps with silicone is mandatory for:
- Cold storage with temperatures <0°C, as water icing between the joints will shift the panels over time.
- Cold rooms where high hygiene standards prevail, e.g. when storing fresh meat or fish.

3.4 Electrical safety

All electrical equipment inside the cold store must meet special requirements. It is advisable to maintain a high degree of protection or IP class (international protection class) in accordance with the IEC 60529 standard or the European standard EN 60529. IP 56 or IP 65 protection should be used, as this prevents water from entering the electrical components. Proper earthing of the entire cold room is also required. This practice manual does not provide a more detailed guideline on electrical installation, the cold room user must have the electrical installation carried out and checked by a certified electrician.

4 Calculation of thermal load and thermodynamics

First, a distinction must be made between heat and thermal energy. Heat is thermal energy in transit, it is the flow of thermal energy.

In the following text, the symbols are used as shown below:

Term	Device
Heat q (physically correctly: heat flow q˙)	Watt [W]
Thermal energy Q	Joule [J]

All units are in the SI metric system.

In the following chapter, the three different types of heat transfer are discussed in detail. These include:

- Conductive – transfer of heat through contact
- Convection – Air flow passing over a surface
- Radiation – Heat transfer by radiation, mainly from the sun.

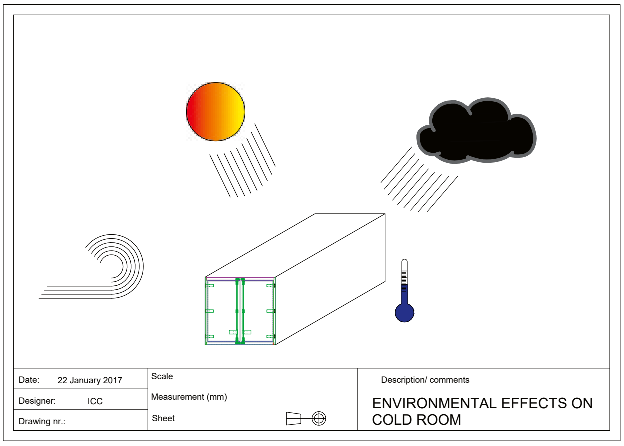


Figure 5: Environmental conditions that influence the thermal conditioning of a cold store (source: HEAT, own drawings)

4.1 Conductive heat transfer

Conductive heat transfer occurs when two materials with different temperatures are in contact with each other. This can happen when the cold store wall is adjacent to an existing wall and this wall is warmer than the cold store wall. Therefore, physical separation between the external walls and the cold store itself is important. The mechanism of heat transfer can be quite complex when the cold store and the outer walls are in contact:

- The outside wall is heated by the sun through radiation- and there is additional heat transfer similar to a cold room in the open air subject to direct sun radiation.
- Heat is also transferred between the cold store metal faced panels and the wall when they come into contact.

Heat conduction occurs when two materials come into contact and exchange internal energy through the movement of atoms, electrons and molecules. Heat flows from hot to cold due to the difference in internal energy; the hotter the material, the more energy is available for transfer.

The mathematical law is called Fourier's law. The law for a one-dimensional object is as follows:

$$q = \lambda * \frac{dT}{dx} \qquad (4)$$

q = heat flux (W/m^2)
λ = thermal thermal conductivity (W/m*K)
dT = Temperature difference across the wall
dx = thickness of the wall

This equation describes the heat transfer through a wall with thickness dx and temperature difference dT. There are three main parameters:

- λ, which is determined by the properties of the insulation material.
- dT, temperature difference between the inside of the cold store and the outside. Therefore, sufficient sun protection is extremely important.
- dx, thickness of the insulating material.

To determine the amount of heat that passes through a wall, the heat flow must be multiplied by the surface area. This is shown below in a simple calculation.

4.2 Convective heat transfer

The way **convection** works is that a stream of air flowing past a surface serves as a medium for heat transfer. A distinction is made between natural and forced convection, the latter being induced by an external source such as a fan. The transfer takes place through the movement of a fluid or gas, which in this case is air, but in other cases can also be water or other liquids or gases that trigger convection as soon as there is a temperature difference. The liquid changes its density due to the heat exchange when it comes into contact with a hotter surface and a displacement takes place. A typical example is the radiator in a house. The air that comes into contact with the radiators warms up and rises, causing a recirculation of colder air to warmer air.

The law describing this phenomenon is also known as Newton's law of cooling, which states that the rate of heat loss from a body is proportional to the difference in temperature between the body and its surroundings due to a flow of air.

$$\dot{q} = h * (Ta - Tb) \qquad (5)$$

q = heat flux (W/m^2)
Ta, Tb = temperature of the object and the liquid (K)
h = heat transfer coefficient (W/m^2 * K)

The heat transfer coefficient depends on the type of flow and the fluid (air) that hits the object. In the case of a cold store, the starting point is to determine the total temperature of the room induced by the cooling unit.

It is important that the cold room is not flooded with air from outside. The heat flow is multiplied by the surface area of the room. The best solution is to place the cold store in a building with as little moving air as possible. Therefore, the doors of the cold room must always be kept closed, as there is a convective flow between the cold air in the cold room and the outside environment. If the outdoor area is large enough, this may result in a very fast and complete exchange of air inside the cold store (in a matter of minutes).

4.3 Radiative heat transfer

Radiative heat transfer is not critical for the cold store, as radiation from the sun only affects the outside of the cold store (supposing the cold store is inside a building and not in the open air). Other sources of radiation are not present or are negligible. The only sources that can cause radiative heat transfer in a cold store are the luminaires. For this reason, the lights should always be switched off when leaving the cold room and it is preferable to use energy-saving lamps or LED lights.

Any object that has a temperature higher than absolute zero (0 Kelvin or -273°C) emits radiation. The thermal energy is converted into electromagnetic radiation, which is mainly emitted in the infrared wavelength range and exchanges energy with the surface it hits.

Stefan Boltzmann developed a law that describes the phenomenon:

$$\dot{q} = \epsilon * \sigma * T^4 \quad (6)$$

$\dot{q}$ = heat flux (W/m^2)
T = temperature of the object (K)
ϵ = emission factor, which depends on the surface and the colour
σ = Stefan-Boltzmann constant ($5.6703 * 10^{-8} Wm^{-2} K^{-4}$)

Not all of the radiative power is absorbed by an object.
To reduce the absorptivity of an object, surfaces are therefore often white. A white surface reduces the emission factor ϵ and thus the heat flux. This is also the reason why many outdoor surfaces are white, especially in warm countries.
If the radiative power of the sun needs to be determined, the easiest way is to retrieve data from meteorological institutes.
In developing countries, many buildings have corrugated iron roofs. If a cold store is planned and it is to be located under such a roof, this must be included in the calculations, i.e. the radiation from the sun plays a significant role.
Besides the emission factor, the amount of radiation also depends on the temperature. A steel roof can easily reach 60–70°C and this corresponds to radiation from the sun radiating onto a surface at about $400 W/m^2$. The energy inflow corresponding to the radiation of $400 W/m^2$ must then be included in the output of the cooling unit. Placing the cold store under an insulated roof that better reflects the sun's radiative power is highly advisable, as opposed to planning a larger cooling unit. This results in higher energy consumption and reduces the overall efficiency of the cold store.

5 Calculating the required cooling capacity of a cold store

This chapter discusses all parameters that are required for calculating the cooling capacity of a cold store.

5.1 Energy needed to change the temperature of food

The physical term used to determine the energy required to keep food cool is given by the specific heat capacity. The specific heat capacity (C) indicates the amount of heat or thermal energy to change the temperature of 1kg of mass by 1°C. A distinction is made between the heat capacity for food above and below the freezing point. In a phase change, the heat is used to achieve this change while the temperature remains constant. The energy required for a phase change is called the enthalpy of fusion or latent heat of fusion.

If food needs to be frozen from ambient temperature, the steps are therefore:

- Heat to cool the food down to freezing point
- Heat to carry out the phase change
- Heat to reach the desired freezing temperature.

The following example shows the energy needed to cool fish from ambient temperature to just below freezing.

Table 3: Thermal properties of fish

Property	Value	Device
Freezing point	-2.2	°C
Specific heat capacity above freezing point (C_{above})	3.18	kJ/kg.K
Specific heat capacity below freezing point (C_{below})	1.76	kJ/kg.K
Latent heat of fusion (E)	251	kJ/kg

The latent heat of fusion is the energy required for the phase change from frozen to unfrozen and vice versa. During the phase change, the temperature does not change. The specific heat capacity is temperature-dependent, so it must be multiplied by the temperature difference:

$$Q_{above} = C_{above} * m * \Delta T \qquad (7)$$

Q = Thermal energy (kJ)
ΔT = temperature difference
C_{above} = Specific heat capacity above zero (kJ/kg*K)
m = mass of the fish (kg)

The formula for calculating the thermal energy below the freezing point is the same as the formula above.

For freezing 10kg of fish from ambient temperature 25°C to -18°C, the calculation would then be:

a. Thermal energy for cooling from 25°C to the freezing point -2.2°C:

$$Q_{above} = 3.18kJ/kgK * 10kg * (25°C-2.2°C) = 725kJ$$

b. Thermal energy for the phase change to the frozen state

$$Q_E = E * m \qquad (8)$$

E = latent heat of fusion
m = mass of the fish

$$Q_E = 251kJ/kg * 10kg = 2510kJ$$

c. Thermal energy to further cool the fish from the freezing point to the desired temperature of -18°C.

$$Q_{below} = 1.76kJ/kgK * 10kg * (-2.2°C - 18°C) = 356kJ$$

The total heat energy needed to cool 10kg of fish from 25°C to -18°C is then equal to

$$Q_{total} = 725kJ + 2510kJ + 356kJ = 3591kJ$$

Theoretically, the cooling capacity can be calculated, but one must ensure that the thermal energy is used evenly for cooling.

The cooling capacity required for this depends on the time needed to cool the fish. Assuming the fish needs to be cooled for 18 hours (18 * 60 * 60 = 64800 seconds), the cooling capacity of the cooling unit is then:

$$q_{cooling\ power} = Q_{total}\ [kJ] / time\ [sec] = 3591kJ / 64800sec = 0.055kW = 550W$$

This practical manual is mainly about storing fish on ice inside a cold store. The purpose of the ice is to cool the fish so that it is already at the desired temperature when it is brought into the cold store. The cold storage refrigeration unit then keeps the fish at the desired temperature. Crates are used to transport the fish and ice. There are about 25kg of fish in each crate. It is assumed that the fish has a temperature of about 25°C after being caught and must be cooled down to 2°C, just above freezing point. The latent heat of melting ice is used to provide the energy for this. For 25kg of fish, approx. 6.25kg of ice is needed (approx. 25% of the weight).

Table 4: Thermal properties of ice

Property	Value	Device
Freezing point	0	°C
Specific heat capacity above freezing point (C_{above})	4.18	kJ/kg*K
Specific heat capacity below freezing point (C_{below})	2.1	kJ/kg*K
Latent heat of fusion (E)	333.5	kJ/kg

The thermal properties of ice are listed in the *table above* and in detail the calculation is as follows:

a. Thermal energy to cool fish from 25°C to freezing point 2°C:

$$Q_{above} = 3.18kJ/kgK * 25kg * (25°C - 2°C) = 2070kJ$$

b. Thermal energy by melting ice, phase change therefore we use the heat of fusion:

$$Q_{ice} = 333.5kJ/kg * 6.25kg = 2084kJ$$

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Figure 6: The fish is chilled down using ice before it is moved to the coldstore.

In illustration 7 the fish is cooled with ice. The amount of ice used is sufficient to cool the entire fish. The ice is necessary to cool the fish to the desired storage temperature. It would not be effective to cool the fish with the cooled air in the storage room alone without the use of ice. The heat energy contained in the ice is slightly higher than that required to cool the fish. Sufficient quantities of ice are needed to cover the fish and cool it to the desired target temperature.

In the cold store, boxes containing 25kg of fish and 6.25kg of ice are used so that no additional energy is needed from the refrigeration unit to cool the fish. Instead, the refrigeration unit only serves to keep the fish at the target temperature after it has been cooled down with ice. A positive side effect of storing the fish in boxes with ice is that the fish remains moist and does not dry out. The ice therefore also counteracts moisture extraction by the cooling system. Moisture removal occurs through the condensation of the air flowing back into the refrigeration unit and this removes moisture from the cold room. This is not beneficial for the stored goods.

5.2 Persons entering and working in the cold store

A person working in a cold store gives off heat because their body temperature is about 36–37°C. In large cold stores where temperatures are below -18°C, people wear heavy clothing; this reduces the heat brought inside. This is not always the case with fresh fish or meat, as the temperatures are only about 2–4°C.

Taking into account the heat emitted by one person of 0.27kW, the factors that influence the heat introduced into the cold room are as follows:

- How much time does this person spend in cold storage?
- How often is the cold store entered?

A person who spends 5 minutes (300sec.) in the cold store to do their job 15 times a day:

$$Q_{person} = 0.274kW * 300sec * 15 \text{ (number of entrances)} = 1215kJ$$

A person who spends 5 minutes (300sec.) in the cold store to do their job 15 times a day:

$$q_{cooling\ power} = Q_{total}\ [kJ] / time\ [sec] = 215kJ / 64800sec = 0.019kW = 190W$$

It is advisable to monitor how often, how many and how long people are in the room over a few days and to review and update logistical plans accordingly.

5.3 Optimisation of the logistical plans

Every time a person enters the cold store, the door is opened and the light is switched on. This allows potentially warmer air from outside to enter the cold store. In addition, the heat given off by the lights causes the temperature to rise.

The calculation regarding the light bulbs is similar to the calculations made above for a person entering the room. Assume that 0.2kW (200W) light bulbs are installed and that they are only switched on when the person enters the room. Therefore, the time the bulbs are on is about 300 seconds. Also, the number of times the bulbs are switched on is equal to the number of people entering the room (15):

$$Q_{light} = 0.200kW * 300sec * 15 \text{ (number of entraces)}$$
$$= 900kJ$$

The cooling capacity is then the same:

$$q_{cooling\ power} = Q_{total}\ [kJ]\ /\ time\ [sec]$$
$$= 900kJ\ /\ 64800sec = 0.014kW$$
$$= 140W$$

This means that the total cooling capacity for one person and switched-on lighting is 190 + 140 = 330W.

When the doors are opened, an air exchange takes place; warm air enters the interior of the cold room. This is amplified by the differences in atmospheric pressure inside the cold store. If the cold store is designed correctly, the atmospheric pressure inside the cold store is slightly lower than outside. A constant exchange of heat takes place when the doors are constantly open. Therefore, double doors or an additional space in front of the cold store are necessary to adapt to the cold exchange. In large cold stores there is a tunnel with double doors so that the amount of exchanged air is reduced to a minimum.

Table 5: Practical air exchange rates per volume and temperature of the cold room (complete table in Annex I)

Volume of the cold store, Vcr (m^3)	Number of air changes iu for rooms >0°C	Number of air changes iu for rooms <0°C
25	19.5	14.5
30	17.5	13
40	15	11.5
50	13	10

For a volume of $40m^3$, the practical data for air exchange is 15 times per day. The calculation assumes that the enthalpy difference of the air is known. For these purposes, the *table in Appendix 2* is used here. At an ambient temperature of 35°C and a cold room temperature of -18°C, the enthalpy difference of the air is equal to $137kJ/m^3$. At an ambient temperature of 25°C, the enthalpy difference is already reduced to approx. $100kJ/m^3$. It is therefore important that the area in front of the cold store is as small as possible and has the lowest possible temperature.

Assuming a cold store of $40m^3$ has an outside temperature of 35°C and a desired inside temperature of -18°C, the amount of lost heat energy is calculated at 15 air changes per day:

Air exchange volume

$$V_{air\ exchange} = V_{cr} * \text{number of door openings} * f \qquad (9)$$

Vcr = Volume cold store

f = correction factor, 2 for goods that remain in the cold store for a short time (a few days) and 0.6 long-term storage for cold store <= $40m^3$.

The air exchange volume is then the same:

$$V_{air\ exchange} = 40m^3 * 15.2 = 1200m^3$$

The heat that enters the room every day in a 24-hour period is then the same:

$$Q = \Delta E * V_{air\ exchange} * 1\ day \qquad (10)$$

ΔE = enthalpy difference according to Annex II (kJ/m^3) is then the same:

$$Q = 137kJ/m^3 * 1200m^3 = 164.400kJ$$

This is quite a high value, which must then be discharged by the cooling unit. It is therefore advisable to have a space in front of the cold room to limit the air exchange. The volume for the space in front of the cold room is 25% of the size of the cold room. According to these considerations, the volume of air exchange is $10m^3$ instead of $40m^3$. If the temperature in this room is additionally lowered to 25°C, the heat energy supplied to the cold store changes drastically:

The total air exchange per number of openings is then:

$$V_{air\ exchange} = 10m^3 * 15.2 = 300m^3$$

The enthalpy difference between -18°C and 25°C is equal to 69.8 and thus the heat energy supplied:

$$Q = 69.8kJ/m^3 * 300m^3 = 20{,}940kJ$$

Compared to the 164,400kJ without an antechamber, the 20,940kJ is a big improvement.

Figure 8 shows an anteroom; the entrance to the cold room is on the right-hand side, the exit on the left-hand side. This area is closed off by another door, which reduces the volume of exchanged air when the cold room is opened.

Figure 7: Anteroom entrance to a cold room

The layout design of the cold store and the surrounding area as well as the logistics play a decisive role in the energy consumption of the refrigeration plant.

5.4 Heating effect on fruit and other crops

When fruit or crops are stored in cold storage, additional heat is generated by the decomposition processes taking place. The dissipation of heat energy is given by the specific respiration heat per day. The decomposition of fruit and crops has led to controlled atmosphere cold stores where chemicals are added to the air to reduce the chemical process of decomposition. This can also keep fruit and crops fresher for longer.

As this practical handbook does not deal with fruit and crops, the following only briefly explains how to calculate heat.

$$Q = m * a * t \quad (11)$$

m = mass (kg)
a = specific cellular heat (kJ/kg*day)
t = number of days

5.5 Cold store insulation heat loss

An insulated cold room can never achieve complete insulation (100%). Therefore, the temperature cannot remain constant. The challenge is to balance the amount of insulation with the refrigeration unit and the goods placed in it. Cold rooms are used for 8–10 hours in a working day. During the night, the insulation should reduce the work of the refrigeration unit to a minimum.

Considering that cold rooms last 10 or more years, the energy and related costs can add up to a considerable sum. For the calculation, it is assumed that a cooling unit normally operates 18 h/day. If it is possible to reduce the energy consumption of the cooling unit by 1kW cooling capacity, then the following applies:

*10 years * 365 days * (18 h) * 1kW = 65,700.00kWh*

In addition, large refrigeration units are more expensive to maintain and the goods heat up more quickly during power outages.

The cold store shown in *chapter 6* was used as an example for the calculation. It has a size of:

L * W * H : 4.4 * 3.8 * 2.4m.

The heat loss is calculated according to Fourier's law (par. 5.1.1.) and the important parameters are:

- The properties of the foam such as the thermal conductivity λ (W/m*K) given by the supplier
- Temperature difference between the inside (desired temperature) and the outside (ambient temperature) of the cold room
- Thickness of the foam insulation.

With regard to the last point, it is not the total thickness of the panel that is of interest, but only the thickness of the foam. The total thickness means the thickness of the panel including the facing material. A steel sandwich panel with a total thickness of 152mm has a thickness of the insulation of 150. 1mm must be deducted for each steel cover.

A cold store is a long-lasting system that will be in place for a considerable amount of time. For the following calculation it is therefore assumed that the cold store is placed under a cabin that prevents direct sunlight from hitting the surfaces. The heat influence on the roof is particularly high; depending on the location, approx. 400W/m^2 must be added.

If the outside ambient temperature is 35°C and the cold store building is well ventilated, the outside temperature for all walls will be 35°C. For the roof, 11 K is conservatively added, the allowance for a black roof in direct sunlight. More information on this can be found in VDI 2078[2].

The floor of the cold store is placed on concrete and the temperature of the floor is a crucial factor. Whether the concrete slab is placed on the floor, on a plinth or with additional space underneath has an impact on the calculations. The floor temperature does not vary much over the course of a year and at a depth of about 50cm a constant value is expected. This will also be the temperature of a floor when it is placed directly on the ground.

If there is a base or an additional room under the cold room floor or the cold room is placed inside a building, e.g. on the 2nd floor, the ambient temperature can be assumed.

If the ambient temperature outside the cold store cannot be determined, then the highest ambient temperature for all walls and for the roof should be used and 11 K added.

The next step is to include the thickness of the insulation and the insulation properties in the calculations. The cold store insulation provides the data for heat loss. The refrigeration system is designed based on this heat loss and the food stored in the cold room. Most of the time, certainly during nights and weekends, the cold store will not be open. Therefore, maintaining a constant temperature is a big cost factor.

The higher the heat loss when the cold room is not in use and runs at a constant temperature, the higher the operating costs.

2 VDI 2078: Calculation of thermal loads and room temperatures (design cooling load and annual simulation).

5.6 Logistical aspects

There are several reasons why planning the logistics around a cold store is particularly important. Certain aspects should be considered in the planning, how to work with and around the cold store and what systems are needed, etc. Some of the aspects to consider are:

- The amount of food to be in the cold room, as this is used to calculate the thermal load
- How often are the doors opened and the lights switched on, as this increases the temperature in the cold room
- How often will people go into the cold room, as this heats up the cold room temperature through body heat.

When operating a cold store, the following possible priorities must be observed once the cold store is in operation:

- To get as much food in as possible
- To make the room as full as possible
- And to make the cold store produce ice to cool the goods.

These problems are typical and usually occur as soon as a cold store is installed and in operation. To avoid ineffective use of a cold store and thus reduce efficiency, planned logistical aspects should be well thought out beforehand and carried out as thoroughly as possible. The cold store designed and implemented for the Kenyan pilot project is a 5-tonne cold store, meaning that 5 tonnes of fish embedded in ice can be stored in it. The fish are cleaned and washed before entering the cold store and placed in a box together with the ice. Each crate contains 25kg of fish and 6.25kg of ice weighing about 35kg, i.e. 200 crates are needed for 5 tonnes of fish. A logistical plan of how best to bring the goods to the cold store helps the efficiency of the cold store.

The cold store is designed for 15 door openings per day and these door openings also include the times needed for maintenance, i.e.:

- Check that not all the ice has melted
- Extract water from the melting ice
- General examinations.

A logistical plan is proposed below to reduce the number of door openings and thereby improve the efficiency of the cold store:

- Start cooling the room a few hours before bringing in the goods
- Check the temperature of the cold room
- Clean and wash the fish (outside the cold store) and then place it under ice
- Prepare the boxes for placement in the cold room
- Place these boxes in the anteroom and close the door
- Open the cold store and push the boxes in
- Close the cold store and stack the boxes.

Following the above steps is efficient and beneficial for the stored goods and limits opening the doors several times and leaving the cold room door open. If a proper logistics plan and procedure is not followed, the following problems may occur:

- humid and hot air may enter the cold room because the doors are ajar
- humid air may turn to ice on ceilings and food
- the cooling unit may freezee faster and require additional maintenance
- the cooling units may have to be defrosted and hot air is blown into the cold room as a result
- the goods may heat up
- more cooling may be needed and energy costs may rise.

During the year, GIZ Proklima and its experts noted many different practices in terms of logistics once the systems were in place. In general, it was found that doors were often left open or in some cases even replaced by curtains to facilitate access for loading and unloading. Also that goods were removed from and brought into cold stores in units that were too small resulting in additional door openings. The anterooms were extremely warm due to heat from hot air of the refrigeration units, instead of venting the hot air through a roof or windows. It is therefore important to develop a 'best practice' logistics plan and processes and have a guideline against which to check working practices once the cold store is up and running.

It is recommended to consider the following steps when creating a logistical process plan:

1. Which goods are to be stored? This determines the required cooling capacity.
2. At what temperature should the cold room operate, especially with regard to the standards set by the health department?
3. How should the cold store be loaded: all the goods at once or several times a day?
4. Is the cold store completely emptied when the goods are delivered? If so, it may make more sense to have several smaller cold stores instead of one large cold store.
5. What type of hygiene level is required? Dry, packaged or wet goods such as meat and fish require different approaches.

It all starts with a logistical schedule! Simple as it may be, it helps the cold store operator to check the efficiency of the work processes and improve them if necessary.

6. Carefully check and monitor ambient temperatures and humidity before deciding on a particular cold room. The data assessment should be very conservative, otherwise an undersized cooling system and insufficient insulation could be the result.
7. Perform various calculations based on the different expected seasons in the region.
8. Train staff in the use of the cold room and clearly define the limits of use.

5.7 Power outage time

In some areas, a reliable energy source and supply from a reliable grid system may not be possible. A reliable energy source is important as it ensures continuous cooling of the goods. If the cold store is operated with a non-reliable energy source, opening the cold store should be avoided during power outage periods.

The cold room should not be opened while the power is down. A closed cold room loses very little of its cooling capacity!

To bridge energy loss periods, good insulation is crucial. A closed cold store that is well insulated loses little heat, in the example from Kenya about 600W in 24 hours, i.e. 20W per hour. With well-chilled fish on ice, the temperature drop is minimal for a few hours. If there are regular power outages lasting longer than 4 hours, then an alternative power source is strongly advised. In countries where HACCP rules are applied and controlled, it is already mandatory to have and use an alternative energy source when performing a hazard analysis.[3]

3 HACCP hazard analysis and critical control points

5.8 Summary thermal energy loss cold store

From a thermal point of view, a cold store is made up of various elements:

- The cold store as a physical shell
- Food stored in cold storage
- The refrigeration/air conditioning system
- Logistics regarding the storage of goods in the cold store.

The desired capacity of the cold room must be calculated before planning the cold room itself. Although there are calculated standard values, these should only be considered as guidelines. Specific adjustments for the respective region and for the planned use of the cold store should be obtained. The following data is needed for the calculation:

- Cold room dimensions, insulation material and properties
- Physical properties of the stored goods (heat capacity above and below freezing point, freezing point, latent heat)
- Storage temperature of the goods
- Specific respiratory heat for fruit, vegetables, etc.
- Number of times at which the doors are to be opened
- How many workers enter the room when the doors are opened
- How long are the people in the cold room
- Temperature of the goods brought into the cold store
- Quantity of goods and intervals (time) in which goods are brought into the cold store
- Quantity of goods removed from the cold store and at what intervals
- Type and power of lighting and other electrical equipment in the cold room

In many countries, GIZ Proklima has local staff who can help operators choose the right refrigeration technology. For more information on climate-friendly cooling, visit www.green-cooling-initiative.org

- How are the goods placed in the cold room and what is the distance between the goods? Consider as a reference distance the width of a European standard pallet (EPAL)[4] with an additional free space of 20cm on each side facing the goods
- What are the climatic conditions at the location of the cold store in order to determine the ambient temperature
- Where to place the cold room (fully shaded area as in a building or outdoors)
- Is the cold room on a concrete floor in direct contact with the ground or is it a floor with additional space underneath (e.g. on a plinth or on a higher level of a multi-storey building)?

With the above information, the cold store operator can calculate the possible temperature loss for a particular cold store:

- Empty cold store including insulation
- Thermal energy required to maintain the temperature of the goods
- Thermal energy generated by the respiration of goods caused by the chemical decomposition of fruit, vegetables, etc.
- Thermal energy loss due to the opening and closing of the doors
- Thermal energy supply due to people entering the cold store
- Thermal energy contribution of luminaires and other electrical consumers.

The sum of the thermal energy losses and the required heat output make up the input for the selection of the cooling unit.

There is a wide range of refrigeration equipment available, with the preferred solutions using natural refrigerants. Natural refrigerants have shown better energy efficiency values and are more accessible, especially in developing and emerging countries. Moreover, from an environmental point of view, these natural refrigerants are the only sustainable solution for refrigeration, as they have no ozone depletion potential and have only a minor impact on the climate. In addition, the end-of-life treatment of systems and appliances containing natural refrigerants is much less costly than for appliances using synthetic refrigerants.

4 Length: 800mm, Width: 1,200mm, Height: 144mm

5.9 Selected system design based on calculations

The above calculations enable the future operator of a cold store to choose the most suitable system.

In the case of the fish cold store in Kenya, for which many of the above example calculations were carried out, the following system design was chosen:

- Fish placed on ice to reduce the cooling capacity of the cold store.
- The cold room is placed indoors to avoid heat radiation from the sun and convective heat transfer from wind and possible rain.
- Thick insulating panels in PU to reduce heat loss to a minimum when the room is not in use or in the case of electricity savings.
- An anteroom in front of the cold room to reduce the temperature loss of the latter by opening the doors.
- A well-thought-out logistical concept that includes both the food coming in and out and the opening of the doors, as well as the staff in the room.
- The incoming temperature of the food is well controlled.

6 Cold store design

6.1 General design considerations

The first step is to determine the purpose of the cold room and what is to be kept frozen or fresh. The production process is also important for the design, if goods need to be washed and cleaned or go through other processes. These production processes are important because the working route must be defined. Here, the working route means the transport of the goods, the cold chain. Meat, fish and other goods, for example, have to be cleaned for hygienic reasons and must not be mixed with the finished goods.

In a straight production line, the goods come into the area, are cleaned, washed and packed. From there they go to the cold store. One of the factors affecting the cooling of the cold store is the area in front of the door. Preferably, a separate room is built to reduce the amount of warm air that would enter the cold room when the door is opened.

The following subchapters provide an overview of the various construction elements in a cold store.

6.2 Cold store layout

A possible layout for a cold room is shown in the following figure:

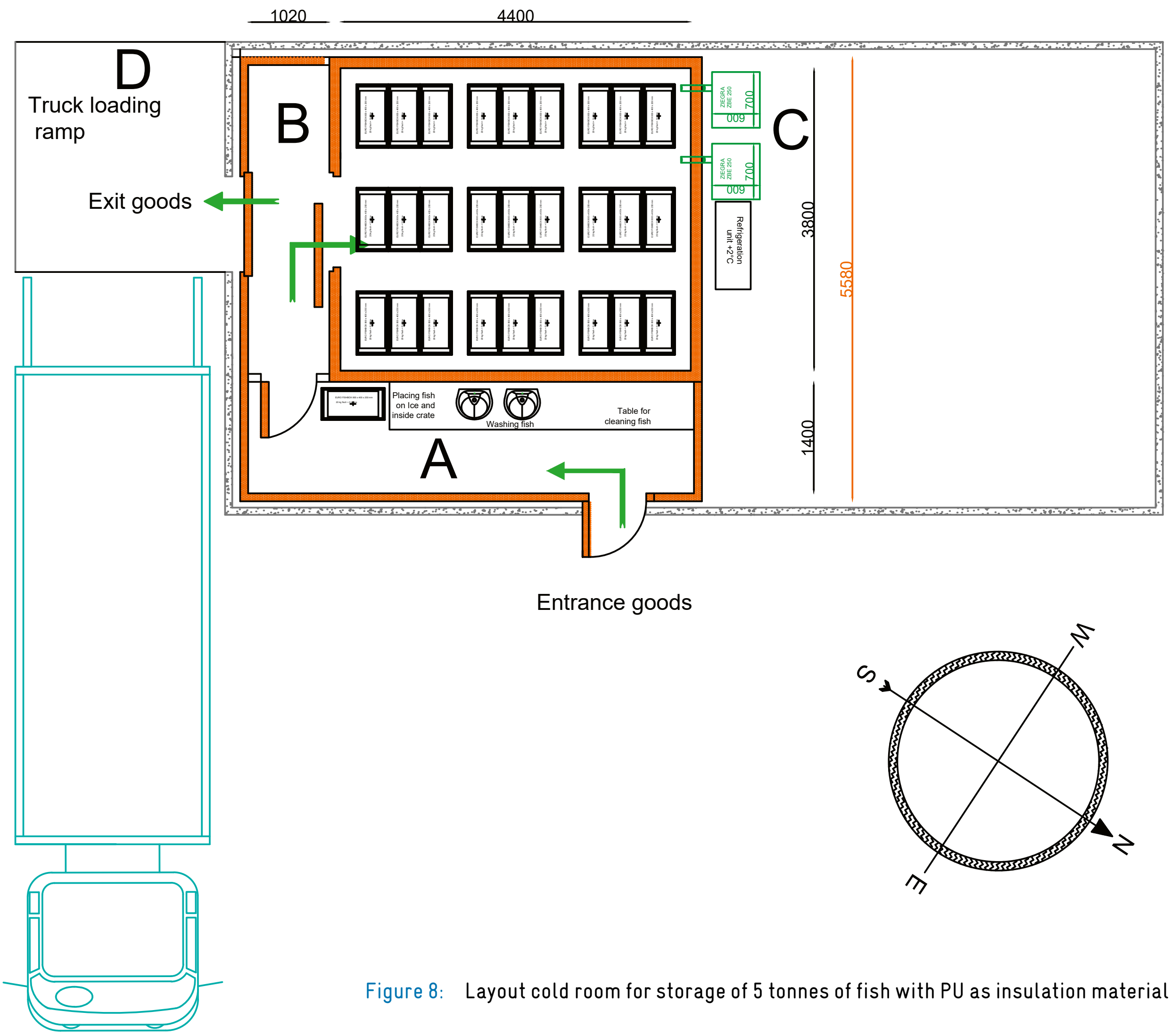


Figure 8: Layout cold room for storage of 5 tonnes of fish with PU as insulation material

The cold room 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).

A hose is used to discharge the ice either directly in the cold room (option c) or inside the anteroom (option d). From there, the ice can be taken in open boxes to where it is needed so that excess water can drip off. The advantage of option c is that a container of ice is placed in the cold room to act as a backup cold store in the event of a power failure.

An ice maker is a refrigerated appliance that generates heat. Therefore, it is preferable if it is not placed in areas that need to be kept cool.

Various considerations were made for the cold store to store fish:

- **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 T 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.

To improve the quality of the water used for ice production, Lakeview Fisheries installed a reverse osmosis water purification system.

6.3 Selection of the natural refrigerant (focus: propane)

Currently, most refrigeration systems in developing countries still use **HFC refrigerants or HFC-based hydrofluoroolefins (HFOs)**. Unlike conventional HFCs, HFOs are unsaturated. Both HFCs and HFOs are synthetic chemicals. Conventional HFCs have a very high global warming potential, while HFOs have a low global warming potential. Both HFCs and HFOs, as synthetic chemicals, have a **harmful effect on the environment when released**. As synthetic chemicals, they do not occur naturally in the atmosphere or the environment. Some HFCs and HFOs break down into **trifluoroacetic acid (TFA)**, a persistent acid that accumulates in the environment and can impair or inhibit vital organic processes. The increased use of HFOs has long-term effects on the environment, the full implications of which are unclear at this stage. For this reason, the use of so-called "natural refrigerants" with no or very low global warming potential is recommended. In the following chapter, different climate-friendly refrigerants are presented and compared in their field of application.

The previous chapters described the refrigeration design considerations to achieve the required cooling capacity. The proposed cooling system consists of two components:

- Component 1: An **ice machine** to produce the required amount of ice to cool the fish to 0° C.
- Component 2: A cooling system to keep the temperature at 0°C.

The ice maker should produce a sufficient amount of ice. For a fish cold store with five tonnes of fish cold storage, the cooling capacity of the ice maker is 0.8kW and the cooling capacity of the refrigeration system is 1.9kW. The ice maker with 0.8kW cooling capacity produces 230kg of ice flakes per day for about 1 tonne of fresh fish.

Choice of refrigerant: Propane (R290)

The recommended refrigerant for both the ice maker and the cooling system is the natural refrigerant **propane (R290)**, as the cooling capacity is less than 5kW. *Table 6* gives an overview of the possible refrigerant options for the ice maker and the cooling system. The filling quantity of the ice maker is 118 grams and that of the cooling system 150 grams. According to the refrigeration safety standard IEC 60003-2-89, the maximum permissible filling quantity is up to 500 grams. At these low refrigerant charge levels, the flammability of propane (classification A3) is within safe limits. As a rule, locally trained service technicians can safely handle these filling quantities.

The advantages of propane (cooling capacity less than 5 kW) are:

- Propane is a climate-friendly refrigerant with a low GWP (<3)
- It has excellent energy efficiency properties
- The upfront investment costs are manageable
- Propane plants have limited system complexity that can be handled by qualified local service technicians in developing countries.

For systems with a cooling capacity above 5kW, the following options are available with natural refrigerants:

- 5–500kW with propane as refrigerant and with secondary cooling circuit
- Over 5kW with R744 (carbon dioxide) sub- or transcritical
- Over 200kW with R171 (ammonia) systems.

This guide focuses on the design of smaller cold stores which have a refrigeration system with a cooling capacity below 5kW. For larger cold stores that require a cooling capacity of more than 5kW, other design considerations are required that are beyond the scope of this guide.

Table 6: Comparative overview of the different refrigerant options

Refrigerant	GWP of the refrigerant	Energy efficiency	Costs	Complexity	Affordability
Natural refrigerants					
R290	√√√	√√√	√√√	√√√	√√√
R 744 (CO_2)	√√√	√√√	√√	√√	√√
R 717 (NH_3)	√√√	√√√	√	√	√ – √√√ (3)
Synthetic HFC refrigerant					
R 404A, other HFCs	–	√	√ (1)	√√√	√ (2)
U-HFC (HFO)	√√√	√√√	√ (1)	√√	√ (2)

Note (general): √√√ significant advantage, √√ small advantage , – no advantage or negative
Note 1: The cost of the system hardware is cheap, the cost of the refrigerant is very high!
Note 2: Affordability becomes negative as the use of HFC refrigerants becomes more restricted
Note 3: Affordability of ammonia depends on availability of specialised technicians

6.4 Other natural refrigerant alternatives to propane

Below we provide a brief description of alternative natural refrigerants with a brief assessment of their suitability for smaller cold storage solutions.

R744: R744 (CO_2) refrigeration systems are undergoing a steep technological evolution and may become a suitable technical solution for refrigeration systems in developing countries. However, R744 systems operate at high pressures, which requires special training for service technicians. For smaller refrigeration systems, qualified R744 service technicians are not yet readily available in developing countries. Larger systems can afford to train and deploy specialised service technicians for maintenance. In addition, R744 as a refrigerant has a low critical point at 31°C, which means that the refrigerant does not effectively condense when the R744 system is operated at higher ambient temperatures. Additional measures (additional re-cooling units/ transcritical CO_2 systems) allow condensation even at higher ambient conditions, but at the expense of the energy efficiency of the system.

R717: Ammonia is a natural refrigerant with excellent thermodynamic properties and higher ambient conditions in developing countries. From a climate protection point of view, R717 is a very favourable refrigerant, with zero GWP and ODP. The achievable energy efficiencies with R717 are excellent. The disadvantages of R717 are its toxicity. Due to its toxicity, the use of the refrigerant in populated areas requires special permits. Service technicians require special training and certification.

In addition, the plants are more complex and the components more expensive. To avoid corrosion, the use of R717 requires the use of stainless steel materials. Consequently, R717 refrigeration systems require larger scale plants which have cooling capacities above 500kW with a dedicated and trained service technician workforce.

Not recommended from an environmental perspective: Synthetic refrigerants

HFCs (**R404A, R407A, R407F, R442A and R32**): The HFC R404A has an extremely high GWP of 4470 compared to 3 for R290. R404A and other HFC refrigerants with high GWP for refrigeration systems are still common in most developing countries. Refrigeration systems using refrigerants with GWP above 2500 are banned for most applications under the European F-Gas Regulation. New systems placed on the market will be restricted to a GWP below 150 from 2022. With the restriction on the use of high GWP refrigerants, also triggered in developing countries by the Kigali Amendment phase down, the cost of maintaining R404A systems will increase due to the introduction of quota systems restricting the use of high GWP refrigerants. The replacement of high GWP refrigerants with alternative lower GWP HFC (e.g. 407A, 407F and 442A) will reduce the energy efficiency of these systems.

U-HFC (HFO): These latest generation refrigerants have a low GWP. While HFCs are non-flammable (A1), HFOs have a higher flammability (A2L). Due to the higher flammability, the use of HFOs requires the skills of refrigeration technicians for flammable natural refrigerants. In both cases, refrigeration technicians must be qualified to service and maintain the equipment. The refrigeration systems are more complex due to the temperature glide. HFOs require complicated and costly recovery and destruction at the end of their life. Proper end-of-life disposal is usually not available in developing countries and have significantly higher costs than natural refrigerants.

Supplier of R290 ice cube makers and refrigeration systems for cold stores

The use of ice makers and refrigeration systems for cold stores is a proven and well-functioning technology. There are several established suppliers of ice makers and refrigeration systems for cold stores. *Table 7* gives an overview of ice makers and refrigeration systems for cold stores. The table shows only an overview of some established suppliers, without being complete or exhaustive.

	Ice maker	Refrigeration
System supplier	Ziegra ice machines (R290)	Rivacold Spa (R290 and R744)
	Marel (R290, CO_2, NH_3)	Teko GmbH (R290 and R744)
	Scotsman Ice (R290)	Emicon Spa (R290 and R744)
	Recom (NH_3)	Zanotti Spa (R290)

Table 7: Overview of suppliers for cold store ice cube makers and refrigeration systems

6.5 Alternative energy supply, roof insulation

As described above, an interruption in the power supply from the grid may require an alternative energy source. Different sources can be used, such as an independent power generator, biomass, wind generators or solar panels. Solar power was chosen for this cold store. The design of the cold store requires a power consumption at a peak demand of about 2.6kW. To meet this demand, 10 to 12 solar modules, which can be mounted on the roof, are sufficient.

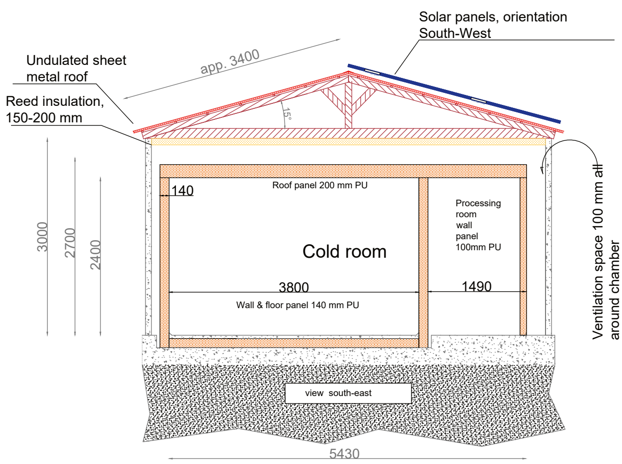


Figure 9: South-east view of the cold store and the building with embedded floor

The panels are placed on the roof and receive ideal solar radiation from the southwest, depending on the orientation of the building. Two panels can be placed side by side on the roof. With 5 or 6 columns, 10 to 12 panels can easily be placed to provide the required output. As the roof is made of corrugated steel panels, reed or other insulation is required between the cold store and the steel roof in addition to the ventilation system around the cold store.

It is advisable to have a layer of air between the panels and the outer walls. This prevents conductive heat from being transferred directly to the cold storage panels. This layer of air creates a cushion that provides additional insulation. This air can circulate at low speeds by natural convection.

The position of the cooling unit is at the rear of the cold room. Centred in the middle to allow well-distributed airflow to the sides and front of the cold room.

Figure 10: Preparing the roof panel for installing the cooling unit

Figure 11: Refrigeration unit on the roof and ice cube makers dispensing ice directly into the cold room

Units in which the condenser, evaporator, compressor and control are housed in one unit are optimal. This avoids the use of piping, complicated installation and reduces the risk of leakage. In the case of multiple cold rooms, centralised units can be considered, but it is important to take into account how the cold rooms are used and what temperatures are required. A suitable logistical model is required for dimensioning the required cooling load if all or only a few cold rooms are used.

The picture below shows the position of the solar modules, which are mounted at an angle of 15° and consist of modules with an output of 260 watts (typical size 1665 * 991mm).

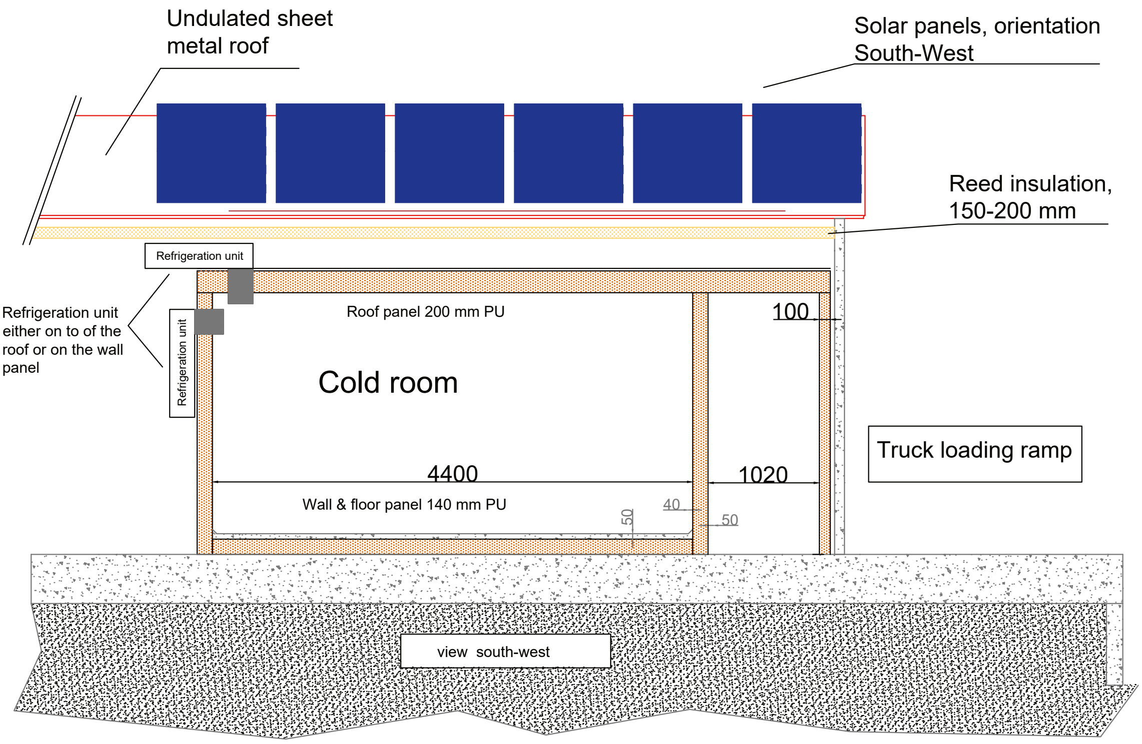


Figure 12: Southwest view of the cold store and the building

Figure 13: The Lakeview Fisheries team together with the technical consultant Igor Croiset (HEAT) commissioned by the Green Cooling Initiative.

Figure 13 shows the insulation embedded in the concrete. When constructing the floor, an opening should be made, which is then filled with insulation and then a cement floor is placed on top. The advantages for this method are that:

- This can be done over the entire area of the cold store as well as over the processing area
- Different types of insulation material can be used, which are cheaper than metal-coated sandwich panels
- After sealing the cement floor with special varnishes, it is easier to clean
- A door threshold between the cold store and the processing area is not needed, so heavy machinery can be used to transport goods in and out.

However, this method may not always be possible, especially if the cold store is installed in existing buildings. In this case, the cold room floor will be higher. An option in this case could be to level the entire floor after installing the cold room.

7 Solar-powered fish cold stores

In the previous chapters, the suggestion was made to combine a cold storage facility with natural cooling with solar-powered off-grid solutions. Especially in regions where electricity supply cannot always be guaranteed, it is important for the efficiency of the chiller and the efficiency of the cold store in general that additional energy sources are available.

Especially in regions with high solar irradiation, PV systems are an optimal solution to ensure an off-grid energy supply. The following subchapter provides a brief introduction to the different PV systems, electricity storage systems as well as basic introductions to the professional installation of PV systems and adequate maintenance measures.

7.1 Introduction to solar photovoltaic technology

Renewable energy is defined as "natural energy reserves derived from energy resources that are either permanently available or renewable in the foreseeable future". One of the largest renewable energy sources is radiation from the sun.

One way of using the sun's energy is PV technology, with which sunlight can be converted directly into direct current. Solar cells, which are predominantly made of the semiconductor silicon, are used as energy converters. The scope of this technology ranges from solar-powered devices in the milliwatt range to large-scale power generation plants in the megawatt range.

The main item commercially available in the PV market is the PV module. PV modules are rated according to the power delivered under standard test conditions (STC) of 1kW/m² sunlight and a PV cell temperature of 25°C. Their power measured under STC is expressed in "peak watt" or Wp rated power. Note that the specification 175Wp means that PV manufacturers produce modules with the ability to generate 175Wp of electrical power (rated power) under STC of 1kW/m² sunlight, 25°C cell temperature.

PV modules are integrated into systems designed for specific applications. The components that are added to the module form the Balance of the System (BOS). BOS components can be divided into four categories:

- Batteries – store electricity to provide power when needed at night or on overcast days
- Inverters – are needed to convert the DC power generated by the PV module into AC power
- Controllers – manage energy storage in the battery and deliver power to the load, and
- Structure – required for mounting or installing the PV modules and other components.

Not all systems require all of these components. In systems where there is no AC load, for example, no inverter is required. In grid-connected systems, the utility grid acts as a storage medium and batteries are not required. For PV water pumping systems, where a water reservoir buffers short-term differences between supply and demand, batteries are usually not required. Some systems also require other components that are not strictly related to PV. For example, some stand-alone systems include a fossil fuel generator that provides electricity when the batteries run out; and water pumping systems require a direct current (DC) or alternating current (AC) pump.

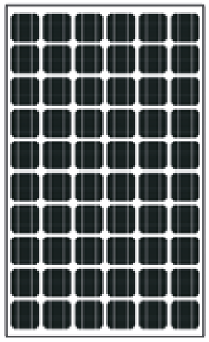
There are different types of companies and players involved in the photovoltaic industry. Typical players are PV cell/module manufacturers, BOS manufacturers, product distributors and traders, and system integrators.

7.2 Overview of PV cell technology

There are different types of PV cell technologies. Depending on the planned application, the costs and the required power. The power is the main criterion for the space required to place the PV.

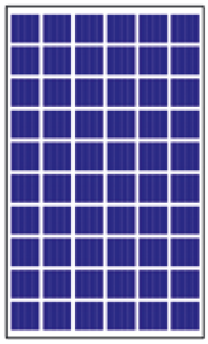
Monocrystalline PV cells

- Also called monocrystalline silicon.
- Recognisable by an outwardly uniform colouration and appearance.
- Typical efficiency 14–20% highest values because they are made from the highest quality silicon.
- 1 KWp installed power requires 5.5–7.5m².



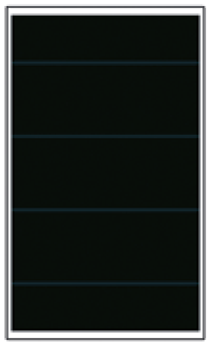
Polycrystalline PV cells

- Polycrystalline solar modules have a slightly lower heat tolerance than monocrystalline ones. They perform slightly worse at high temperatures than monocrystalline ones.
- Typical efficiency 11–16%.
- 1 KWp installed power requires 6–9m².



Thin-film PV cells

- Typical materials and their efficiency:
  - Amorphous silicon (a-Si) (5–9%)
  - Cadmium telluride (CdTe) (9–12%)
  - Copper indium gallium selenide (10–13%)
- Low cost and efficiency.
- Requires larger area than mono- and polycrystalline



All panels: © shutterstock/chemistrygod

Table 8: Overview of common solar PV technology options

7.3 PV system orientation

- To achieve maximum electricity yield from the PV system, the PV module should face south (for the northern hemisphere) and be inclined at an angle to the latitude.
- In some cases, PV modules are installed at different azimuth angles for various reasons.

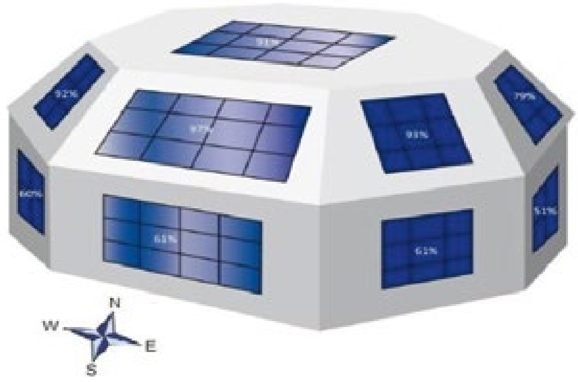


Figure 14: Alignment of the PV modules

7.4 Shading of PV systems

- Shading of PV modules must be avoided as far as possible: Partial shading brings the power generation of the entire string to a standstill!
  - i.e. all coupled, directly connected modules are affected.
  - this is more critical than with solar thermal collectors.
- Shading can be caused either by other objects (trees or buildings) or by self-shading by other PV module strings.

Figure 15: Minimum permissible distance

7.5 Grid-connected net metering

Connecting solar panels or solar systems to the local grid enables one of the most beneficial aspects of generating electricity from the local grid: net metering or net billing. On a sunny day, when more electricity is generated by a solar PV system than is consumed, this excess solar electricity is delivered back to the utility grid, with the effect of flipping the connected electricity meter. When this happens, the operator of a solar system usually receives a credit from the local utility company for the amount of electricity generated by the grid-connected PV system.

If more electrical energy is consumed during the billing period than is generated by the solar panels, the net amount of electricity normally consumed would be billed. However, if more solar energy is generated than consumed, the utility company credits the net amount of electricity generated, which in turn means either a reduction in the monthly electricity bill or a positive payment.

When installing a PV system and if net metering is provided by the local electricity utility, it may be mandatory to install an additional electricity meter instead of using a single electricity meter that is able to subtract kW/h.
This new meter would allow the net energy consumption to be measured both when entering and leaving the system. This new meter allows measurement of net energy consumption, both entering and leaving the system, and would be used to reduce the electricity bill. However, each

electricity utility has its own policy regarding the buy-back of energy generated by small solar power plants. While net metering is the ideal way to resell solar-generated surplus power, some companies buy the power back at a lower wholesale price than the power consumed from the same utility. This means that more solar power has to be generated than is normally consumed, just to avoid additional costs.

Grid-connected PV systems always have a connection to the public grid via a suitable inverter, since a photovoltaic panel or array (several PV panels) only supplies direct current. In addition to the solar modules, other components that make up a grid-connected PV system – compared to a stand-alone PV system – are as follows:

Inverter: The inverter extracts as much direct current as possible from the PV generator and converts it into clean grid alternating current at the correct voltage and frequency to feed into the grid or supply domestic loads. It is important to choose the best quality inverter possible, and the most important considerations when choosing a grid-connected inverter are power – maximum high and low voltage power the inverter can handle, and efficiency – how efficiently the inverter converts solar power into AC power.

Electricity meter: The electricity meter, also called a kilowatt-hour (kWh) meter, is used to record the flow of electricity into and out of the grid. Two kWh meters can be used, one showing the electrical energy that is consumed and the other recording the solar electricity that is fed into the grid. A single bidirectional kWh meter can also be used to show the net amount of electricity that is taken from the grid. A grid-connected PV system slows or stops the aluminium disc in the electricity meter and can cause it to run backwards. This is commonly referred to as net metering.

AC breaker panel and fuses: The breaker panel or fuse box is the normal type of fuse box supplied with a domestic power supply and installation. Additional breakers should be installed for inverter and/or filter connections.
Safety switches and wiring: A photovoltaic array always generates an output voltage when exposed to sunlight, so it must be possible to disconnect the panels from the inverter for maintenance or testing purposes. Disconnect switches rated for the maximum DC voltage and current of the array and safety switches for the inverter must be separate and easily accessible to disconnect the system. Other safety features required by the electrical contractor may include earthing and fuses. The electrical cables used to connect the various components must also be correctly designed and sized.

The electricity grid: Finally, the electricity grid itself to which it is connected. Without the electricity grid, it is not a grid-connected PV system.

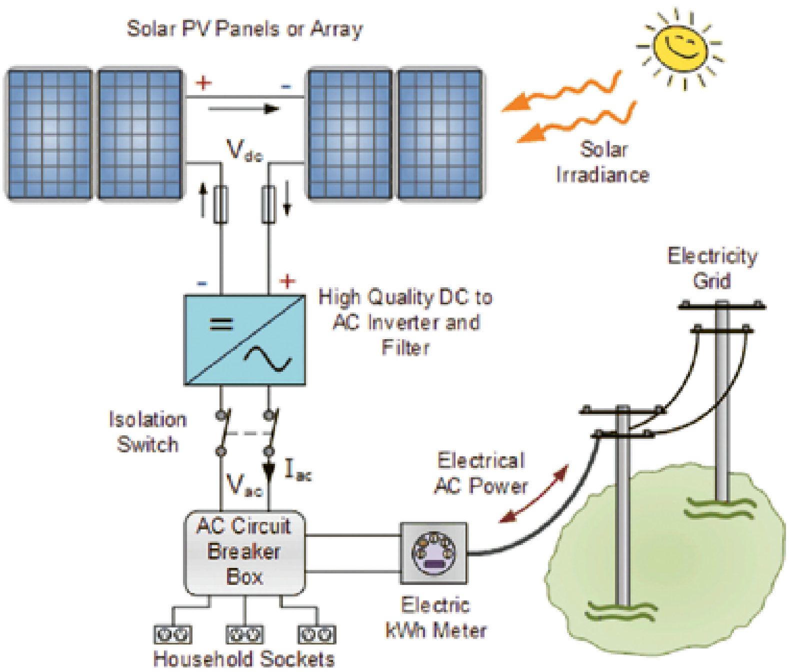


Figure 16: Scheme of grid-connected PV systems
Source: https://www.alternative-energy-tutorials.com/images/stories/solar/alt24.gif

A grid-connected system without batteries is the simplest and cheapest solar power system available, and since there are no batteries to charge and maintain, it is also the most efficient. It is important to note that unlike an off-grid system, a grid-connected solar power system is not an independent source of electricity. If the supply from the grid is interrupted, the power will fail, even if the sun is shining. One way to overcome this is to incorporate some form of short-term energy storage into the design.

7.6 Mains-connected system with batteries

A small photovoltaic solar system equipped with storage batteries can also be operated near the local electricity supplier. Short-term peak demand is covered by the battery without drawing energy from the grid. This avoids paying additional charges incurred by using energy from the grid. When used in grid-connected PV systems, storage batteries can be divided into two categories. Short-term storage for shortages of a few hours or days to cover short periods of bad weather and long-term storage for shortages over several weeks to compensate for seasonal fluctuations in solar radiation between summer and winter months.

Incorporating batteries into a grid-connected system requires more components, is more expensive and lowers the overall efficiency of the system. But for many homeowners in remote areas who regularly experience a loss of grid supply in bad weather conditions or have critical electrical loads that cannot be interrupted, some form of backup energy storage within their grid-connected system can have great benefits.

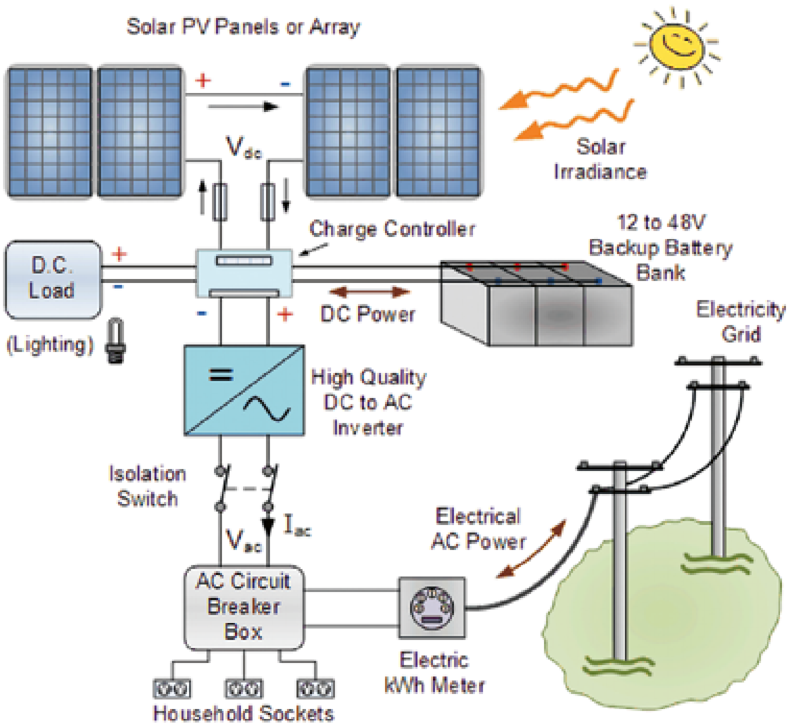


Figure 17: Schematic of grid-connected PV systems with batteries
Source: https://www.alternative-energy-tutorials.com/images/stories/solar/alt25.gif

7.7 Batteries

If an off-grid PV system needs to provide energy on demand and not when the sun is shining, a battery is required as an energy storage device. The most common battery types are lead-calcium and lead-antimony. Nickel-cadmium batteries can also be used, especially if the battery is exposed to a wide range of temperatures. Due to the variable nature of solar radiation, batteries must be able to withstand many charge and discharge cycles without damage. The amount of battery capacity that can be discharged without damaging the battery depends on the battery type. Lead-calcium batteries are only suitable for shallow cycle applications where less than 20% discharge per cycle occurs. Nickel-cadmium batteries and some lead-antimony batteries can be used in deep cycle applications where the extent of discharge may exceed 80%.

Depending on the conditions on site and the presence of a backup generator, battery banks are sized to provide system autonomy from a few days to a few weeks (e.g. in some very specialised applications such as systems above the Arctic Circle). Batteries are characterised by their voltage, which for most applications is a multiple of 12V, and their capacity, expressed in ampere-hours (Ah). For example, a 50Ah, 48V battery stores 50 × 48 = 2,400Wh of current under rated conditions.

Note that optimising battery size is critical to achieve good battery life, suitable system performance and optimal system life cycle costs. Unnecessary battery replacement is costly in remote applications.

Lead-acid gel battery

For Pico PV systems such as Solar Home Systems.
Maintenance-free.

- 12V / 12Ah
- 12V / 18Ah
- 12V / 24Ah

Sealed Deep Cycle AGM Battery

Suitable for high current discharge applications such as inverters, bow thrusters, winches and engine starting.

- 12V / 20Ah – 200Ah

The single-cell OPzS battery is a closed stationary battery with liquid electrolyte

Optimal for use in areas with high load in charging and discharging operation. Life expectancy of up to 1500 cycles at 80% depth of discharge.

- 1.8V / 200Ah – 3250Ah

Table 9: Overview of common solar cell battery options

7.8 Inverters

The basic function of an inverter is to "invert" the DC output to AC. AC is the standard used by all commercial equipment, which is why many consider the inverter to be the "gateway" between the photovoltaic (PV) system and the energy consumer. Inverter technologies have evolved significantly to provide other various functions and services in addition to converting DC to AC to ensure that the inverter can operate at optimum performance.

Four main functions or features are common to all transformer-based grid-connected inverters:

- Reversal
- Maximum Power Point Tracking
- Mains isolation
- Integration and packaging.

Inversion. The method by which direct current from the PV generator is converted into alternating current is called *inversion*. Apart from use in small off-grid systems and small solar devices, the use of pure direct current from a PV generator, module or cell is not very practical. Although many appliances in homes and businesses use direct current, large loads and the electrical power infrastructure are based on alternating current. This goes back to the early days of Edison versus Tesla, when alternating current prevailed over direct current as a means of electrical power distribution.

An important reason why alternating current has become popular is that power can be increased and long distances can be covered with low losses and with minimal use of materials. This could change in the distant future when more energy is generated, stored and consumed using direct current. Today, the technology exists to boost direct current to high voltages for transmission over long distances, but it is very complex and costly. For the foreseeable future, alternating current will continue to transmit electricity between power plants, cities, households and businesses.

In an inverter, the direct current from the PV generator is converted to alternating current via a series of semiconductor switches – MOSFETs or IGBTs – which essentially switch the direct current back and forth to produce alternating current.

Maximum Power Point Tracking. The method an inverter uses to stay on the constantly moving maximum power point (MPP) of a PV generator is called *maximum power point tracking* (MPPT). PV modules have a characteristic I-V curve that has a short-circuit current value (Isc) at 0Vdc, an open-circuit voltage value (Voc) at 0 A and a "knee" at the point where the MPP is found – the point on the I-V curve where the voltage multiplied by the current gives the highest value, the maximum power. As the cell temperature increases, the voltage decreases. The module power also depends on the irradiance. When the sun is brighter, the module current is higher, and when there is less light, the module current is lower. As the intensity of the sunlight and the cell temperature vary significantly throughout the day and year, the MPP current and voltage of the array also change significantly, which has a strong impact on the inverter and system design.

Grid Disconnection. As required by UL 1741 and IEEE 1547, all grid-connected inverters must disconnect from the grid when the AC grid voltage or frequency falls above or below the limits prescribed in the standard. The inverter must also disconnect when it detects an island, which means that the grid is no longer present. In both cases, the inverter must not connect or export power until the inverter records the correct grid voltage and frequency for a period of 5 minutes. These precautions prevent a PV system from injecting voltage or current into disconnected utility lines or switchgear and posing a hazard to utility personnel. If an inverter is left on or turned back on before the utility is reliably reconnected, the PV system could backfeed a utility transformer. This could create utility pole or medium voltage potentials that could be several thousand volts. Every grid-connected inverter undergoes a variety of tests to ensure that this situation can never occur.

Integration and packaging. Manual AC and DC disconnect devices are provided in inverters or PV systems to allow the inverter to be disconnected from the grid and PV generator when service technicians, installers or other qualified personnel need to shut down the inverter or access the main inverter enclosure. Automatic AC disconnect devices – such as an AC contactor – are used to minimise or eliminate night-time tare losses and reduce vulnerability to damage from night-time surges and lightning strikes. Switching off power supplies, chips and components of all kinds at night also extends their lifespan.

When packaging inverters, all components are combined into a single, shippable unit. (The largest 3-phase inverter packages for commercial and utility applications can be delivered in more than one housing). The packaging also protects the inverter from external influences and keeps unwanted external influences (e.g. from people) away from the units. The use of high-quality materials and surfaces is necessary to meet the requirements of the application.

Off-grid PV inverter 3300W

- Output power: 3300W
- Output type: 2 phases
- Input voltage. 9–17V

Off-grid PV inverter 6000W

- Output power: 6000W / 8000W
- Output type: 2 phases
- Input voltage:172.5V, 264.5V, 172.5V, 264.5V

Grid-connected solar inverter

- Output power: 1-200kW
- Output type: 3 phase
- Input voltage. 120V, 192V, 240V, 360V

Table 10: Overview of common solar PV inverters

7.9 Solar charger

Solar PV charge controllers, also called solar charge controllers, are used in solar PV systems to protect the battery from overcharging and overdischarging. Both conditions lead to damage of the battery. The regulator is a very important part of any power system as the latest technologies come with some highly efficient battery charging routines. An advanced charging routine ensures that the battery is charged as quickly as possible while ensuring that the battery is not damaged by overcharging. The most advanced solar PV controllers use Maximum Power Point Tracking (MPPT) charging, which can provide a power increase of up to 33% over normal controllers, especially in cold but sunny conditions. The charge controller can also provide charging information to the user, often via a small digital display. Some devices record charge data over time, and many offer a range of electrical protection features such as overvoltage protection. Some solar charge controllers also offer a low-voltage disconnect (LVD) function. This function is useful in decentralised PV solar systems to ensure that the connected loads do not discharge the battery to the point of damaging it.

Solar charge controller

- 12 / 24VDC Automatic detection
- Built-in fuse
- Multi-colour LED state of charge indicator
- Current from PV indicator
- Low voltage disconnect (LVD).

Table 11: Example of a solar charge controller

7.10 Dimensioning of PV solar systems

The first step in designing a PV solar system is to determine the total power and energy consumption of all loads that need to be supplied by the PV solar system as follows:

Calculate the total watt-hours per day for each appliance used: Add up the Wh needed for all appliances to get the total Wh per day to be supplied to the appliances. The power consumption of appliances is usually given in watts (W) (e.g. a small portable TV has about 20W. You can find this information on the data sticker that most electrical items have). To calculate the energy consumed over time, the power consumption is multiplied by the hours of intended use.

The 20W TV in this example, which is switched on for 2 hours, draws 20 * 2 = 40Wh from the battery.

A simple way to reduce electricity consumption is to replace halogen luminaires with LED luminaires. LED luminaires typically consume 80% less energy for a similar light intensity. LED luminaire models are available from 12V to 220V.

Size of the PV modules: Different sizes of PV modules generate a different amount of power. To determine the size of the PV modules, the total peak power (Wp) generated must be calculated. The Wp generated depends on the size of the PV module and the climate of the site. The "panel generation factor" must be taken into account, which is also different for each location. For Kenya, the panel generation factor is 5.62.

Calculate the total watt peak power required from the PV modules: Divide the total Wh needed per day from the PV modules by 5.62 to get the total Wp power needed for the PV modules to run the appliances.

Calculate the number of PV modules for the system: Divide the answer obtained in the above point by the nominal power Wp of the available PV modules. Round up to the next full number. This then gives the number of PV modules required. The result of the calculation is the minimum number of PV modules. If more PV modules are installed, the system will have better performance and the battery life will be improved. If fewer PV modules are used, the system may not work at all in cloudy conditions and the battery life will be shortened.

Inverter sizing: An inverter is used in the system where AC power output is required. The input power of the inverter should never be less than the total W power of the units. The inverter must have the same rated V as the battery.

#	Device	Consumption Wh/d
1	TV (20W) on for 2h/d	40
2	Radio (10W) on for 5h/d	50
3	Water pump (20W)on for 2 h/d	40
4	Main light (30W) on for 3h/d	90
5	Spotlight (10W) on for 8h/d	80
6	Refrigerator (250W) on for 5h/d	1250
Total		**1550**

Table 12: Exemplary calculation of Wh consumption per day

For stand-alone systems, the inverter must be large enough to handle the total W power used at any given time. The inverter size should be 25–30% larger than the total W-power of the units. If the unit type has a motor or compressor, the inverter size should be at least three times the power of these units. The capacity of the inverter must be increased to handle the surge current during start-up of these units.

For grid-connected systems or grid-connected systems, the input power of the inverter should match the power of the PV generator for safe and efficient operation.

Battery sizing: Battery capacity is measured in ampere-hours (e.g. 20Ah). You need to convert this to Wh by multiplying theAh number by the battery voltage (e.g. 12V).

X (Battery size in Ah) * Y (Battery voltage) =
Z (Power available in Wh)

For a 20 Ah, 12 V battery, the watt-hour rating is
20 (X) * 12 (Y) = 240 Wh (Z).

This means that the battery could supply 240W for 1 hour, 120W for 2 hours or even 2W for 120 hours, i.e. the more energy consumed, the faster the battery discharges.

It is not possible to use all the power of a battery at once, as the voltage will drop below the requirements of the unit and it will no longer be able to supply power.

Lead-acid batteries give off about 50% of their rated power. (e.g. a 10Ah battery has 5Ah of usable power).
Li-ion batteries give off about 80% of their rated power. (e.g. a 10Ah battery has 8Ah of usable power).

A common question regarding batteries is:

***Q.** Are car batteries as suitable for solar as commercial batteries?*

***A.** The answer to this is: No, they are not. The reason is that a commercial battery is designed to be discharged and recharged. A car battery is designed to deliver a lot of current quickly, but it is not able to handle a low internal charge and then fully recover.*

The battery type recommended for use in a PV solar system is a deep cycle battery. A deep-cycle battery is specifically designed to be discharged to a low energy level over a period of years and quickly recharged or cyclically charged and discharged day after day. The battery should be large enough to store enough energy to run the equipment at night and on cloudy days. For the required size of the battery, calculate as follows:

$$\textit{Battery Capacity [Ah]} = \frac{\textit{(Total Watt-hours per day used by appliances * Days of autonomy)}}{\textit{(0.85 * 0.6 * nominal battery voltage)}}$$

Sizing the solar charge controller: The solar charge controller is usually sized according to amperage and voltage capacity. Select the solar charge controller to match the voltage of the PV system and batteries, then determine which type of solar charge controller is suitable for the applications. Ensure that the solar charge controller has sufficient capacity to handle the current from the PV array. The sizing of the controller depends on the total PV input current supplied to the controller and also on the configuration of the PV panels (series or parallel connection).

According to common practice, the short-circuit current (Isc) of the PV generator is taken for dimensioning the solar charge controller and multiplied by 1.3

Solar charge controller rating =
Total short circuit current of PV array * 1.3

Table 13: Example of power consumption and size of the PV panel

Determine the electricity consumption requirements:	
Total consumption of the appliance	1550Wh/d * 1.3
Total	2016.3Wh/d
PV panel size	
Total Wp of PV panel power	$T\,Wp = \frac{2016{,}3Wh/d}{5{,}62} = 358.77Wh/d$
Total	$T = \frac{358{,}77Wh/d}{175Wp/panel} = 2{,}0$
Number of panels	2

This exemplary system should be operated with at least 2 PV modules with an output of 175Wp.

Inverter design
Total wattage of all units = 20+10+20+30+10+250W = 340W. For safety, the inverter should be rated 25–30% larger.

The size of the inverter should be about 425W or more.

Table 14: Example of battery sizing

Dimensioning the battery	
Total consumption of appliances	1550W
Rated voltage of the battery	1V
Days of autonomy	3 days

$$C = \frac{1550W * 3}{(0.85 * 0.6 * 12)} = 759,80Ah$$

The battery should have a nominal capacity of 12V 800Ah for 3 days autonomy.

Table 15: Example for the design of the solar charge controller (solar module specification 175W)

Design of solar charge controllers	
Maximum power	175Wp
Open-circuit voltage	44,6V
Maximum power point voltage	35,4V
Short-circuit current	5,43A
Maximum power point current	4,95A

Source: Solarworld SW 175 mono

Solar charge controller power =
(2 panels * 5.43A) * 1.3 = 14.11A

The exemplary solar charge controller should have a rated output of 15A at 12V or more

7.11 Installation

The installation of PV solar systems requires special skills and knowledge. The installer assumes all risks of injury, including the risk of electric shock. Module installation should only be carried out by qualified persons.

Each individual module can generate DC voltages of more than 30V in direct sunlight. Contact with a DC voltage of 30V or more is potentially dangerous. Care must be taken when wiring or handling modules exposed to solar radiation.

Arcing may occur when disconnecting wires connected to a photovoltaic module that is exposed to sunlight. Arcing can cause burns, start fires or otherwise cause safety problems. Care must be taken when disconnecting wiring on modules exposed to sunlight.

PV solar modules convert light energy into DC electrical energy and are designed for outdoor use. Proper design of support structures is the responsibility of the system designer and installer.

The modules can be ground-mounted, pole-mounted or roof-mounted.

Paint or adhesives should not be applied directly to the module. When installing the modules, all applicable local, regional and national rules and regulations must be observed. If required, a building and/or electrical permit must be obtained. Do not store the modules outdoors or in a damp environment prior to installation. Improper transport and installation may damage the module glass or frame.

For a successful installation, the following points should be observed:

- Select a suitable location for installing the module.
- For optimal performance, the module must face due south in northern latitudes and due north in southern latitudes.
- For detailed information on optimal module orientation, refer to standard solar PV installation instructions or contact a reputable solar installer or system integrator.
- Shading of the module reduces the electricity production.
- Select the appropriate mounting structure and hardware.
- Do not install the module near equipment or in places where flammable gases may be generated or collected.
- Observe all instructions and safety precautions enclosed with the mounting system to be used with the module.
- Do not drill holes in the glass surface of the module. Otherwise the warranty will be invalidated.
- Do not drill any additional mounting holes in the module frame. Otherwise the warranty will be invalidated.
- For normal installation, the modules must be securely fastened to the mounting structure with four mounting points. If strong wind or snow loads are expected, additional mounting points should also be used.
- Load calculations are the responsibility of the system designer or installer.
- The mounting structure and hardware must be made of durable, corrosion-resistant and UV-resistant material.

Do not attempt to dismantle the module and do not remove any attached type plates or components. Otherwise the warranty will be invalidated.

Do not use mirrors or other aids to artificially concentrate sunlight on the module.

7.12 Safety precautions

Solar modules generate electrical energy when exposed to sunlight. DC voltages can exceed 30V for a single exposed module.

Only connect modules with the same rated output current in series. When modules are connected in series, the total voltage is equal to the sum of the individual module voltages.

Only connect modules or series combinations of modules with the same voltage in parallel. When modules are connected in parallel, the total current is equal to the sum of the currents of the individual modules or series combinations.

Bypass diodes are pre-mounted in each module. Do not remove these diodes. Keep children away from the system during transport and installation of the mechanical and electrical components. Cover all modules completely with an opaque material during installation to prevent electricity from being generated.

The mounting structure and hardware must be made of durable, corrosion-resistant and UV-resistant material.

Do not wear metallic rings, watch bands, ear, nose or lip rings or other metallic devices during installation or troubleshooting of PV systems.

Use appropriate safety equipment (insulated tools, insulated gloves, etc.) approved for use on electrical installations.

Observe the instructions and safety precautions for all other components used in the installation, including wiring and cables, connectors, DC disconnectors, mounting materials, inverters, etc. Only use equipment, connectors, wiring and mounting parts that are suitable for use in a PV system. Always use the same type of module within a given PV system.

Under normal operating conditions, PV modules will generate currents and voltages that differ from the values listed in the data sheet. The values in the data sheet apply to standard test data.

Short-circuit currents and open-circuit voltages should be multiplied by a factor of 1.25 when determining component voltage ratings, conductor ampacity, fuse size and the size of controls connected to the module or system output. An additional multiplication factor of 125% (80% derating) may be applicable.

Drainage holes must not be covered with parts of the mounting system. The junction box has a vent hole that must be mounted facing downwards and not exposed to rain. The junction box should be on the higher side of the module when mounting to angle the vent properly.

Please observe the following points for safe installation and operation:

- Do not lift the module by the junction box or the module's electrical cables.
- Do not stand or step on the module.
- Do not drop the module and make sure that no objects fall on it.
- Do not place heavy objects on the module.
- Do not scratch the anodised layer of the frame (except at the earth connection).
- Do not scratch the glass surface.
- All module frames must be properly earthed.
- Observe all local electrical rules and regulations.
- A bond or toothed washer is required to make a proper and reliable electrical earth connection to the anodised aluminium frame.
- Equipment listed and labelled for earthing metal frames of PV modules may earth the exposed metal frames of the module on earthed mounting structures.
- Consider using a cable lug suitable for outdoor use if the module earth conductor is to be larger than AWG 10.
- When using installation lugs, the earthing conductor should be secured with the set screw.
- Do not use modules with different configurations in the same system
- Cover the system modules completely with an opaque material to prevent current from being generated when disconnecting conductors.
- Follow local regulations to determine overcurrent, conductor ampacity and size requirements.
- Installation must be carried out in accordance with local regulations.
- For best performance, make sure that the positive and negative DC lines are close together to avoid loops.
- In cases where two or more modules are connected in series in a system, if one part of the modules is covered and the other part is exposed to the sun, the high reverse current will flow partially or completely through the module, causing the modules to overheat and even damage them. Bypass diodes used in the modules can protect the modules from such effects of excessive reverse current. The bypass diodes are integrated in the junction box.
- Test procedure for modules connected in series before connection to the PV system.
- Using a digital multimeter, check the total open-circuit voltage of the modules connected in series. The result should be equal to the sum of the open circuit voltage of the individual modules, which you will find on the label of the modules. If the total open circuit voltage is much lower than expected, please proceed as follows.
- Troubleshooting for undervoltage:
- There are two causes of low open-circuit voltage: environmental changes or circuit faults. The decrease in irradiance or the increase in ambient temperature reduces the open circuit voltage, which is normal. Troubleshooting here refers to low voltage caused by circuit faults, usually due to incorrect connection of terminals or damage to bypass diodes.
- First check all cable connections and ensure that they are well connected to the PV system. Then check the modules one by one as described below:
- Measure the open circuit voltage of a module.
- Cover the module completely with opaque material. Disconnect the module from the installation.
- Remove the opaque material from the module and measure its open circuit voltage.
- If the measured voltage is one third or two thirds of the nominal value, this indicates that the bypass diodes are defective and should be replaced.

7.13 Maintenance

Since there are usually no moving parts in PV systems, minimal maintenance is required. However, routine maintenance is required to ensure that the system is functioning properly. It is good practice for a PV contractor (or system integrator) to provide the owner with an operation and maintenance (O&M) manual. The manual should include basic system data, test and commissioning data, O&M data and warranty information.

The PV modules require regular visual inspection for signs of damage, soiling or shading. Although they are usually designed and installed to be self-cleaning with rainwater, the modules should be hosed down if dust accumulates. It is not uncommon for PV performance to improve slightly the day after a rain.

At regular intervals, the system fixings must be checked for corrosion. This ensures that the PV system is securely fastened.

Any PV system connected to the electrical installation of a building is considered part of the electrical installation. The qualified electrician (LEW) appointed by the building owner is responsible for maintaining the electrical installation to ensure electrical safety.

Recommended preventive maintenance for photovoltaic systems
Preventive maintenance should be carried out every six (6) months.

The *following table* shows the components/devices and the corresponding remedial actions to be carried out during preventive maintenance work.

Table 16: Suggested preventive maintenance work

S/No.	Components/ Devices	Descriptions	Remedy/action
1.	PV modules	1. Dust/residue on the surface. 2. Ensure that there is no physical damage to the surface. 3. Check for loose wire connection. 4. Check the wiring conditions.	1. Wipe clean. Do not use any solvents other than water! 2. Recommend replacement. 3. Tighten the connection again. 4. Replace wiring, if necessary.
2.	Inverter	1. Check functionality. Check for loose connection of the wiring. 2. Check for abnormal operating temperature	1. Recommend replacement. 2. Tighten the connection again. 3. Recommended exchange.
3.	Lightning / overvoltage protection	1. Check for loose connection of the wiring. 2. Check all wiring conditions. 3. Check fuses, blocking diodes, circuit breakers, surge arresters. 4. Check functionality.	1. Tighten the connection again. 2. Replace wiring, if necessary. 3. Make sure that you use DC-capable components on the DC side! Recplace them if necessary.
4	Wiring / junction box	1. Visual inspection for wear and tear. 2. Check for loose connections.	1. Replace if necessary. 2. Tighten the connection again.

ANNEXES

ANNEX I: Field report on the installation of the pilot fish cold store

This field report reflects the personal impressions of Igor Croiset (HEAT GmbH), the technical consultant deployed by GIZ on site.

"When we started the project, we first looked at the major fish markets in Nairobi and the fish supply routes. Most of the fish sold in Nairobi comes from the Kenyan lake areas, with Lake Victoria being the largest lake with the largest supply of fish. We found that the big fish markets have limited refrigeration capacity, that the fish spoils quickly and has to be sold the same day.

An important issue was the transport of the freshly caught fish by the traders to the markets. Lake Victoria is about 400km away from Nairobi and the fish have to be transported from Lake Victoria to the fish market in Nairobi. There are many fish farmers on the shores of Lake Victoria who work under difficult conditions without roads. From the early morning harvest of the fish at the lake to the fish market in Nairobi, the fish is on the road for several hours without being refrigerated. The cold chain is non-existent and the fish associations around Lake Victoria also have limited refrigeration facilities.

For the local market in the towns around the lake, e.g. in Kisumu, the citizens consume the freshly caught fish the same day under relatively fresh and proper hygienic conditions. For the fish farmers who sell their fish to Nairobi, where most people live, delivering fresh fish under the right conditions is a challenge. Every day, about ten tonnes of fish are transported from the Lake Victoria area to Nairobi via the long road transport. To improve market conditions for the fish farmers, it would be ideal if they could catch the fish over several days, store it under hygienic conditions and then transport a full truck of fresh fish to the market in Nairobi.

To store the fish in larger quantities, fish farmers need to refrigerate the fish. Under the right conditions, the fish cools in a bed of baskets filled with ice flakes, which allows for good transport. The ice flakes allow the fish to cool to 0°C for several days of storage under new conditions. Under these conditions, local fish farmers store and deliver fresh fish to the Nairobi fish market.

We have discussed the above concept with local fish farmers around Lake Victoria, with the following key elements for the design:

- Identify an economic quantity of fish to be caught each day.
- Agreement on the appropriate cooling capacity of the cold store (approx. 5 tonnes of fish) and the routine harvesting and storage time (two to three days each).
- The transport ships to the market in Nairobi.

We have defined the design and performance of the cold room as follows:

- In accordance with good international practice and hygiene regulations, the fish has to be refrigerated and stored near zero degrees, requiring the installation of an ice machine.
- Use of plastic baskets produced in Kenya and sourced locally.

- Cold store with a processing area for embedding the fish in the ice flakes and a refrigeration unit.

- Installing solar panels because electricity is often scarce and power sizing is critical to maintaining the cold chain.

In close cooperation and coordination with several farmers and associations, we defined the design parameters. Based on the design parameters, we were able to draft Terms of References and launch a tender seeking suitable operating companies to implement and manage the model cold store. More than ten applicants were shortlisted and in a pitch in Nairobi, a jury of experts and representatives of the Ministry of Environment selected Lakeview Fisheries.

In collaboration with Lakeview, we agreed on the final detailed design of the shop, including the choice of metal-coated sandwich panels. BASF South Africa provided the polyurethane raw materials for the panel manufacturer as a free in-kind contribution to the project. Installation and commissioning was challenging, mainly because of the large-sized sandwich panels, the lack of experience of the local staff and the remote location on an island. A major obstacle was the operator's requirement to integrate the cold room into an existing part of the building. Another problem was the flatness of the floor. It sounds strange, but 200mm thick sandwich panels are incredibly stiff and bulky. If the floor is not flat, you have to adjust them, which is time-consuming, and if the roof is already built, handling is rough. The cooling systems have worked well from the start and there are good service technicians in Kenya trained by GIZ.

Important learning aspects were:

- Prepare the construction work carefully, this reduces the build-up of the cold room enormously.

- Make sure there is a qualified installation team and electrician.

- Have enough tools and accessories on site – the time it takes to get them is often lengthy and holds up operations.

- Spend time training staff, especially on the logistical aspects of organising how to fill a cold room without keeping the doors open for long periods of time. These logistical aspects of placing fish in baskets with layers of ice are relatively new, but hugely important.

Lastly, we would like to thank the Lake View team for their enthusiasm, **cooperation** and willingness to learn.

ANNEX II: Practical data air exchange rates for cold stores according to size and temperature

Volume of the cold store, V_{cr} (m^3)	Amount of air changes i_u for rooms >0°C	Amount of air changes i_u for rooms <0°C
2.5	70	62
3	63	47
4	53	40
5	47	35
7.5	38	28
10	32	24
15	26	19
20	22	16.5
25	19.5	14.5
30	17.5	13
40	15	11.5
50	13	10
60	12	9
80	10	7.7
100	9	6.8
150	7	5.4
200	6	4.6
250	5.3	4.1
300	4.8	3.7
400	4.1	3.1
500	3.6	2.8
600	3.2	2.5
800	2.8	2.1
1000	2.4	1.9
1500	1.95	1.5
2000	1.65	1.3
2500	1.45	1.3
3000	1.3	1.05

ANNEX III: Air enthalpy difference according to cold store and ambient temperature

Difference of air EnthalpykJ/m³

	Atmospheric external temperature°C															
	5.00		10.00		15.00		20.00		25.00		30.00		35.00		40.00	
Coldroom Temperature (°C)	70%	80%	70%	80%	70%	80%	70%	80%	70%	80%	70%	80%	70%	80%	70%	80%
-40.00	83.30	85.40	97.10	100.00	113.00	117.00	121.00	126.00	138.00	147.00	161.00	171.00	187.00	201.00	220.00	231.00
-35.00	73.30	75.30	86.70	89.60	102.00	106.00	110.00	115.00	127.00	135.00	149.00	159.00	174.00	188.00	207.00	225.00
-30.00	64.20	66.20	77.50	80.10	92.60	96.50	99.80	105.00	117.00	125.00	138.00	148.00	163.00	177.00	195.00	213.00
-25.00	55.10	57.10	68.00	70.80	82.90	86.80	90.10	95.10	107.00	114.00	127.00	137.00	152.00	165.00	183.00	201.00
-20.00	46.10	48.00	58.80	61.50	73.40	77.10	80.40	85.30	96.60	104.00	117.00	127.00	141.00	154.00	171.00	189.00
-18.00	42.80	44.70	55.40	58.00	69.80	73.50	76.80	81.60	92.80	100.20	113.00	122.60	137.00	149.60	166.60	184.20
-15.00	37.80	39.70	50.20	52.80	64.50	68.20	71.30	76.10	87.20	94.60	107.00	116.00	131.00	143.00	160.00	177.00
-10.00	28.70	30.50	40.80	43.40	54.80	58.40	61.40	66.10	77.00	84.20	96.60	106.00	120.00	132.00	148.00	165.00
-5.00	19.20	20.90	31.00	33.50	44.60	48.20	51.20	55.80	66.40	73.50	85.50	94.40	108.00	120.00	136.00	153.00
0.00	9.10	10.90	20.80	23.30	34.40	37.90	40.80	45.40	55.90	62.90	74.90	83.70	97.40	109.00	125.00	141.00
5.00	1.00		9.60	12.00	22.80	26.20	29.00	33.50	43.70	50.50	62.10	70.60	83.90	95.40	111.00	127.00
10.00	1.00				10.60	13.80	16.60	20.90	30.90	37.50	48.80	57.20	70.10	81.30	96.50	112.00
15.00	1.00						2.80	7.00	16.80	23.30	34.50	42.70	56.40	66.40	81.40	96.50

For more precise data refer to the Mollier h,x diagram of air

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