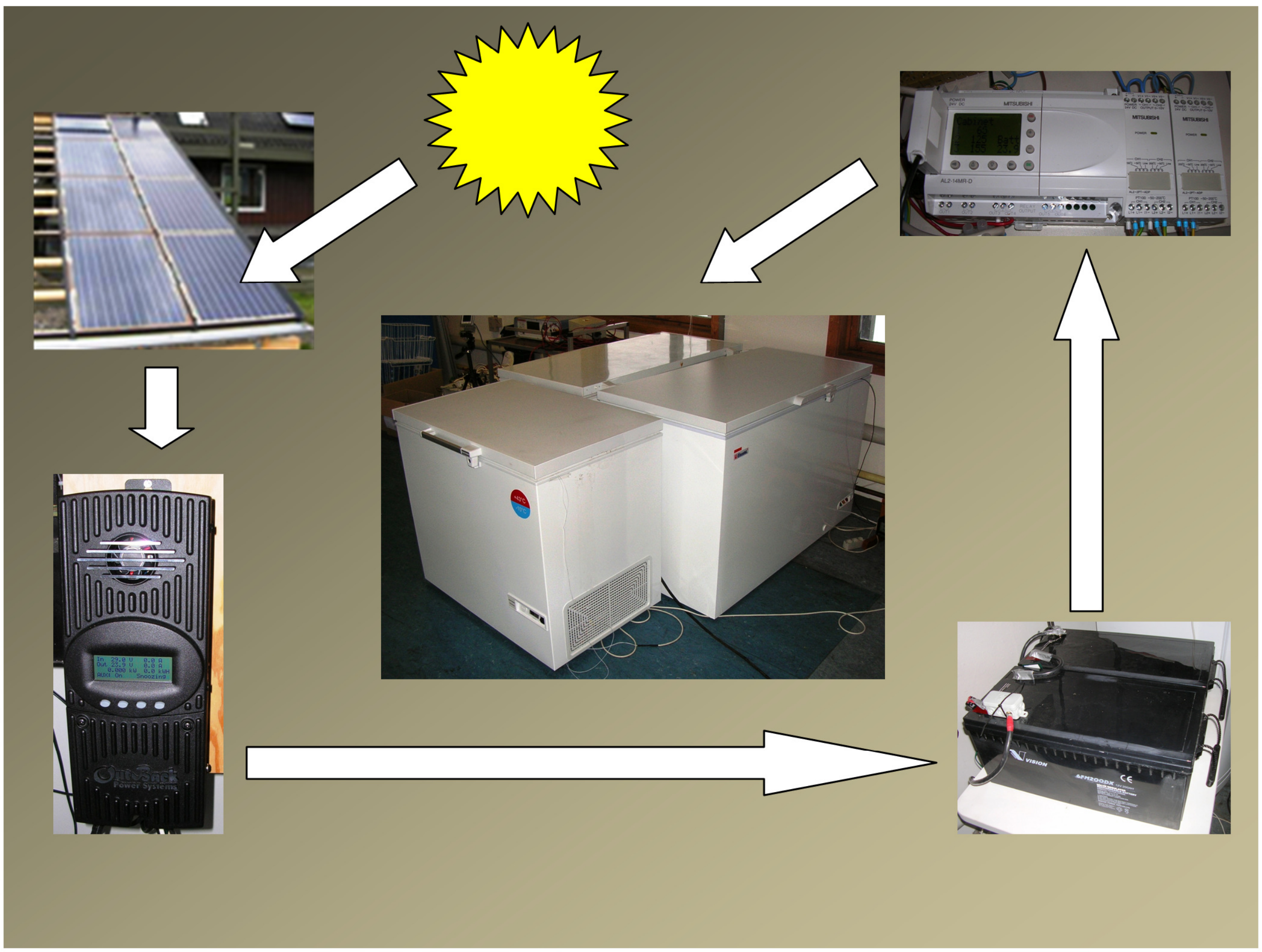
EUDP project
Contract No.:
EFP07-II no 33033-0297

Standalone cool/freeze cluster driven by solar photovoltaic energy.



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Introduction

The current report has been prepared under the project “Cold storage driven by solar and wind energy” and is financed by the Danish Energy Authority (EFP07-II no 33033-0297).
The objective of the project is to develop and demonstrate a grid-independent cold storage system for perishable food, medicine or other goods, with a special focus on the need for such systems in developing countries with a sparse and unreliable supply of electricity. The project is directly based on the result from the international “SolarChill” project where a unique battery less solar driven vaccine refrigerator was developed by Vestfrost in cooperation with Danish Technological Institute.

The project partners are:
- Danish Technological Institute (Project manager)
- Danfoss
- Grundfos
- Fresvik (Norway)
- Karise Klejnsmedie

Teknologisk Institut
Energi & Klima
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1. Background

The current project is directly inspired by the so-called SolarChill project, which is an ongoing international project aiming at the development and demonstration of battery less solar PV (photovoltaic) refrigerators. The SolarChill project has already been successful in the demonstration and dissemination of a large number of PV driven vaccine refrigerators of chest type named SolarChill A. The core technology is a DC driven soft-start compressor, developed by Danfoss, that allows direct connection to a relatively small PV array. By avoiding the battery, the system becomes inherently robust, and cheaper than competitive products. The energy is stored as latent heat in icepacks. SolarChill A is now being produced by the Danish company Vestfrost, and has recently been approved by WHO.
This principle has been further refined and extended to a so-called SolarChill B refrigerator intended for the general market of households and small restaurants and shops. This product is still not in mass production, but some prototypes have been demonstrated in practical application.
The consortium behind SolarChill has received more awards for the project, and has received numerous requests from interested customers and partners. Danish Technological Institute has been heading the technical part of this project, including product development and testing.
In 2009 the World Bank joined the SolarChill partnership and infused additional funding (through a GEF project) into the SolarChill project. This project intends to carry out extended field tests in Colombia and Kenya and will transfer the technology to potential producers in the two countries.

Inspired by this success, the current project aims at scaling up the same principles to a typical community or commercial type of cold store facility. A large scale system would benefit from a better volume/surface ratio and a relatively lower cost per unit of storage volume. The focus is on the areas of the world without access to regular grid power, but with plenty of natural solar and/or wind resources for grid independent power supply.

2. Requirements for cooling and storage of perishable goods

When designing a standalone refrigeration system, it is obviously very important to define the performance in terms of temperature level, maximum temperature fluctuations, freezing capacity, storage volume etc. Various sources have been used to find recommended storage temperatures for some typical goods which may represent user's needs in developing countries. The following is from the web site [1].

<u>Temperatures and ventilation</u>
Different applications have different requirements for temperature control and ventilation. Figure 16 shows the temperatures needed for the storage of butter, meat, fresh fish and milk. Very often storage of vegetables is complicated by the need for careful *ventilation to remove unwanted gases*, and to avoid humidity conditions, which would spoil the produce. Relative humidity requirements vary depending on the moisture content of the produce. A simple method of increasing humidity is to sprinkle water on the floor. In vaccine and blood storage very careful temperature control is required.

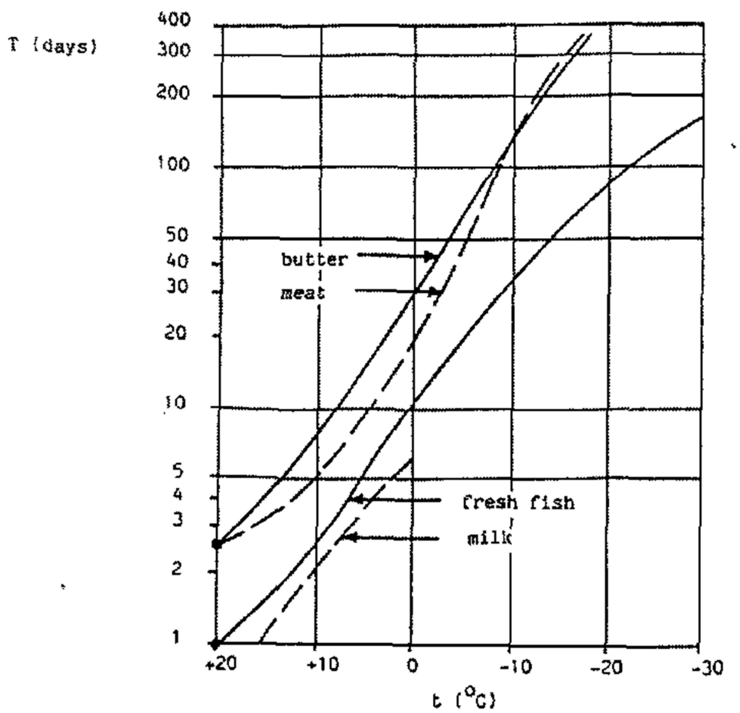


Figure16 Maximum storage time vs temperature for some products.
Source: REFRIGERATION FOR DEVELOPING COUNTRIES. Practical Action, UK

Temperature
All fruits and vegetables have a 'critical temperature' below which undesirable and irreversible reactions or 'chill damage' takes place. Carrots for example blacken and become soft, and the cell structure of potatoes is destroyed. The storage temperature always has to be above this critical temperature. Even though the thermostat is set at a temperature above the critical temperature, one

has to be careful that the thermostatic oscillation in temperature does not result in storage temperature falling below the critical temperature. Even 0.5°C below the critical temperature can result in chill.

	Temperature °C	**Relative humidity %**	**Maximum storage time recommended (ASHRAE handbook 1982)**	**Storage time in cold stores for vegetables in tropical countries**
Apple	0-4	90-95	2-6m	-
Beetroot	0	95-99	-	-
Cabbage	0	95-99	5-6m	2m
Carrots	0	98-99	5-9m	2m
Cauliflower	0	95	2-4w	1w
Cucumber	10-13	90-95		
Eggplant	8-10	90-95		
Lettuce	1	95-99		
Leeks	0	95	1-3m	1m
Oranges	0-4	85-90	3-4m	
Pears	0	90-95	2-5m	
Pumpkin	10-13	70-75		
Spinach	0	95	1-2w	1w
Tomatoes	13-21	85-90		

Table: Ideal storage conditions for various goods

It can be seen from the table that there are basically three groups of fruit and vegetables: those stored at 0 - 4°C; those stored at 4 - 8°C; and those that require a storage temperature above 8°C. It is often more convenient to concentrate on one of these groups.

Source:
http://www.appropedia.org/Cold_storage_of_fruits_and_vegetables_(Practical_Action_Brief)

3. Literature survey on cold stores

In this chapter, some of the highlights found in the literature and on the internet regarding solar & wind powered refrigeration systems are presented.

The idea of using renewable energy for refrigeration purposes is not a new one; in particular solar energy has been suggested as a power source, because it is globally available and generally in phase with the refrigeration demand. Previous refrigeration projects have mostly been based on solar thermal energy from concentrating or flat plate solar collectors. The heat would power an adsorption or absorption refrigerator, working dependent on the collector outlet temperature, cold store and ambient temperatures. The main advantage of this design principle is the relatively low cost of the solar collectors as compared with photovoltaics, but it suffers from a poor COP of the cooling circuit and does therefore require a large solar collector surface.

Fig.1. Thermally powered solar refrigerator in Burkina Faso (adsorbent: Zeolite)

With progress in solar photovoltaic module manufacturing, the cost/performance ratio has been dramatically improved, so that solar electric power is now an option for refrigeration purposes too. The main advantage is that standard cabinets and compressors (for DC) can be used. Solar powered refrigeration is mostly known from medical refrigerators for use in remote areas, where no grid power is available. These refrigerators normally use a battery for energy storage and for provision of start current for the compressor. There are many years of field experience with solar PV refrigeration, showing that they work well as long as the batteries are kept in a good condition. However, the batteries are often not replaced with the original type at end of service life, or they are stolen or misused. In the international SolarChill project, the battery has been exchanged by a thermal storage (ice) in order to avoid the only vulnerable component in the system (the battery). After an intensive field test, SolarChill is now being produced and marketed by Vestfrost, DK.

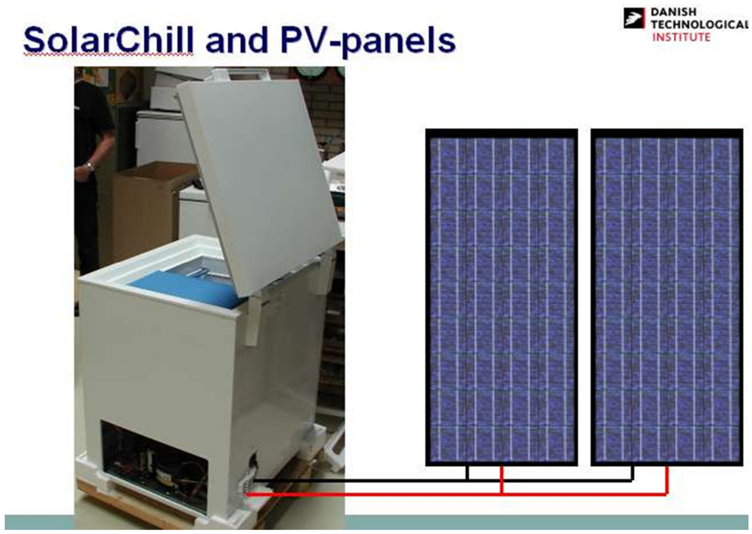


Fig.2 SolarChill refrigerator with direct drive compressor

To the knowledge of the author, wind energy for specific refrigeration purposes has not been realised so far, though wind power is often used as an important power source in small isolated electricity grids, where any appliances may be connected, thus also refrigerators. The only reference found on wind powered cold stores is a European (EU) project on thermal storage of excess wind power connected to the grid. In this proposal, the cold stores are controlled to switch on when wind power is exceeding the general power demand, and off when there is lack of electricity. In this way they serve as free energy storage for wind electricity[1].

It seems from literature, that most projects have been carried out in the field of small scale solar refrigerators for vaccine and household use, and in the market there are many representatives in this category, for example SunDanzer and Vestfrost.
Larger systems have only been investigated sporadically, with German ILK Dresden as an important exception. This R&D institute has developed a series of solar PV driven refrigeration containers in 10ft or 20ft standard size for different purposes:

- General cooling of goods and foodstuffs (23 m^3 / 3.4 kWp)
- Ice making container (250 kg/day / 5,1 kWp)
- Milk cooling center with 70 kWh ice storage (1000 l / 3.4 kWp)
- Water cooling (2000 l / 680 Wp)
- Medical storage (200-1000 l/ 1.7 kWp)

It is not clear how many units have been produced so far of each unit.
Both ILK, SunDanzer and SolarChill are using ice as a means of energy storage.

The US company SunDanzer has developed a refrigerated container for military purposes, see picture below. These units are available with single or dual compartment/dual temperature. They

[1] Night Wind: storage of wind energy in cold stores An EU – FP6 research project

operate as coolers, refrigerators, or freezers. They are also available with or without the solar power system and some models utilize thermal energy storage to reduce or eliminate the need for batteries. SunDanzer® solar refrigerator and freezer models feature 4.67" (12 cm) of polyurethane insulation. The brushless DC motor compressor operates on 24 or 48VDC. The cost is 25,000-62,500 USD for a 20ft unit depending on specification (without PV system).

Figure3. SunDanzer container for solar PV cooling. Source: [*http://www.sundanzer.com/documents/SolarContainers.pdf*](http://www.sundanzer.com/documents/SolarContainers.pdf)

Another important reference system has been reported from India, where a PV driven storage for 10 tons of frozen fish has been constructed and investigated in an R&D project. The size of the storage is 21 m^3, and it is powered by a PV array of 4 kW peak. A battery is used to power the compressor at night and on cloudy days.
The operating experience is positive, in the sense that the design was appropriate for the load. However, from the inauguration of the plant in 1991 until reporting in 1996, a severe deterioration of the PV modules and the batteries could be observed. The salt mist from the sea was very corrosive to all electrical connections.

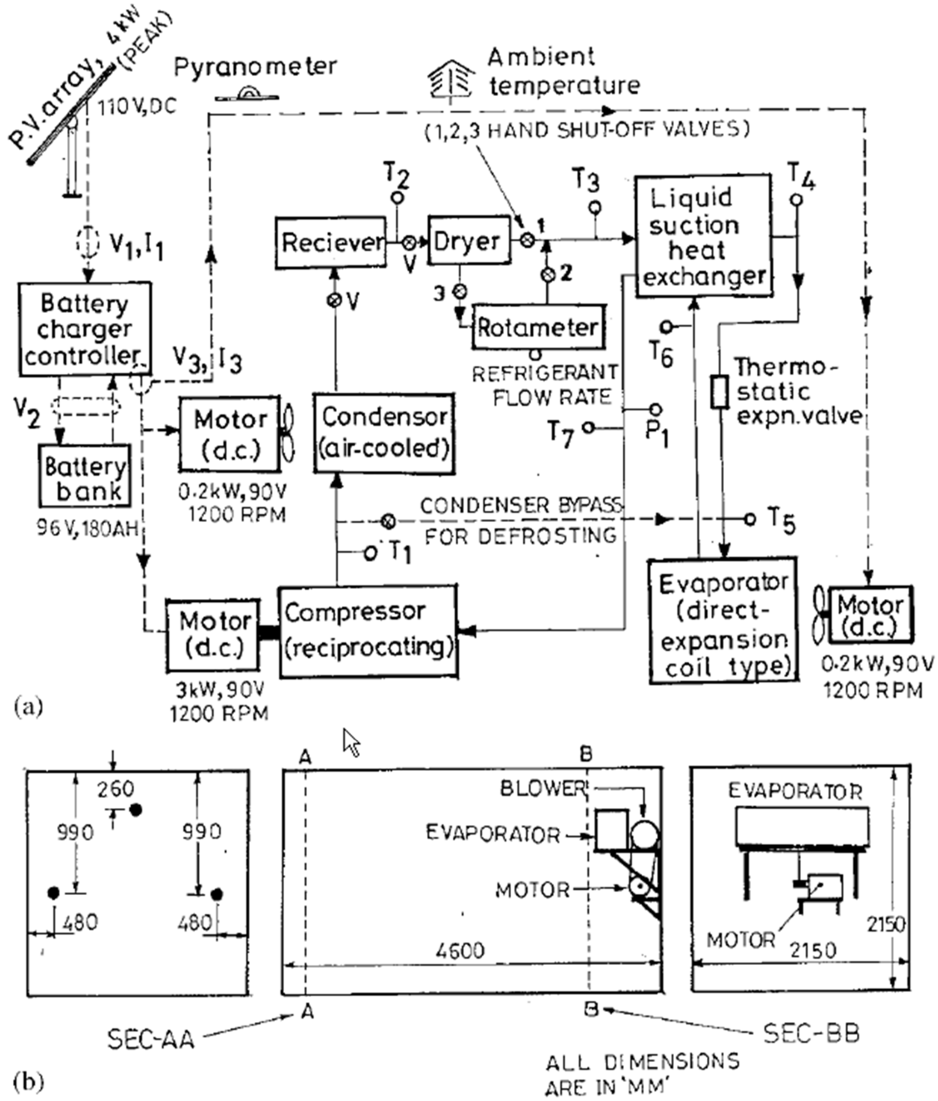


Fig.4. Diagram of the Indian cold store

4. Experiences with hybrid photovoltaic/wind power supply

Electricity from wind turbines and from photovoltaic modules, is by nature fluctuating in time; it is therefore a straightforward idea to combine the two in order to reduce the peaks and lower the risk of a total loss of power, because solar and wind tend to supplement each other. Such a system is called a hybrid power plant, and is most often equipped with batteries as energy storage. The batteries are relatively smaller in such a system when compared to a pure wind or a pure PV system of same installed power value, how much depends on the daily load profile and the fluctuations of the inputs. There are two main configurations used today for hybrid power systems:

1) DC system with a battery bus bar connecting the PV system via a charge controller , and the wind turbine via a separate regulator
2) AC system with bi-directional battery charger/inverter and connection of PV array by a grid inverter, and the wind turbine by AC regulator or dedicated inverter.


Fig.5 Hybrid 3 phase AC system with SMA inverters (Spain)

The advantage of the slightly more complicated AC system is that standard AC appliances can be connected, as for example 230 V cooling compressors. The German inverter manufacturer SMA is the main provider of this system type.
For small-scale supply a pure DC system may be the cheapest option, while the special DC appliances will usually be more expensive than their AC counterparts. If an inverter is connected to the battery, AC appliances may however still be used at the cost of lower total efficiency.

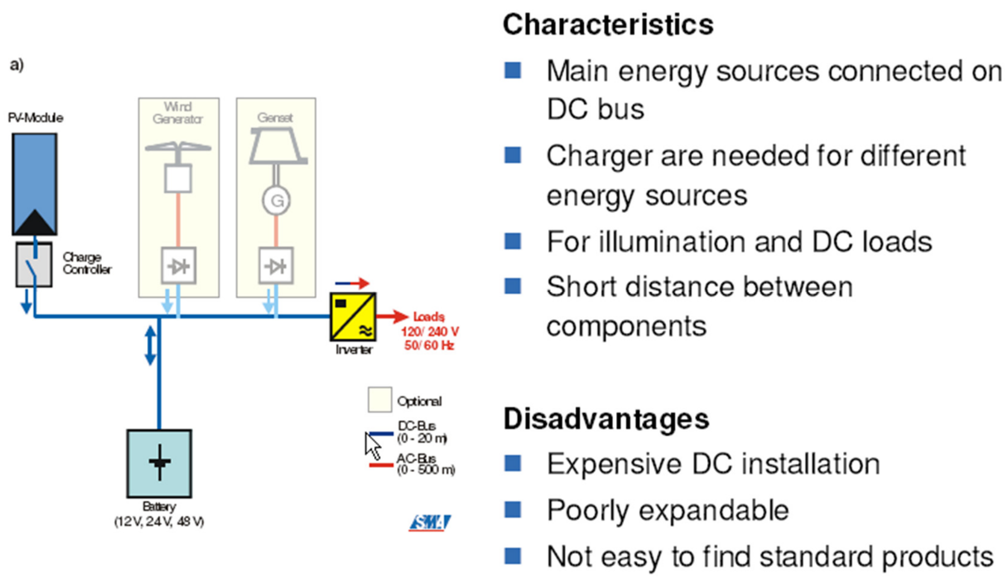


Fig.6 Hybrid system with DC bus

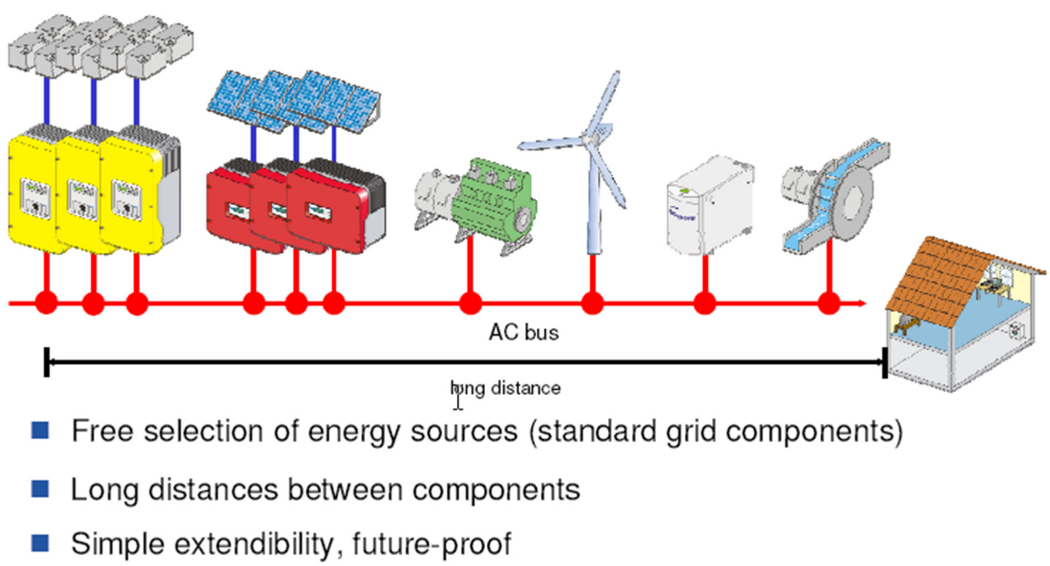


Fig.7 Hybrid system with AC bus

reCUBE

PV max. generator output	1.4 kW (different values on request)
Wind turbine (9 m/s wind speed)	0.75 kW (different values on request)
Battery	420 Ah / 24 V (different values on request)
Rated output	3.0 kW (different values on request)
Peak output 5 s	4.5 kW (different values on request)
Output voltage	acc. to local requirements
Type of output voltage	pure sine-wave voltage, electrically isolated between input and output
Rated frequency	acc. to local requirements
cos-phi	any value allowed
Distortion factor for rated output	< 3%
Max. efficiency	> 95%

Fig.8. KACO reCUBE is an example of an off-grid turn-key power supply system with AC output.

In some cases the appliance can be directly driven by renewable energy sources without the use of a battery bank. This is the case for the power supply the SQFlex pumps from Grundfos. In their system, a special regulator converts PV and wind power directly to 3 phase AC power fed to the pump motor. The same idea may be used to run a variable speed compressor for refrigeration purposes if the market volume is sufficient.

A Danish study[2] from 1999 has investigated the symbiosis between wind power and PV for a hybrid energy system with battery storage. The analysis showed that for Danish conditions the optimum distribution between wind power and PV was 1:1 (1 m^2 PV modules to 1 m^2 swept area of the turbine).

[2] PV & Wind Hybrid System, Lars Yde, Folkecenter for Renewable Energy, 1999

5. Simulation of hybrid power supply

Simulation of hybrid energy systems is a prerequisite for design of site specific energy solutions. A free simulation software named HOMER for hybrid energy supply is available from NREL, USA at https://analysis.nrel.gov/homer/ . The following analysis is based on simulation using this software package.
It is assumed that the cooling system will in general be fed from a hybride system consisting of PV / Wind Turbines and a battery bank. Homer is used to estimate the optimum size for each of the main components for a given site and load pattern.
To simulate the operation under various climatic conditions with either windy or sunny conditions the project includes calculations of the energy system based on Cape Verde Islands climatic conditions, which is both very windy and sunny. The distribution of wind and solar energy for other sites can then be estimated by multiplying a reduction factor on the available climate data. The calculation is based on a 100W average consumption equal to a daily consumption of 2.4 kWh /day. The various climatic data are obtained from the software program MeteoNorm version 4.0. An additional simulation where the load is distributed at different times of day was also carried out. Prices used for the financial simulations have been taken from catalogues and websites, and are inherently subject to some uncertainty. Prices are exclusive of installation. All technical data are derived from the Homer program. Economic data for the Homer simulation / calculation is introduced to the best estimate based on catalogue values assigned prices for transportation and installation. Price and the replacement interval of components is assessed from the knowledge of stand-alone power plants in general. Especially the batteries require replacement several times during the lifetime of the plant and the future price of these is vital for operating economy.

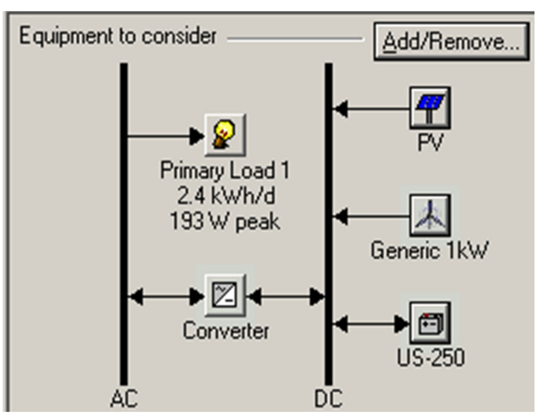


Figure 9. Schematic of the simulated hybrid system

In this project, the only simulation made is for a system with AC loads, meaning that an inverter is included in the system.

<u>Cape Verde</u>
First simulation is for a system made in Cape Verde Island. Data in Table 1 are obtained from the MeteoNorm database and program. This data is used to simulate the system in Homer. The simulation result shows that a combination of PV and battery bank is the best economic solution, despite a very high wind speed. This is due to the relatively high price of the small wind turbine and that there is a good solar irradiance at the site. Figure 10 shows the distribution of the output of systems with, respectively wind / battery and PV / battery.

	Wind speed [m/s]	Clearness index	Daily irradiance [kWh/m2]
January	6.700	0,651	5.190
February	6.700	0,705	6.250
March	6.800	0,676	6.670
April	6.800	0,669	7.060
May	7.100	0,637	6.870
June	6.800	0,575	6.200
July	5.300	0,524	5.630
August	5.100	0,518	5.480
September	5.400	0,554	5.570
October	5.700	0,655	5.970
November	5.800	0,651	5.300
December	6.400	0,619	4.742

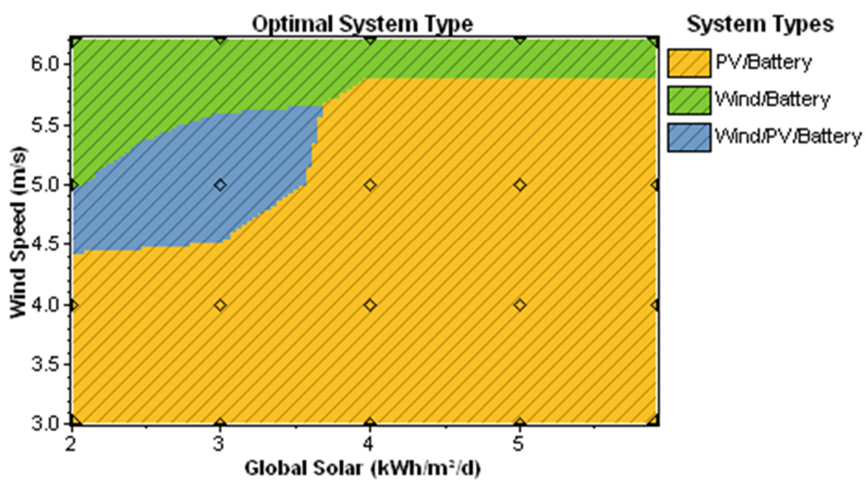


Figure 10 shows the most economic system solution as a function of average wind speed and the daily insolation.

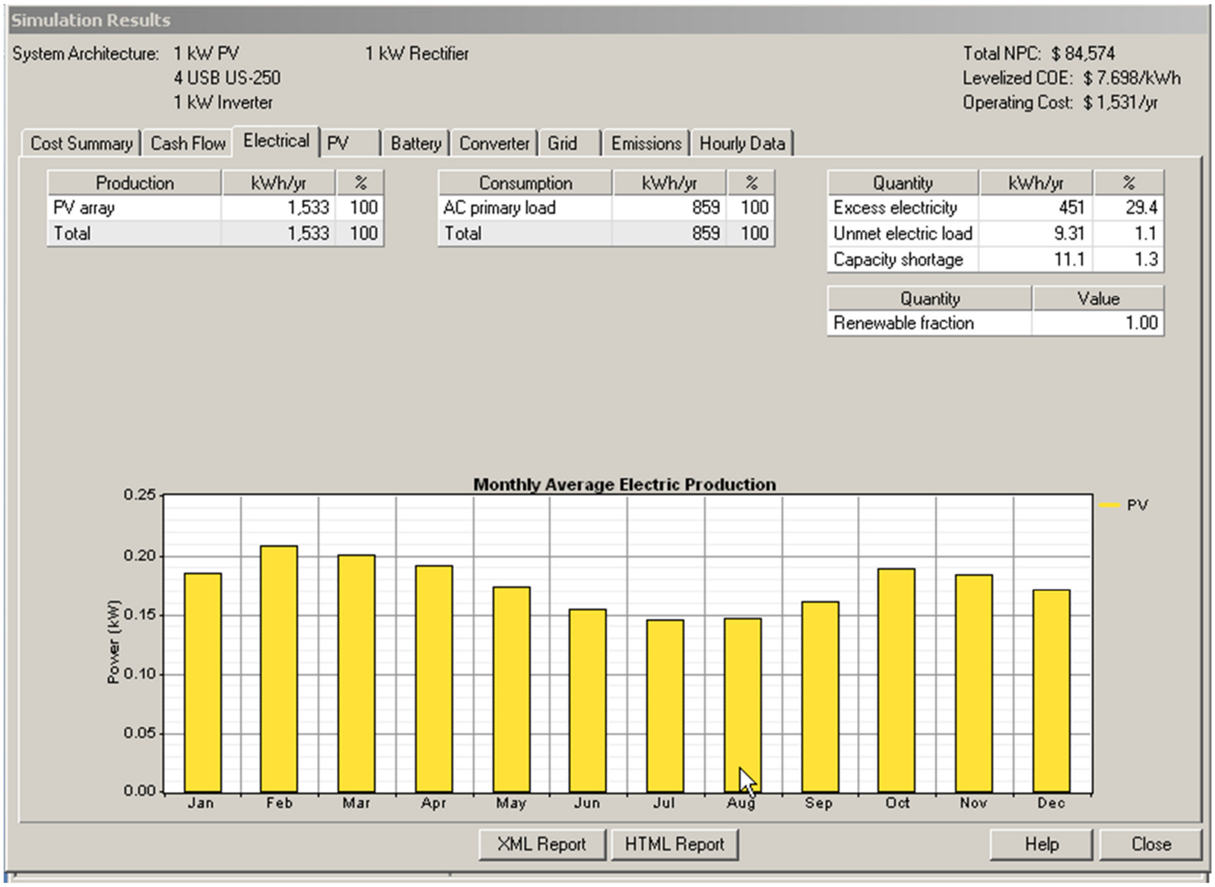


Figure 11. PV system. Annual production from a purely PV based system.

It is estimated that approximately 1% of energy needs is not covered by this system, it means there are periods when the refrigeration system cannot maintain the temperature within the desired limits. To also cover the last 1% would the system size would be excessive.

In Figure 11 we can see that the purchase cost of a pure PV system is cheaper than wind turbines, as shown in Figure 1.4. Prices may fluctuate widely from company to company, so the financial results must be interpreted with caution. Note that the figures are in Danish kroner, although the program provides $.

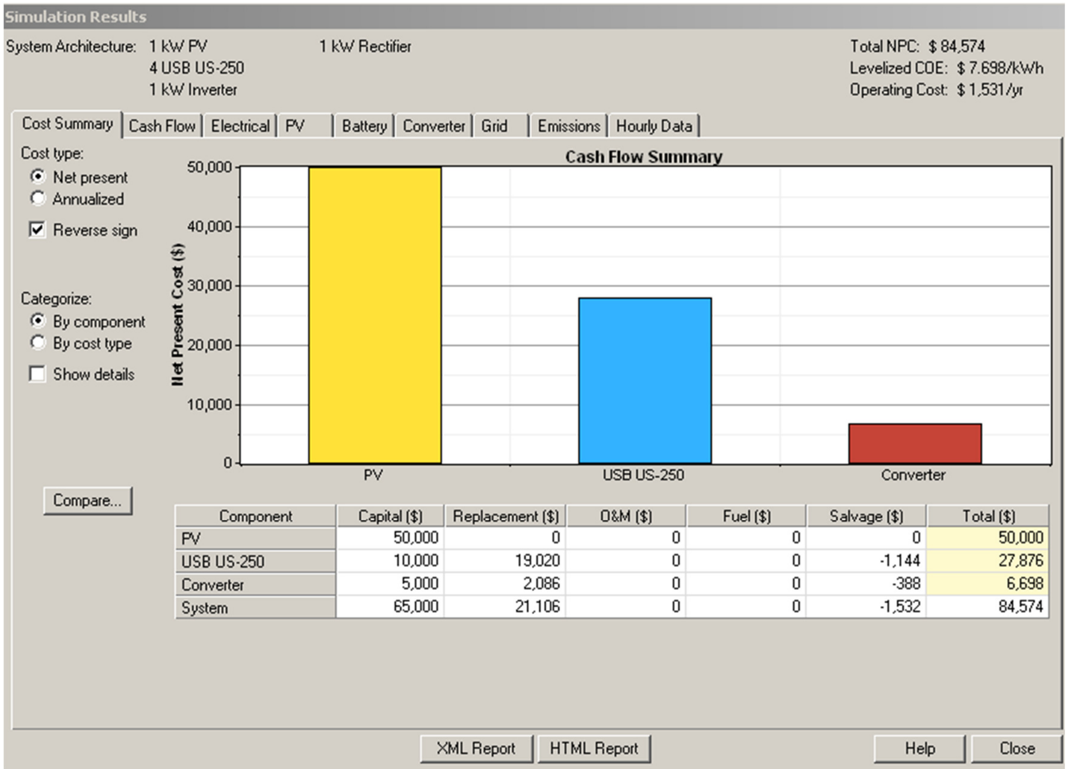


Figure 12. PV system costs

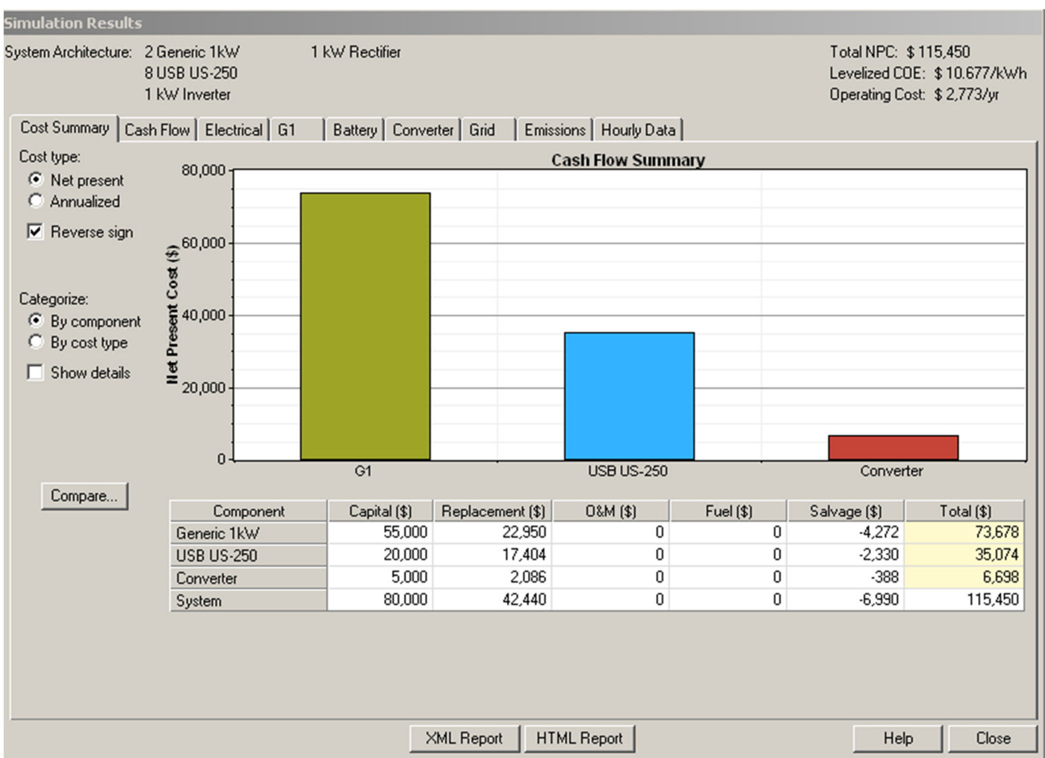


Figure 13 Wind turbine

In figure 13 we can see the purchase cost for a pure wind-turbine system. As expected, the windmill represents the vast majority, but the batteries weigh too heavily.

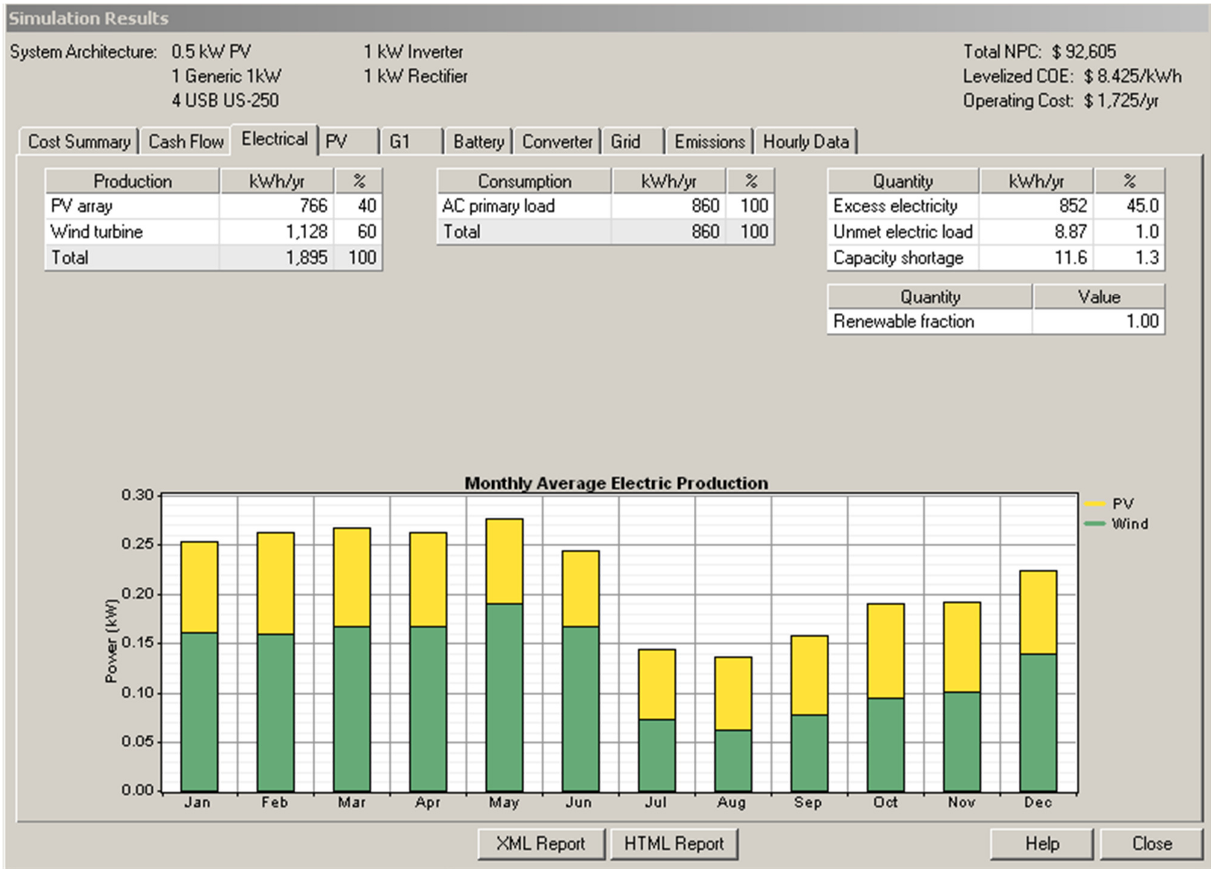


Figure 14

In this figure we can see power shared between a combination of PV and wind hybrid system. Here the PV system only contributes 40% of the power production versus 60% from wind turbines. The system is not quite optimal because there is a large untapped energy quantity of 45%. This is partly due to the chosen big turbine, and that wind energy is fluctuating more than solar energy over the years. This can be addressed by using multiple batteries, but it will increase the purchase price.

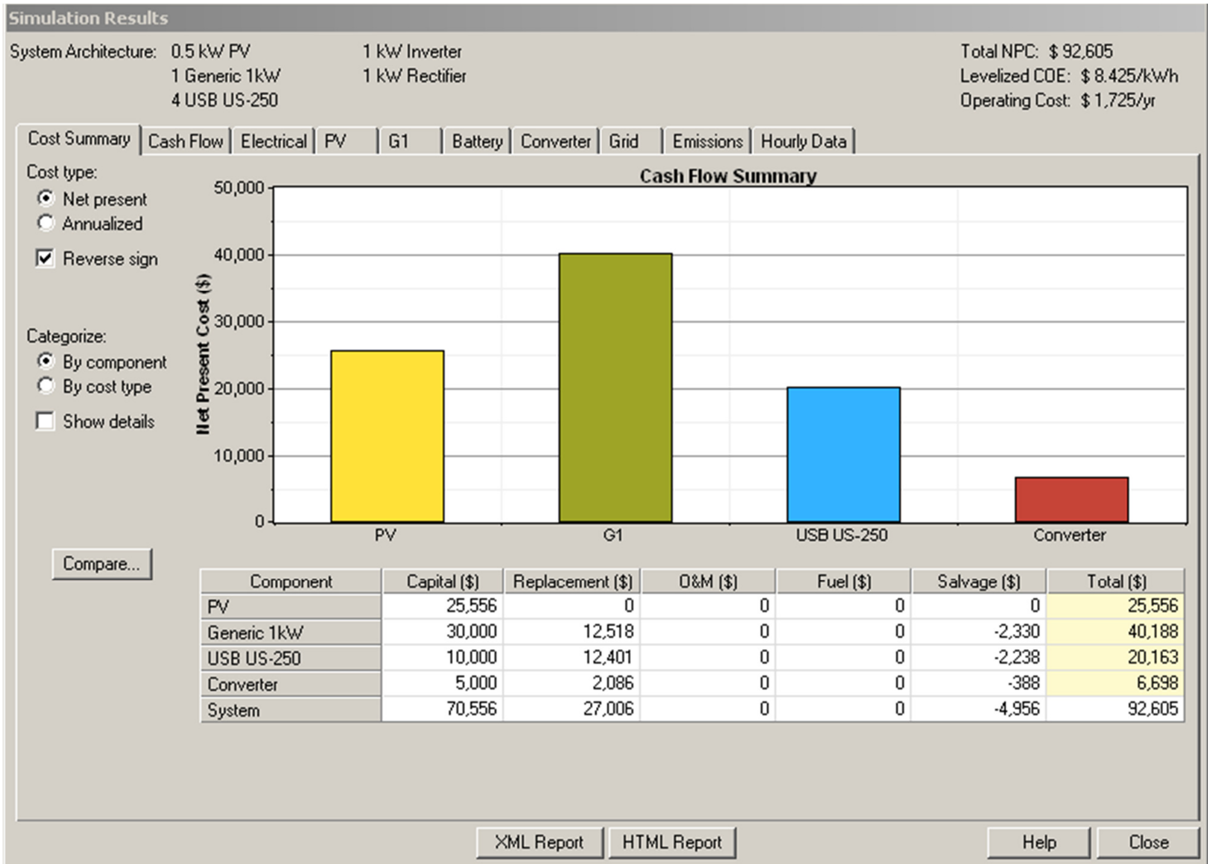


Figure 15. Cost breakdown for the hybrid PV/wind system

Using the standard assumptions for project economy in Homer, a comparison of the three systems in Cape Verde climate gives the following electricity prices:

Pure PV + battery: 7.7 kr / kWh
Pure wind + battery: 6.7 kr / kWh
Hybrid System 8.1 kr / kWh

5.1. Summary of simulations

Taking uncertainty about component costs into consideration, it appears that many areas of the 3rd World will benefit most by choosing a strictly solar based system, when the alternative is very small and expensive mills. The pure wind solution may be the cheapest option for Cape Verde, but here are also quite exceptional wind conditions. Opting out of the wind also offers lower maintenance costs. Only by larger wind power systems this option will be superior, provided that there is a reasonable wind speed. This also corresponds to Grundfos' experiences with their solar / wind powered pumps. The solar systems are by far the most widely used system type, and the hybrid system is used only when there is good wind present.

The exercise of designing an energy supply system has proven Homer to be a useful tool, but there are many assumptions and price data to be assessed in each case. The result depends (as always) on the input from the user.
On the basis of this simulation exercise, it is decided that the cooling system will initially be equipped with a pure PV system, the decision being stimulated by the recently falling prices of PV modules (2009).

6. Concept study of refrigeration systems

In this chapter it is attempted to give a systematic overview of the practicable ways of construction of a refrigeration plant driven by renewable energy.

The examples found in literature on cold stores driven by solar/wind energy are mainly constructed from standard containers. The main advantages of this solution are that isolated containers are widely available at an affordable cost, and that they provide good protection of the installations during transport to their destination. Another reason for their popularity may be that storage systems based on renewable energy are rarely very large due to high cost of the (solar) energy supply, and the size of a standard container is therefore a good compromise.

Site built storages have the advantage that they can be made in any size or shape, either from traditional construction materials or pre-fabricated wall elements. For large storages, it is probably more cost effective to build a single large room than to set up several containers. It is also important to keep in mind that the surface/volume ratio is much lower for a single large building, and the specific energy demand is therefore lower.

6.1. Temperature control and energy storage

With intermittent energy supply from sun and perhaps also wind, it is a prerequisite for stable temperature that some kind of energy storage is implied, either:

A. Thermal storage system

1. Ice-slurry or cold liquid in separate tank(s)
2. Integrated ice storage
3. Solid matter storage, e.g. rock, concrete or pebble bed

or

B. Battery storage system

1. DC battery bank
2. AC battery bank (Battery with bi-directional converter)

The storage compartment temperature is generally influenced by:

- Ambient temperature
- Irradiance on the building
- Wind induced convection
- Power availability
- Goods in/out
- Thermal capacity
- Secondary energy storage (batteries)
- Thermostatic control

Some of these parameters can be controlled, others not. For optimum control, the energy storage must cover demand in the number of days, where no power can be foreseen.

In SolarChill A (vaccine cooler), the temperature was only controlled by thermal design of the ice storage together with a minimum thermostat to prevent sub zero temperatures. In the ILK design, a tank with ice slurry was used as main energy storage, so that the cold could be released in a controlled fashion.
Energy storage in batteries alone is a possibility, but is likely the most costly and vulnerable solution. No examples of cold stores with long term battery supply have been found.

6.2. Compressor options

Given that the cooling system should be made from widely available refrigeration components based on the compression principle, there are different possibilities for compressor selection:

- small scale hermetically sealed DC or AC compressors
- larger AC compressors
- combination, for example DC compressor on solar power, AC compressor on wind power

The BD35 compressor from the SolarChill project has a special control for soft start, and gradual increase of the speed as a function of available power. The experience has been good with direct connection to PV modules, though some optimization is still possible.
If a battery is used, any DC compressor with good efficiency may be used, because start current is then no longer a big issue.
AC compressors are cheaper and found in many sizes, so with an inverter based power supply such compressors could be used as in a grid connected cold storage.
In general, compressors with variable speed are preferable due to increase of system efficiency while the number of daily start/stop sequences is reduced. Compressors driven by permanent magnet motors are the most efficient, but also the most expensive.

6.3. Configuration structure

Apart from the compressor and refrigeration system, it is important to take a closer look at the type of enclosure for the refrigerated volume itself. In the original project application, it has been assumed that the best option was a container or small building, with a central refrigeration system. However, the flexibility and low cost of standard freezer and refrigerator cabinets may open up the possibility of using clusters of such devices as an alternative solution.
Structural options:

- Isolated "container" with one or more refrigeration systems (split units)
- Container as sunshield for installed cluster of refrigerators

One could argue that the latter solution is close to products which are already on the market, such as individual PV refrigerators. However, a cluster of refrigerators at one site could have many advantages such as better protection against weather, theft and vandalism, as well as the larger capacity and flexibility in terms of differentiated storage temperatures and utilisation of the units. The thermal loss associated with openings will also be less for chest type cabinets than for a container with a door, because the cool and heavy air mainly remain inside the cabinet.

With an intelligent power management system, the goods with the highest value could be stored in a refrigeration unit with high power priority, while bottled drinks and other uncritical items could be stored in other low priority units. In the following section some of the advantages and disadvantages of the possible solutions will be presented.

Thermal storage systems (examples)

Type A1. Ice-bank

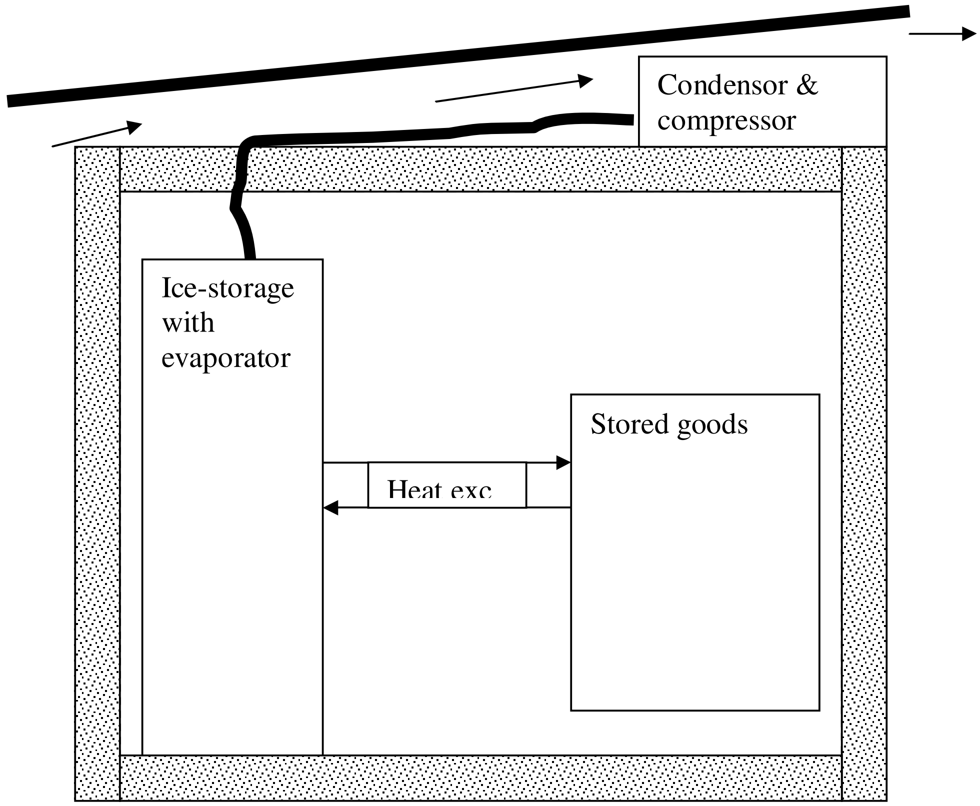


Fig 16

In this case the cold storage uses a well-insulated central ice bank for thermal energy storage. Heat exchange from the storage to the stored goods may be based on air or liquid loops with forced or natural convection.

Pros	**Cons**
Energy efficient	Specialized solution
Accurate temperature control	May be expensive for small system sizes

Type A2. Multiple ice-lined refrigerators

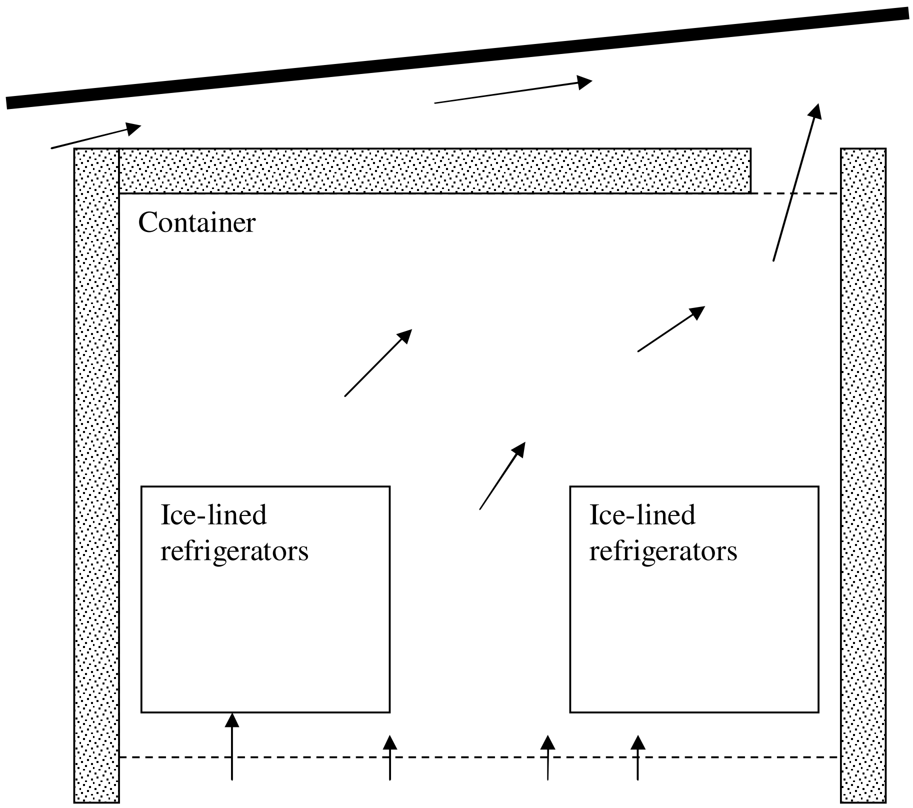


Fig 17

A container with natural ventilation of excess heat and PV roof is used for protection against direct sunlight. The refrigerators could for example be of the type with ice-lining of the walls, which would provide good thermal capacity. These are normally used in regions with unstable power supply. Alternatively one could partly fill up a standard chest freezer with ice packs.

Pros	**Cons**
Simple solution	Less efficient than large cold store per net volume
Standard components	Larger temperature fluctuations due to large refrigerator surface area
Individual compartments (ownership)	Less effective volume
Possibility for combined refrigeration/freezing	
Less infiltration of air in chest type cabinets when compared to vertical door	

Type A3. Mass storage made of stone, concrete or similar

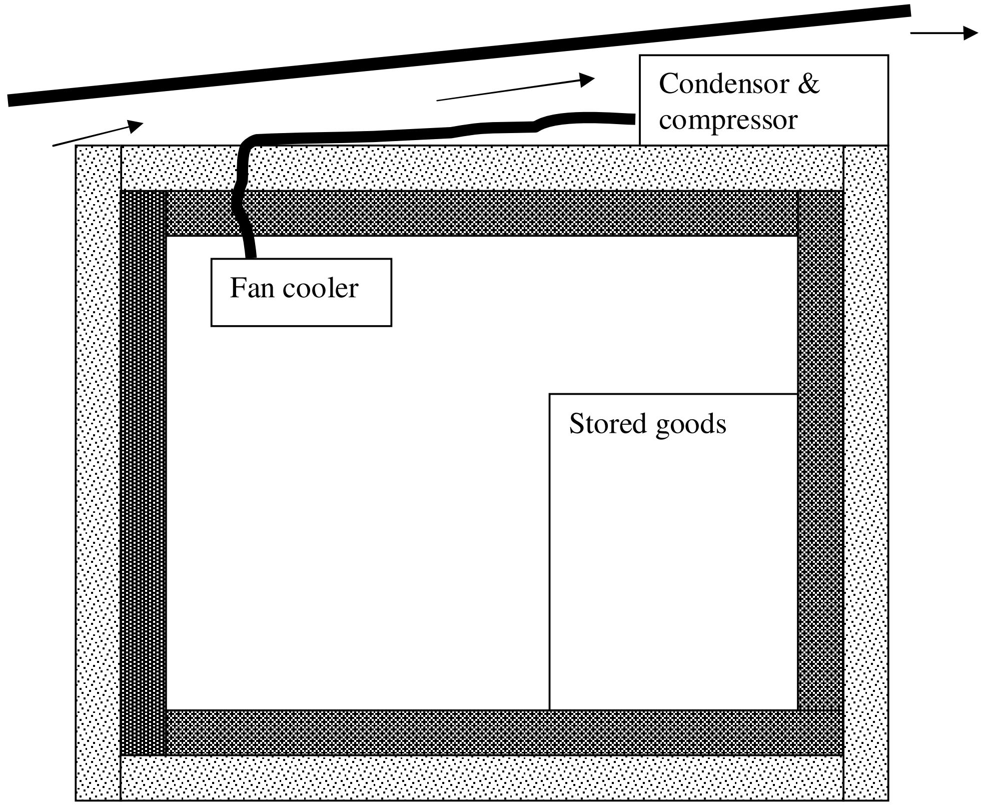


Fig 18

This type uses a heavy construction as sensible heat storage (thermal mass). The building could be made of concrete or thick (mud)brick walls with good external insulation. Additional mass could be added if necessary, for example in the form of water tanks.

Pros	**Cons**
Simple solution	Less temperature control
Standard components	More mass required than for ice storage
Cheap, local materials can be used	

Battery storage systems

Type B1: DC battery bank

This is the traditional type of storage, typically composed of a number of 12 V lead-acid batteries. The total battery voltage will usually be 12, 24, 26 or 48 V dc.
If the compressor is of DC type, it will run directly on the battery, otherwise an inverter is inserted in the circuit. The inverter must be able to deliver the necessary peak current for start of the compressor. If there are more compressors, it is possible to reduce the peak load if they do not start up at the same time.

Pros	**Cons**
Simple solution	Special DC loads or inverter required
Low energy losses	

Type B2: AC battery bank

The AC battery is a combination of the battery bank described above, and a bi-directional inverter and charging unit. (see figure 7).With this type of storage, it is possible to connect AC compressors and other electrical AC consumers directly to the terminals. If a PV system is used to charge the storage, the DC current from the PV plant passes a standard grid-connect inverter and a rectifier, so the voltage of the PV array and the battery are decoupled. AC generators from wind turbines or diesel gen-sets can be connected directly to the AC bus of the system.

Pros	**Cons**
Uses AC standard components	Specialized system, only few suppliers
Easy to expand via the AC bus	Only suitable in larger systems
Multiple generator options	

Type B3: Capacitor

This option is only for very short term storage, and is suitable for provision of the necessary start current for compressors. It must be combined with a long term / thermal storage system. The main advantage of the capacitor is that it does not require any maintenance.

System components and sizing

There are several system components that must be matched to each other and to the total expected cooling requirement of the application. The most important are:

- Gross and net volume of the cold store
- Capacity of battery storage
- Capacity of thermal storage
- Compressor size
- Size of the PV/Hybrid power system

The daily transfer of goods is the single most important design parameter, for example the difference between the same volume of milk and lettuce results in at least a factor of 10 in compressor average power.

Most compressors require a considerable start current, and a standalone system will therefore need a battery or a capacitor to be able to start on PV power alone. However, there are small DC compressors available with a very low start current, like Danfoss BD35. The main advantage is that a vulnerable storage battery can be avoided. On the other hand, a battery is needed to keep the voltage stable if the power is also used for lighting, control and display functions.

For cooling systems of considerable size, there are no large capacity compressors with low starting current available on the market. It is therefore necessary to use a storage battery, or split up the system into a cluster of smaller compressors each featuring a low starting current.

The size of the storage battery is determined by the need for continuous operation of the compressor(s) and by the effective capacity of the thermal storage system. If a small battery is used, the compressor will have to be bigger, so that it can work on full power during daytime. At night, the battery will be exhausted, and the ice storage will absorb heat.
If a larger battery is used, the compressor will only have to deliver a smaller cooling capacity in continuous operation. Some amount of ice storage may still be needed to rapidly cool the goods when they are loaded.

Since a given energy storage capacity is much cheaper for ice than for battery storage, it is recommended to minimize the battery to some hours of full load operation. The cooling circuit and compressors must therefore be oversized relative to the average cooling needs. However, there is a risk of mismatch between the PV array and the battery, meaning that the battery may run full on sunny days, unless the compressors can absorb all the power while building up the ice volume.

Two example cases based on this strategy have been calculated as part of the project:

Case study for a purely PV driven milk cooler:

Capacity	150 l milk per day (29→4°C) . Total cooling need ca 5 kWh/day
PV array	1.5 kWp . Typical electricity production 5 kWh/day
Battery	1 kWh effective capacity (fx. 12 V 100 Ah deep cycle)
Compressor	2 x 250 W power consumption. Runtime 7 full load hours/day
Ice storage	3 days capacity 15 kWh corresponds to about 150 kg ice
Regulators	MPPT charge controller for optimum PV yield. Variable speed DC/AC motor drive.
Accessories	Agitator with high efficient propeller + motor (motor outside insulation) or manual stirring routine.

The system operation will depend of the state of charge (SOC) of the battery in order to maximize the utilization of energy:

- Low SOC: no action, only control+display functions
- Medium SOC: One compressor + agitator if fresh milk has been loaded
- High SOC: Two compressores + agitator if fresh milk has been loaded

Low temperature disconnect: When the ice has been almost fully built up, the compressors are disconnected in order to avoid freeze damages.

Instead of two compressors, one large compressor may be used, if efficient operation can be obtained at part load by variable speed control.
If there is insufficient sunshine, other power sources can be connected to the battery, e.g. generator or wind turbine.

In grid connection mode, the design could be modified so that the battery and one compressor are removed from the system.

Critical parameters for the cooling rate are first of all the initial temperature of the milk, the load pattern, and the heat transfer ratio from the evaporator, through the ice-lining, and to the milk container.

An hour by hour simulation in Excel has been made for different setting of these parameters.

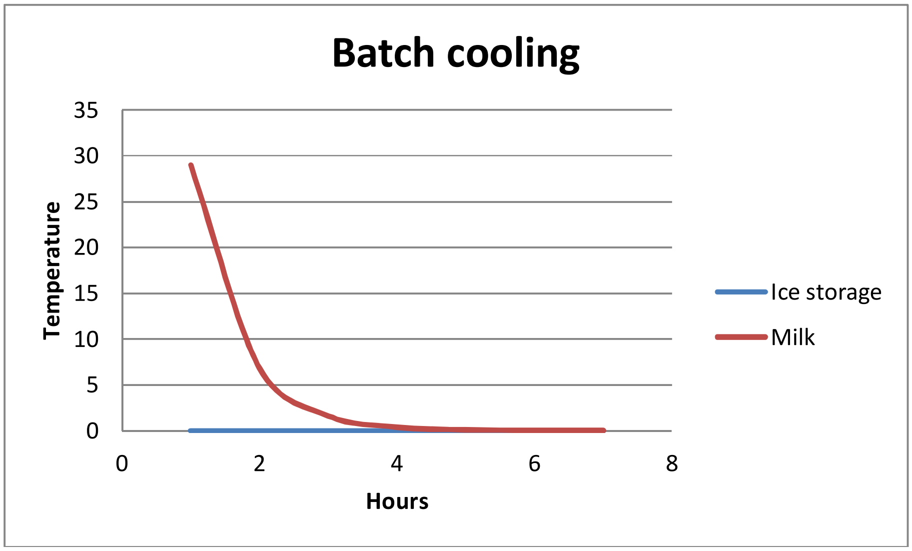


Fig 19
Using a realistic total heat transfer rate of about 400 W/m^{2}K for the milk side (with agitation), and a heat transfer rate of 200 W/m^{2}K for the ice container side, it takes 2 hours to cool down a batch of 150 litres from 29 to 4°C. A heat transfer area of 1 m^2 was used in this example.

<u>Case study for general purpose cold store</u>

Capacity	150 kg (water-equivalent) goods per day (29→4°C) . Total cooling need ca 5 kWh/day
PV array	20 kWp . Typical electricity production 25 kWh/day
Ice storage	160 kg, 3 days capacity
Regulators	MPPT charge controller for optimum PV yield. Variable speed DC/AC motor drive.

Options:
- Pre-cooling/night cooling of goods
- Traditional refrigerators in cool building

7. Design of prototype

For many reasons, it has been decided to work with the “standard chest-type refrigerator” option. Such units are relatively cheap, can be manufactured by many different producers, and are well-known and easy to operate for the end user. The only severe drawbacks are the limited storage volume and the relatively poor energy performance. These problems must therefore be dealt with.

Volume: The largest domestic freezer cabinets are about 400 liters, and can accommodate relatively large quantities of goods. More units can be added and run in parallel operation. If there is no requirement for the full volume, some of the units can be switched off, and thus leave more power for the rest.

Energy consumption: As opposed to a walk-in cold store, the surface to volume ratio is poor for the individual refrigerators, and the heat flux is thus higher. On the other hand, the cold air will tend to stay inside a chest cabinet when the lid is opened. For the container, the cold air will try to escape each time the door is opened. It is not evident which effect is the most important.
It is important to eject waste heat from the common enclosure when the compressors are in operation, in order to decrease the ambient temperature around the cabinets as much as possible. During night time (without operation) it would be better if the container is kept tight, so the heat flux from the surroundings can be minimized.

Possible solutions:

- Use refrigerators with external condenser connected to an exhaust duct. The cabinets are stowed closely together for minimization of the effective surface area.
- Build an external and ventilated enclosure for the cabinets with exhaust to the outside. A fan is set to operate in parallel with the compressors. When all compressors are off, the air around the cabinets will stay still, thus providing some additional insulation.

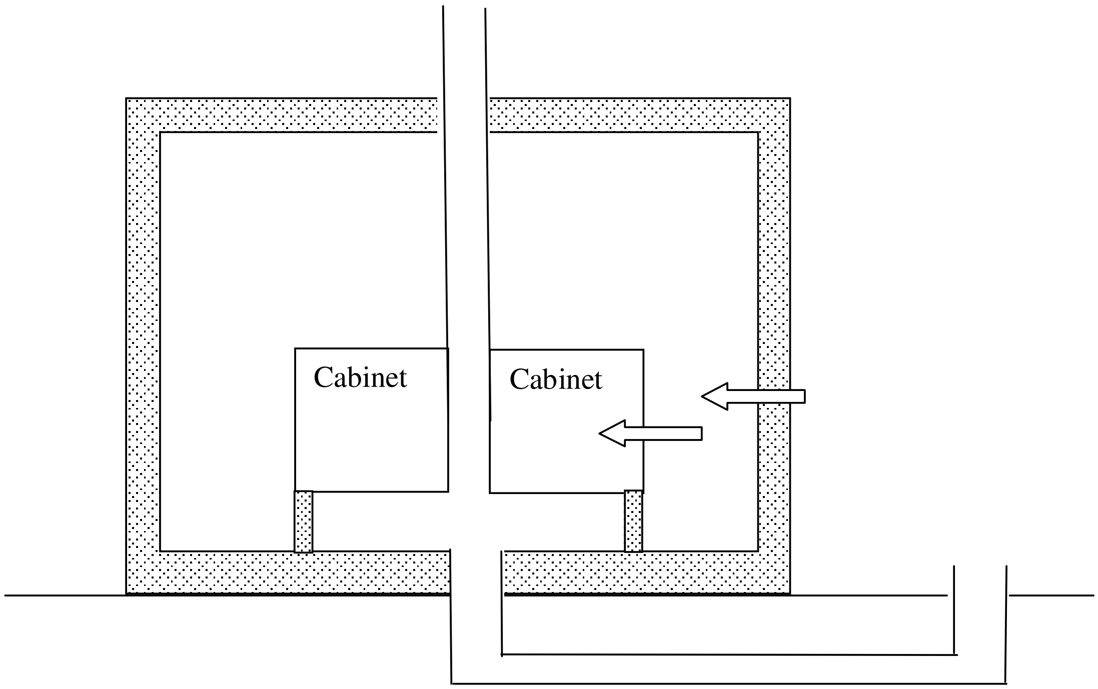


Fig20. Container with integrated chimney and cabinet enclosure. Pre-cooled air is taken from a buried duct. Outer enclosure reduces temperature around the cabinets.

The temperature and heat transport for a container with four chest freezers inside has been calculated. The heat flux to the freeze volume can be reduced during stand-still periods (night) if the outer enclosure could also help keep the cabinets cool. It is assumed that the freezers are -18 °C inside, and that the outside air temperature is 35°C. The insulation (U-value) of the container is then varied from 0.2-10 W/m^{2}K, and the corresponding heat flux calculated:

Dimension	*Fridge*	*Container*	
Length	1,5	4	m
Width	0,7	2	m
Height	0,8	2	m
Number	4	1	
Total volume	3,36	16	m3
Total surface	22,48	40	m2
Surface/volume	6,69	2,5	

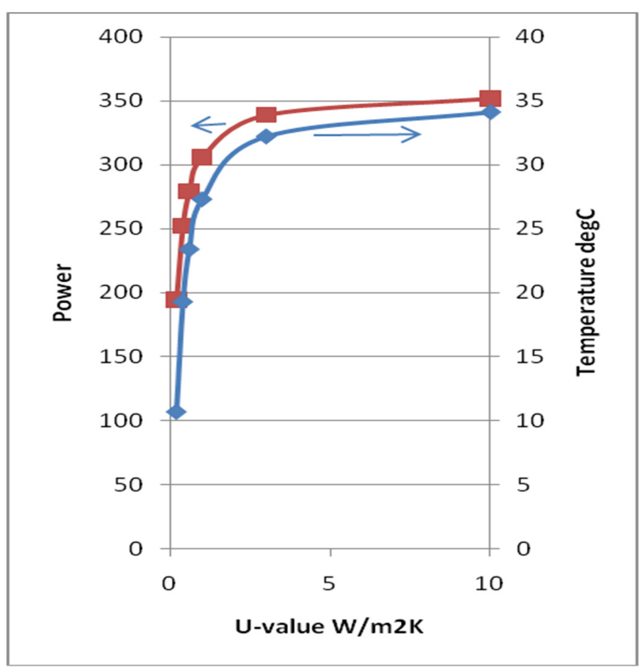


Fig 21

It can be seen that the insulation value of the container has to be rather good in order to have a significant effect on the overall heat transfer from outside (35 degC) to the frost zone (-18 degC). The thickness should be at least 10 cm for conventional insulation materials; a thin layer of insulation has almost no effect at all.

With a well-insulated container it is possible to maintain a temperate climate that may be suitable for storage of vegetables or fruit. In this example, the power required for freezing new goods are not included, it is only reflecting the heat transfer losses.

Some possible cabinets for a prototype system have been identified and listed in Annex 3. The listed energy consumption of comparable models are:

Whirlpool	419 liter	0,97 kWh/d (energy star)
Elcold 51 XLE	418 liter	0,81 kWh/d
Liebherr GTP 4726	441 liter	0,67 kWh/d (Elsparefonden)
Vestfrost SOE-215 DC refrigerator	213 liter	n.a.

Load from door openings

A good argument for choosing a chest type cabinest is the low warm air exchange when the lid is opened, when compared to an upright type refrigeratur / cooled container. For the extreme case that all air is exchanged if a door is opened in a refrigeration container, the following result was found:

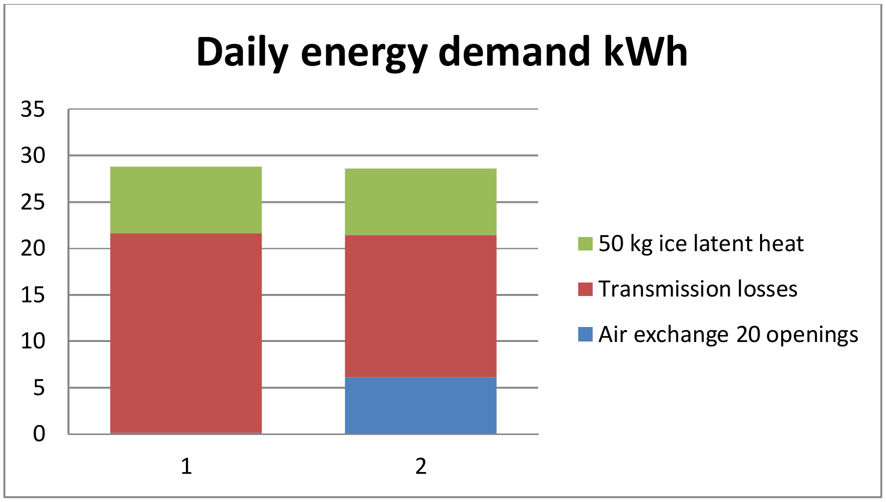


Fig. 22. Cooling demand for a 16 m^3 container(2) and 8 m^3 distributed chest freezers(1) for an example with 50 kg ice load/day and 20 door openings. It is assumed that the effective capacity of the container is 8 m^3, because some of the volume is reserved for walk space and installations. Delta T is -18/35 °C in the example, and wall U value 0,3 W/m2K.

The bar graph shows that the transmission losses are dominant in this case, but other cases could be constructed with more or less input load. It is however clear that the argument on less air infiltration load for the chest cabinets should not be exaggerated. From an energy point of view, the two solutions are equally good.

8. Experiments with a PV powered refrigerator/freezer cluster

Test purpose

The purpose of the test is to evaluate the cooling and freezing capacity and energy consumption of a solar powered refrigeration system during a simulated practical use pattern. The thermostat settings and battery voltage thresholds could also be verified and adjusted as necessary during the test period. As the power supply from the PV array depends on the solar irradiance, it is not possible to run the same test twice. It is a dynamic test where the solar irradiance as well as the ambient temperature varies as a function of time. However, the test is closer to real operation conditions than a laboratory test with simulated power supply.

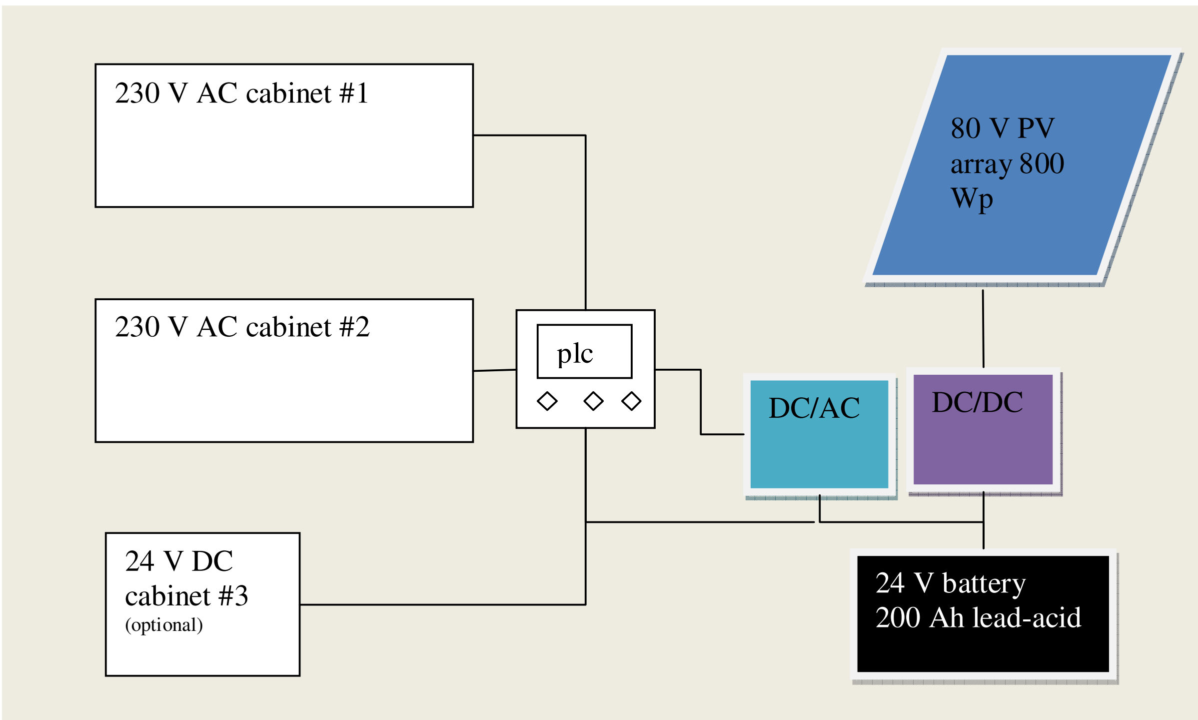


Fig 23 Lay-out of the tested system

The refrigeration system is set up at the solar energy test area of DTI, where a PV array with a nominal power of 800 W had already been established. The batteries and charge controller are purchased from a Danish PV system retailer. The inverter is a trapezoid 50 Hz 230 Vac inverter from a previous project and is a robust type with high surge current. The two AC cabinets are standard low energy household freezers, whereas the DC cabinet is a special ice-lined refrigerator (fresh food/middle temperature) with high thermal capacity in its walls. The selection of large chest type freezers gives low specific energy consumption due to a high volume/surface ratio and low air infiltration. The commercial low energy cabinets are relatively inexpensive, and can operate with an extremely low consumption if the thermostat is set to cooling mode. This idea has also been proposed by other researchers[3].

[3] A fridge that takes only 0.1 kWh a day? Tom Chalko,Renew (Australia) issue 90 (2005)

Fig 24. Cabinets in the test lab and thermal storage in the freezer.

System components:

- PV array: 800 Wp polycrystalline modules, 2x4 in series, system voltage approx. 80 V
- Charge controller: Outback FLEXmax 60 A with MPP tracking
- Inverter: Victron Atlas 24/2000 (2 kVA)with automatic sleep mode and low voltage cut-off
- Battery: Vision 6FM200D-X12V 2x12 V sealed lead acid AGM batteries in series, nominal capacity 200Ah(10h).
- Cabinet#1: Frigor low energy freezer (prototype)
- Cabinet#2: Elcold 31XLE low energy household freezer (run as refrigerator)
- Cabinet#3: Vestfrost icelined refrigerator (DC)
- Controller: Mitsubishi Alpha 2 application controller with pt100 inputs and relay outputs

Fig. 25. PV array with 2 x 4 modules in series and MPP charge regulator

<u>System control</u>
All three cabinets are controlled with a simple PLC controller (Mitsubishi Alpha2), and the temperature range can be shifted from freezing to cooling mode if desired for the AC cabinets. If the battery voltage becomes critically low the PLC will switch off the appliances one by one until the battery is recovered. It has been verified by Elcold that this type of switching does not harm the appliances, as long as it does not result in very short runtimes, where the compressor oil does not have time to distribute on contact surfaces.

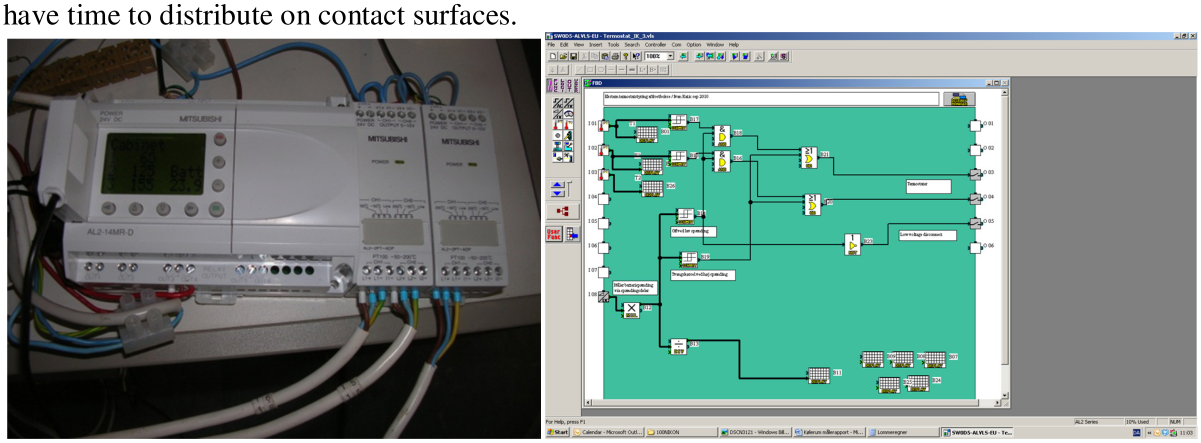


Fig 26. System controller (24V supply) and charge regulator. Screen dump of Mitsubishi block oriented control software

<u>Storage capacity</u>
The energy storage is divided in battery storage and a thermal storage consisting of 15 kg icepacks. The usable storage capacity is calculated as follows:
The 24V battery with 200Ah nominal capacity has a useful capacity of 24h*200Ah*0,5/1000 = 2,4 kWh where 50% depth of discharge is assumed to give a good balance between lifetime and investment cost. The battery is necessary for voltage stabilization at the inverter input, but in principle it could be much smaller and substituted by thermal storage volume. In practice it was not possible, because it should be able to absorb the full PV array current.

Latent heat in cabinet#1 (15 kg of water) is 15kg*335 kJ/kg /3600s/h = 1,4 kWh. Sensible heat between -18 and 0°C gives another 15kg*2,1kJ/kgK*18K/3600s/h = 0,16 kWh. In refrigerator #3 there is a similar capacity, whereas there is almost no fixed thermal capacity in cabinet#2.
The total storage capacity corresponds to a few days of operation.

Fig. 27. Battery pack with two AGM sealed lead-acid batteries

Test schedule

Cabinet	1	2	3
Exchange of icepack-baskets: 10-21 september 2010			
Mode	Freezing	Cooling	Cooling
Base capacity (icepacks)	15 kg	-	Iceliner: 17.6 kg
Input	10 kg (warm)	10 kg from #1	-
Output	10 kg to #2 (frozen)	10 kg to room	-
Exchange of icepack-baskets: 18-25 october 2010			
Mode	Freezing	Cooling	Cooling
Base capacity (icepacks)	15 kg	-	Iceliner:17.6 kg
Input	10 kg cold+10 kg warm	10 kg from #1	-
Output	10 kg to #2 (frozen)	10 kg to #1	-

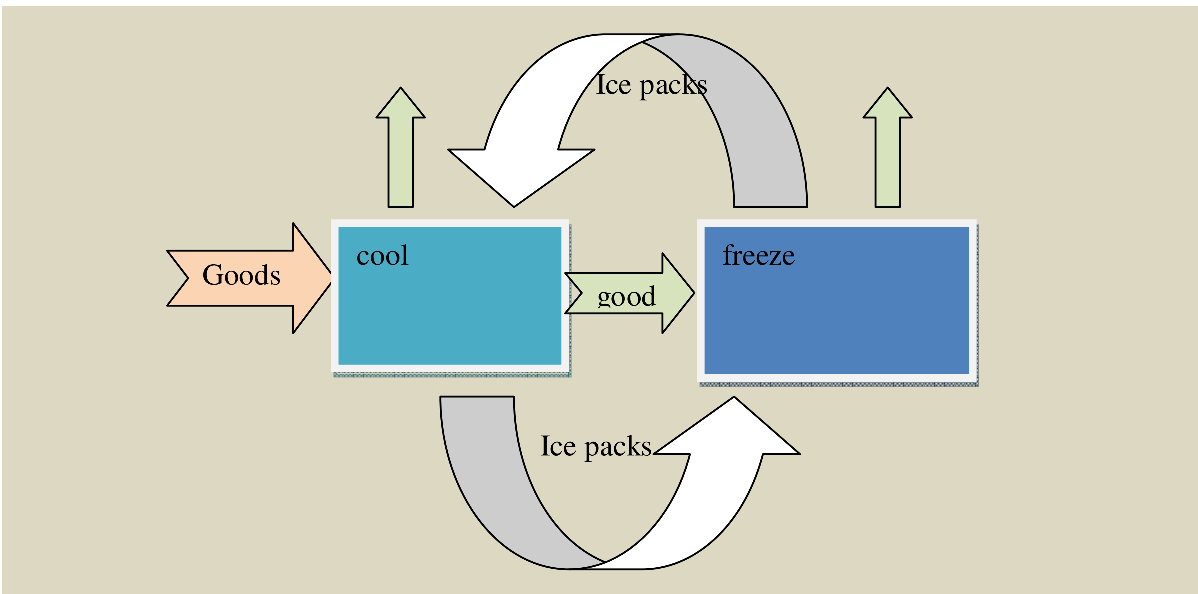


Fig. 28. Flow diagram of icepacks and consumable goods.

Most goods are assumed to be cooled for sale within short time; non sold perishable goods are transferred to the freezer. Liquids will only be stored in the refrigerator. In the test run the real goods have been replaced by icepacks in standard baskets with 5 kg in each basket. The idea is to use some of the frozen icepacks to help cooling down new and warm items in a shorter time than would otherwise be possible.

Results September 2010

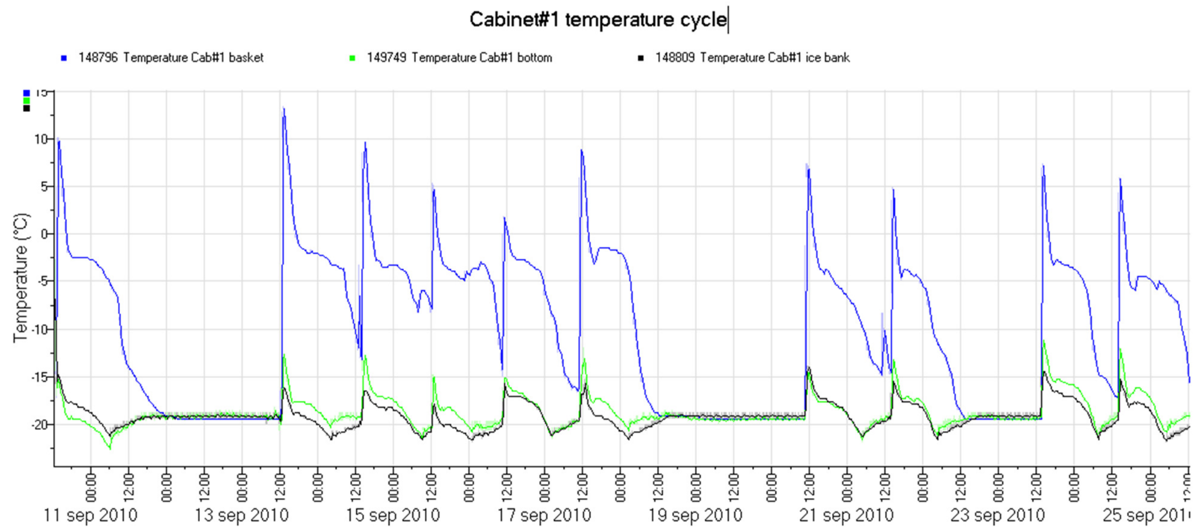


Fig. 29. The graph shows that the warm baskets are cooled down within 24 hours to deep-freeze temperature. When there is no load of new baskets, the temperature is even and constant around -19°C. The double peaks in the basket temperature are almost certainly caused by sub-cooling of some or all of the icepacks.

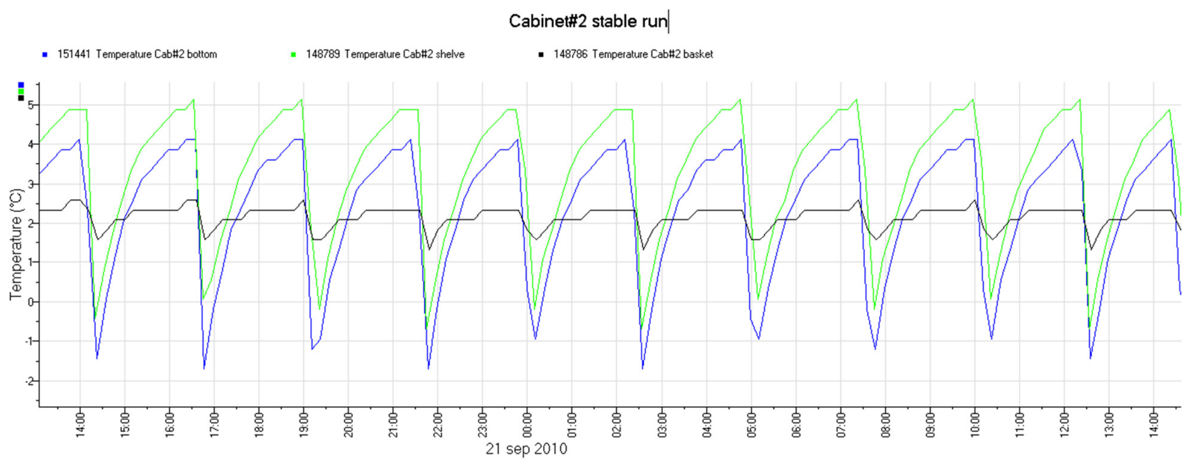


Fig. 30. Detail of the refrigerator running in standby mode, but with a high hysteresis of 5 K. The controller was set to a hysteresis of only 2 K, so it is not evident why it is higher. However, the basket temperature is quite constant due to the thermal mass. Runtime is about 10% of the time.

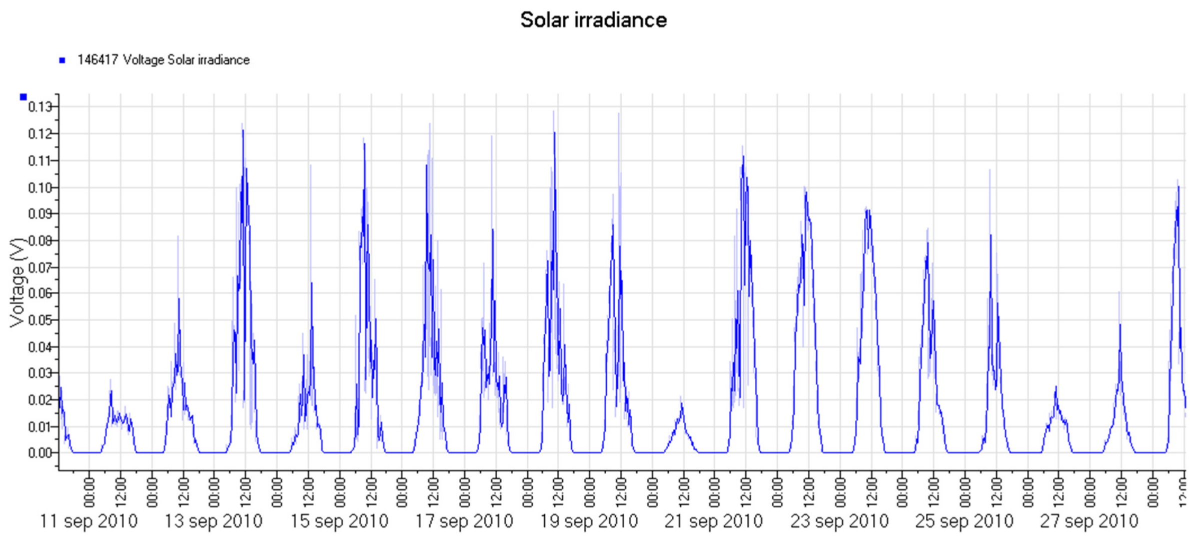


Fig. 31. Solar irradiance for the measurement period was sufficient to run the system. A sensor voltage of 0.127 V corresponds to 1000 W/m^2.

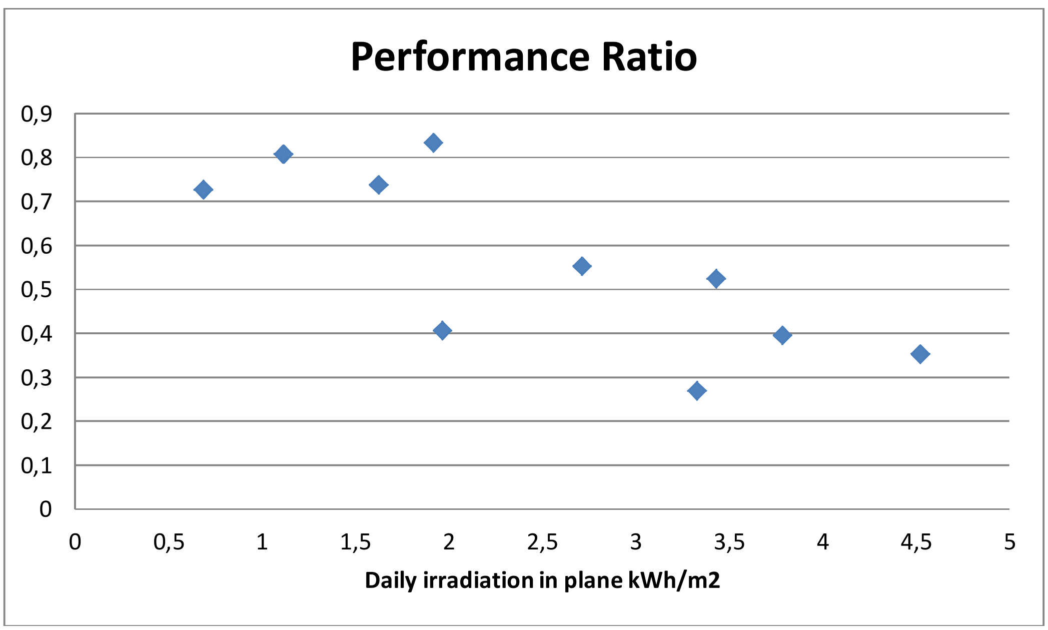


Fig. 32. The power supply system was verified by calculation of the performance ratio, i.e. the ratio between the nominal power output of the PV array and the power being charged on the battery. It can be seen that the performance ratio decreases with daily irradiation, which should also be expected because the battery runs full on sunny days. In average a value of 0,56 was found for PR, quite typical for a standalone PV system.

Results 18-25 october 2010

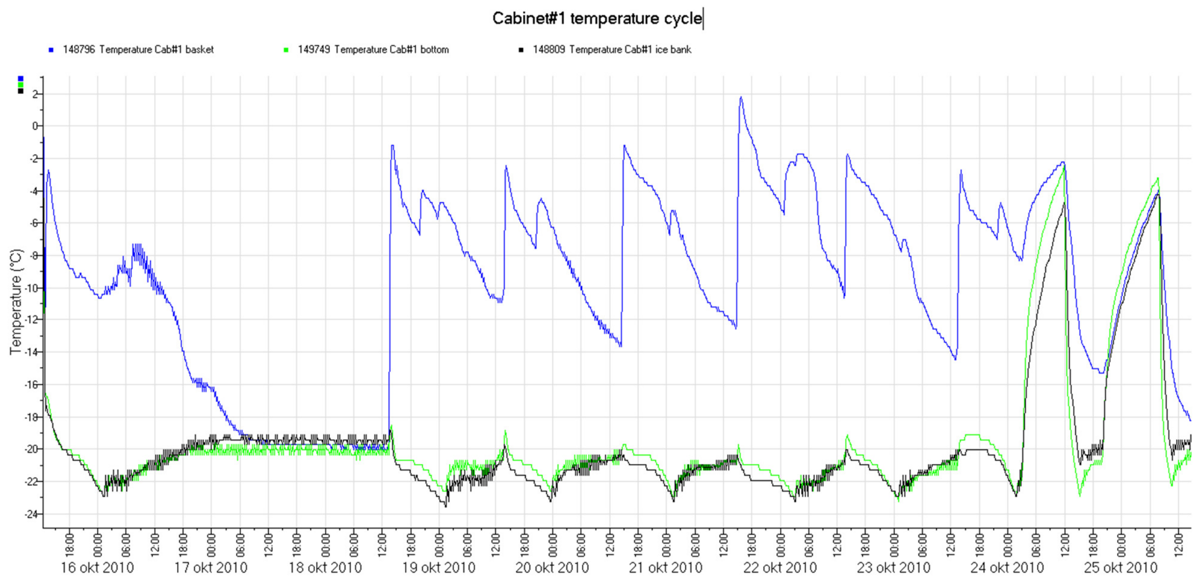


Fig. 33. The first three days of the test is a stabilization phase, where the icepacks are cooled and frozen, respectively. From the 18th the icepacks are loaded every afternoon, and frozen until next day. The double peaks in the basket temperature are almost certainly caused by sub-cooling of some or all of the icepacks. It looks like the basket temperature does not reach full freezing to -18°C, but all icepacks were fully frozen when unloaded. The quite low temperature of the new icepacks (when loading) is likely because the cold air in the cabinet cools down the sensor in the basket immediately after loading. Though the basket temperature cycles a lot, the fixed thermal storage and inside air temperature remains almost constant, unless power is insufficient as it was the case during the last cloudy days.

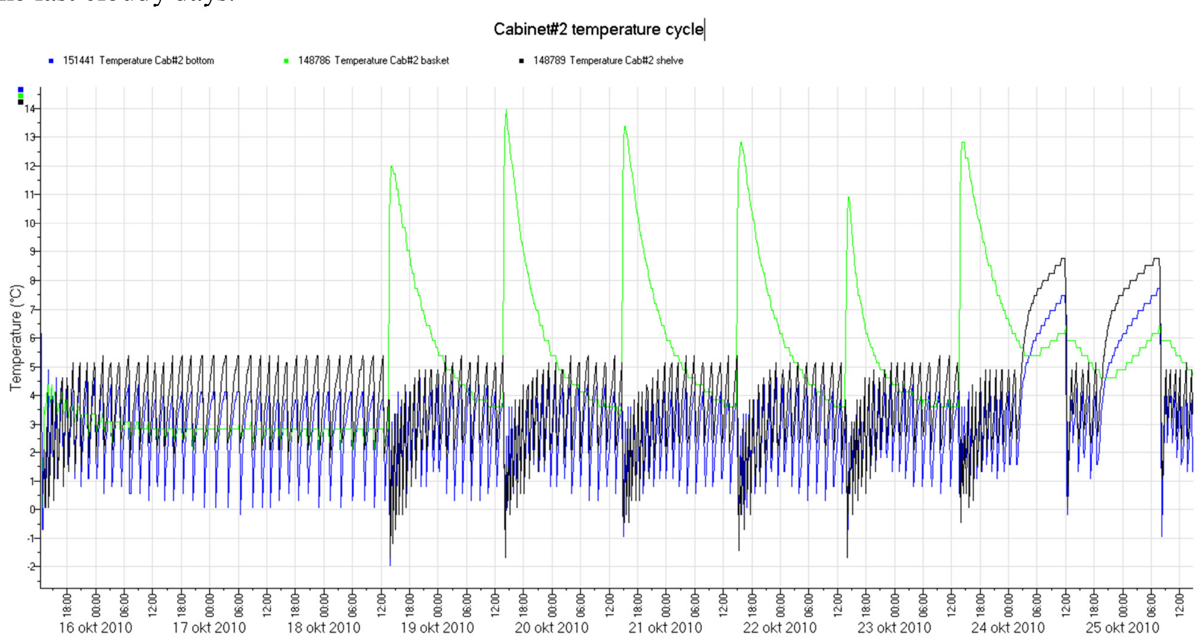


Fig. 34. The refrigerator thermostat was set to operate between 3 and 5°C, but occasionally the air temperature (shelve) becomes sub-zero. This happens when frozen icepacks from the freezer are loaded together with warm icepacks, but only until the temperature is leveled between the two

baskets. The reason for temperature fluctuations may also be caused by the lack of a fixed thermal mass in this cabinet. The warm basket is cooled down quite fast due to this temperature equalization, and the warm packs never freezes. During the last two days, where power was cut off some of the time, the passive heat transfer from the warm to the cold icepacks is evident, because the cabinet temperature is warmer than the icepacks.

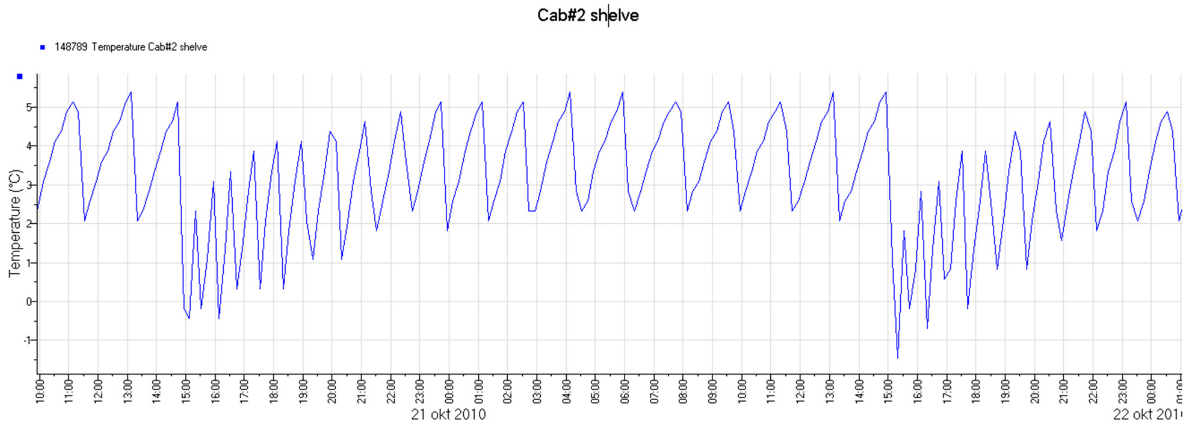


Fig. 35. The graph above shows in detail how the thermostat starts regulation already from 0°C after the frozen packs have been loaded together with warm packs. The on / off time distribution is about 20/80%. A better thermostat sensor position could have improved the regulation pattern.

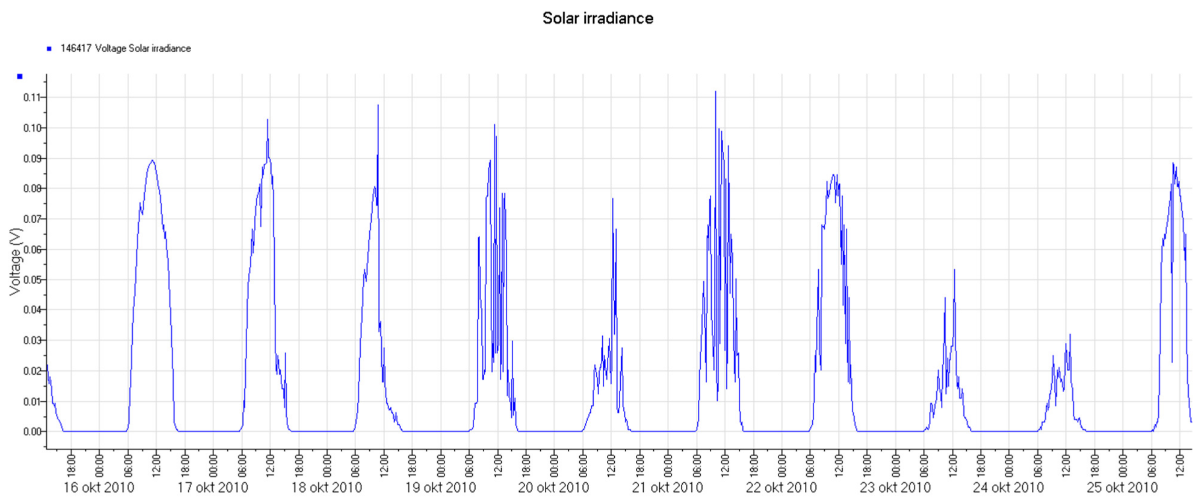
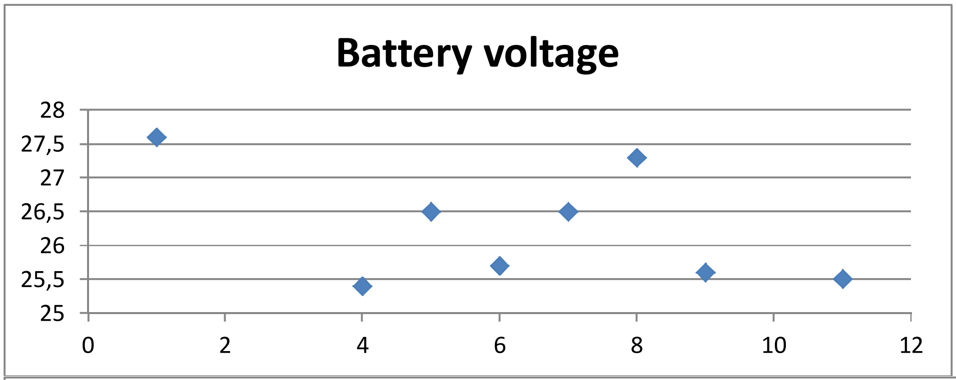


Fig. 36. Solar irradiance was variable and quite representative for a Danish autumn week. Due to low solar energy levels on the 23rd and 24th, it can be seen that the battery voltage becomes low the last days of the test. This means that the inverter has cut off some of the time, and there has therefore been a rise in cabinet temperatures.



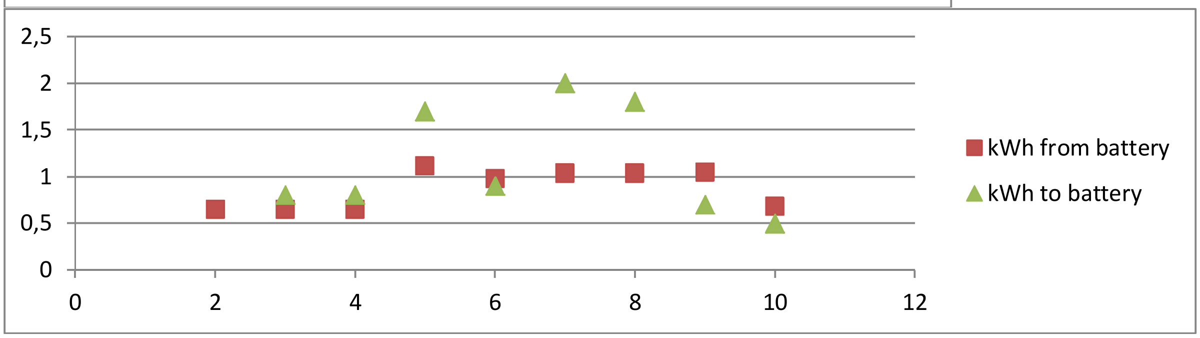


Fig. 37. Battery cycling. Nominal battery capacity = 200 Ah *24 V = 4,8 kWh. The graph shows that the battery is undergoing a daily 20-25% cycle of state of charge (SOC) which is acceptable for a deep cycle lead-acid battery. On the sunniest days the charge is about 2 kWh, of which 80-85% will be available the next day at the inverter output terminals.

Energy consumption

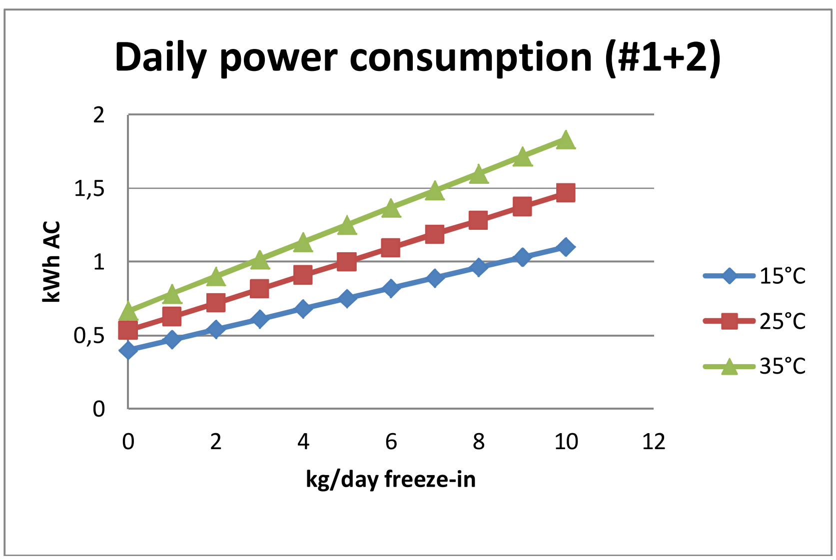


Fig. 38. The electricity supply to the two AC powered cabinets was measured with an ordinary electricity meter, and correlated with the daily exchange of icepacks in the freezer. The measurements are corrected to three different ambient temperatures. If an average COP of 1.4 is used, the measurements are corresponding with the theoretical energy demand for cooling and freezing of the icepacks. The relatively low consumption is reached by a good thermal insulation

and the fact that the cold air exchange is very limited when the lid is opened due to the higher gravity of cold air.

For a typical application in developing countries, the ambient temperature would be 35°C and there would be approximately 1.6 kWh of electrical energy available after a sunny day. Under these boundary conditions it can be calculated that the freezing capacity is about 8 kg/day for the experimental system.
If the frozen icepacks are transferred to the refrigerator and thawed before taking them out of the system, the energy consumption is almost halved or the capacity doubled.

9. Evaluation and perspectives

It is very difficult to estimate the added value of the refrigeration system, but if 8 kg of goods can be sold at an additional price of DKK 40 (for example 10% less waste of meat @ 50 DKK/kg) a simple calculation shows that the investment pays off in less than 5 years:

System costs (hardware) for the prototype:

- PV: 25000, 3 cabinets 15000, batteries 5600, regulator 4500, inverter 2000, PLC 1700. Grand total approx 60.000 DKK ex VAT
- Sale additionally DKK 40 x 300 days *10 years (battery lifetime) = 120.000 DKK

The regulator with MPP function could be saved in a simplified design, where 24V PV modules are connected to the battery via a simpler regulator. It will also reduce the cost if only two large refrigerators are used instead of three smaller ones. The large inverter of the prototype system could be replaced by a much smaller one with integrated charge controller.

Proposed optimized design:

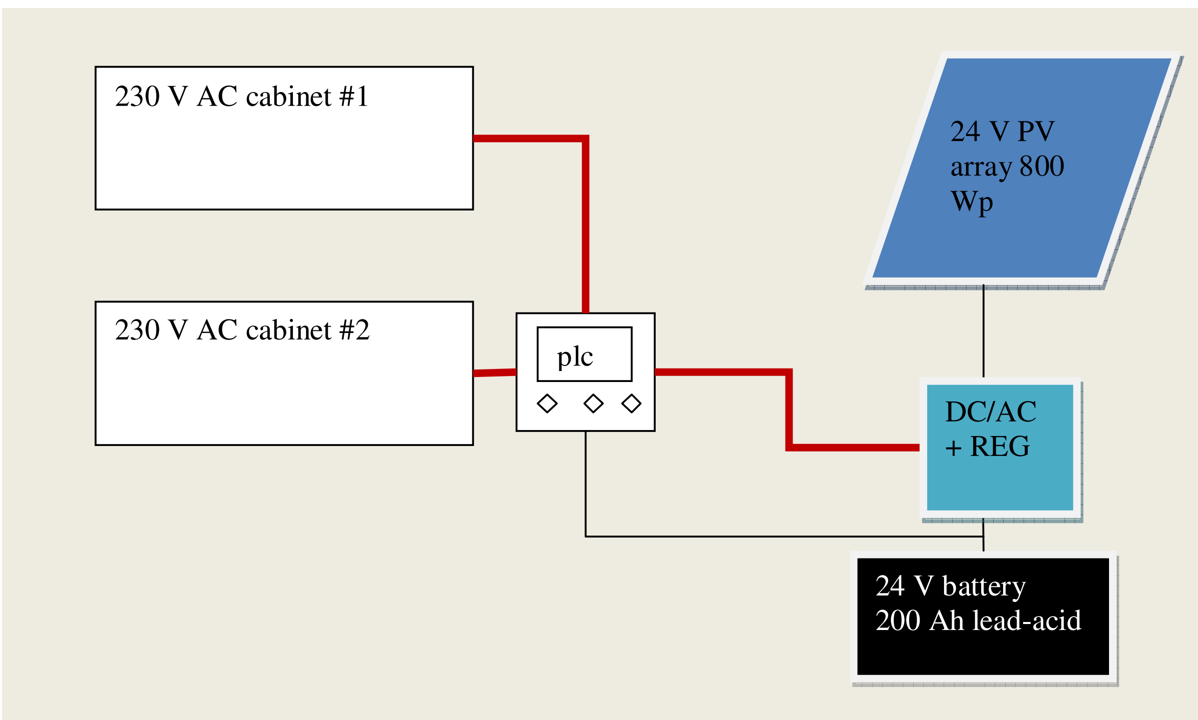


Fig. 39 modified system

- 4 x 200 Wp standard PV modules in parallel
- Charge regulator with integrated inverter 500 VA
- Battery
- PLC controller
- 2 x 500 liter cabinets

Estimated hardware costs < DKK 50,000.

9.1 Spin-off projects

As part of this quite extensive project, there have been a number of contacts with associated activities as well as direct requests from companies operating in 3rd world countries. The two most important cases have been a milk-cooling project in Uganda and a World Bank GEF project regarding improved storage methods for vaccines.

Milk has a relatively high sales value and a very limited storage time if it is not cooled effectively after milking. In many developing countries there is a high loss percentage, or the milk is simply not being produced and distributed to meet the real demand that could be fulfilled with proper cooling and transport. It can also be the case that a central diary collects the milk at a very low price, because they know the farmers do not have possibility to store and sell the milk at the local market as they lack cooling facilities. If the farmers could score this profit, they could invest in development in their local area.

The current design of the PV driven refrigeration system could be modified to milk cooling, and this is actually being investigated by the Danish company “Karise Klejnsmedie” who are specialist in stainless steel processing. They are currently designing a prototype with a cooling capacity of 75 liters/day for test at DTI. If the test results are promising, it is the intention to build a version for field test. It is a challenge that the power consumption for cooling of 75 l milk is quite high, and the desired cooling rate of 30°C in two hours is much higher than a small compressor can cope with. It is therefore suggested to integrate a big volume of ice around the milk containers as a buffer. The PV array will also be bigger than the current prototype, but as the cost of PV has decreased to a favourable level, it is not an obstacle in itself.

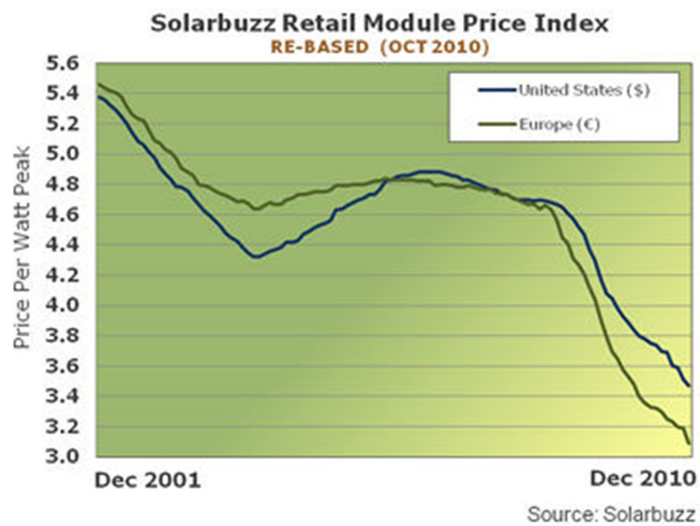


Fig. 40. International price development on PV modules (www.Solarbuzz.com)

The relief organization PATH is a specialist in cold chain vaccine storage and transport in developing countries. One of the major problems with vaccines is that they cannot tolerate freezing, but on the other hand they need cooling. Current use of icepacks in transport boxes requires precise adjustment of icepack temperature before outreach, but still there is a risk of freezing. A new type of icepack with a freezing temperature of 5-6°C may solve this problem, but until now they are frozen in ordinary freezers to -18°C in order to be sure they are totally frozen (avoiding sub cooling). If they could be frozen at, say, 1-2°C they could be used immediately for vaccine transport without risk of freezing the vaccine. It seems that the PLC regulated chest freezer from the current project could be well suited for this purpose, and its size is perfect for the type of rack that is used by PATH to hold the icepacks. The rack with icepacks will be tried in the lab by DTI in the near future.

9.2 Perspectives

Solar powered refrigeration and freezing has drawn attention for decades, and numerous systems have been developed with either thermal or electric energy input. However, the commercial success stories have been scarce. With recent 30-40% lower cost on PV modules, it seems likely that electric system will have advantage over thermally driven systems in general terms.

The current PV based project has deviated somewhat from its original intentions, but nevertheless some important lessons have been learnt and useful results achieved.

First of all, the result shows that a very efficient and flexible refrigeration system can be constructed at reasonable costs from commercially available standard components. The only draw-back of the design is the battery that has a limited lifetime, so the system is not truly maintenance-free. On the other hand, lead-acid batteries are available everywhere in the world at reasonable costs. In a future system it might be possible to reduce the size of the battery further, and increase the thermal storage capacity instead.

The system has been operating without any problems, apart from temporary cut-off during very cloudy periods. In such periods, the controller can give priority to keep the most important cabinet in operation on the expense of less important units.

Future application of a flexible refrigerator/freezer cluster driven by PV power is first of all in non-grid connected areas with reasonably constant daily solar irradiance, i.e. the Sunbelt, where there is a real demand for storage of perishable goods. Typically it could be fish, meat, milk, certain vegetables, cold drinks and ice cream. The profitability will be highest if the goods have a high commercial value per volume and heat capacity unit.

Apart from commercial use, the system will also be very suitable for larger health centres with a need for vaccine storage and freezing of icepacks. A version for this purpose is currently being developed by DTI.

Finally, larger clusters of PV powered cabinets could be constructed on a community basis, where each owner could have a small compartment on a rental basis. The system should be financed by an investor who could earn a profit and take care of maintenance and protection. These systems could be combined with street lighting and other services such as cell phone charging. For even larger cold stores, it is possibly necessary to develop other configurations based on isolated containers or buildings. In this case thermally driven solar refrigeration circuits could become an economic option.

Annex 1. SolarChill B - Prototype and test results

SolarChill-B-chest type
A prototype of SolarChill B chest type has been build for the Danish Technological Institute. Vestfrost has build the unit on basis of their existing cabinet (MK204) and the Danfoss Solar Compressor (BD35K). The cooler is controlled by a mechanical thermostat with sensor inside the cabinet. When the temperature inside the cooler gets to cold, the thermostat will stop the compressor. 17.6 kg icepacks is build in the side walls of the cabinet and this ice bank keeps the food and drinks cold during OFF-time.
The cooler is working in a similar way as SolarChill A

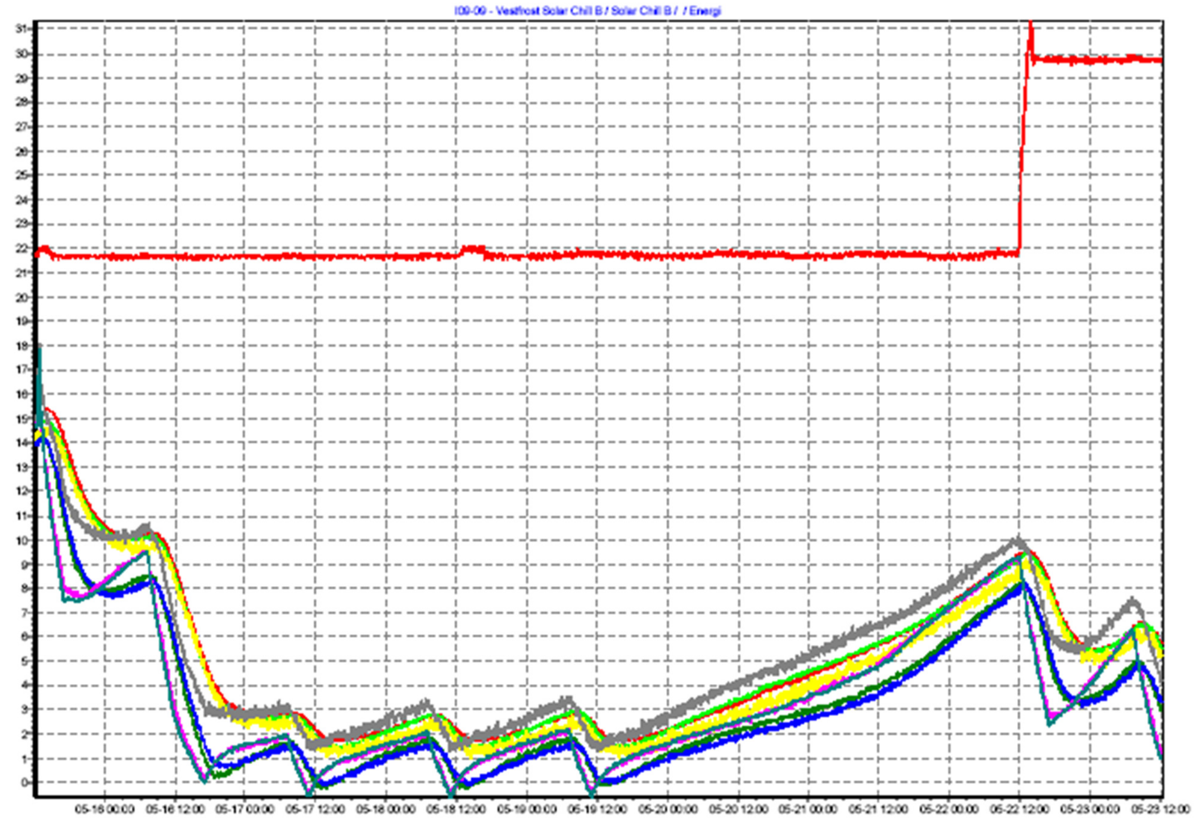
Photo: Test of SolarChill B in climate chamber at DTI. The cooler is powered by power supply (15 V) and power is available 10 hours a day. Temperatures are measured and recorded (8 temperatures inside the cooler and ambient temperature and humidity)

Photo: The prototype has 5 baskets (3 baskets in the upper part and 2 baskets in the bottom). The volume is 137 litres and the cooler can contain a great amount of food and/or a greater number of soft drink cans (see photo). The cooler is intended to be used for household use or small commercial use.
At this photo it can be can seen, that the cooler is packed with 2,5 kg test packages (also used in the European test standards for household refrigerators) in each basket and 8 soft drink cans (33 ml) in each basket. This simulates food and drinks. This is a test method developed at DTI this springtime.

Tests have been made in a climate chamber at DTI, where also other tests are ongoing. The temperature in the climate chamber is defined by other tests, and the temperature has been 22 C in a period and is now 30 C and will stay at 30 C for a while.

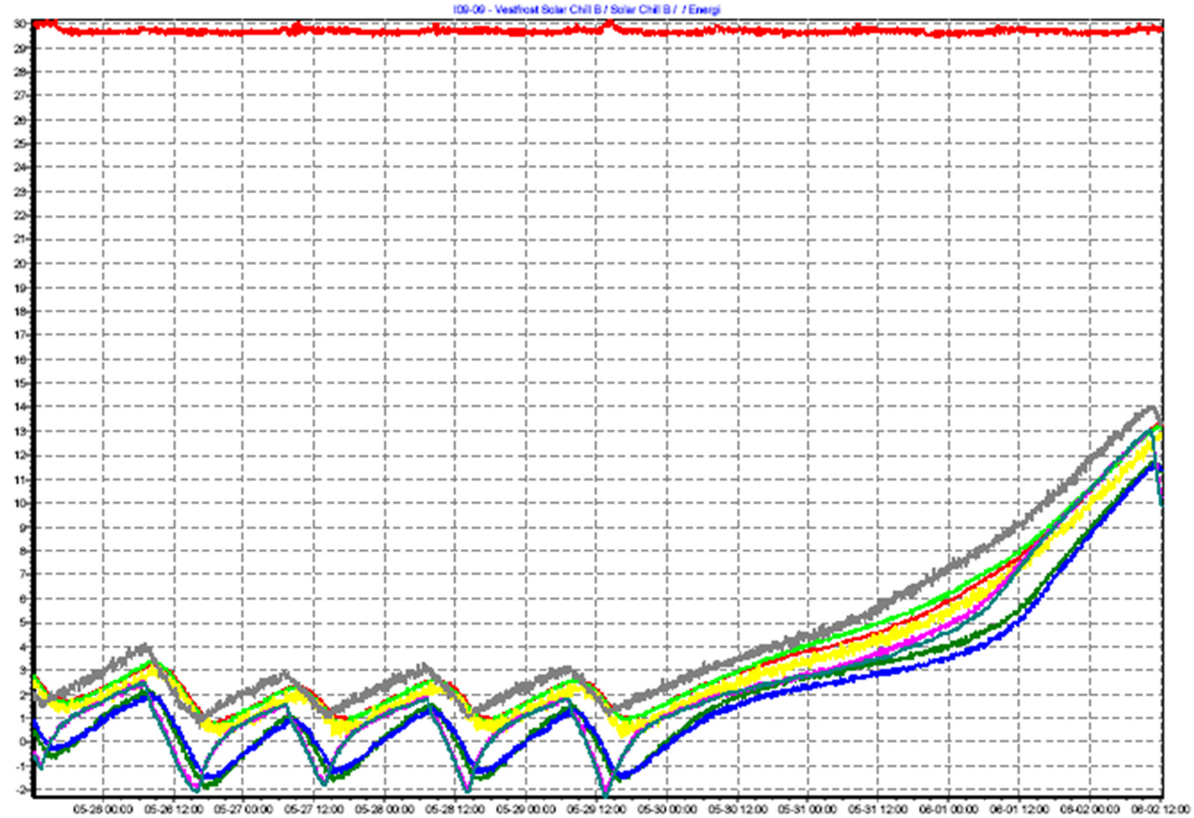
Results at 22 C ambient temperature
The very first tests where used to find correct placement of the thermostat sensor in the upper part of the cooler.

When this was found, stable running and hold-over time test were made.



Curve: Test at 22 C ambient temperature. During stable running the compressor and refrigeration system is running about 3 hours and 40 minutes per day. The temperatures in testpackages are between 0 and + 3 C and the air temperatures are between – 1 and + 3.5 C. The hold over time is about 2.5 days (food temperature has rised to + 7 C, air temperature to + 8 C) and after 3 days the temperature has rised to + 10 C.

Results at 30 C ambient temperature



Curve: Test at 30 C ambient temperature. During stable running the running time is about 6 hours, 20 minutes per day. The temperature in test packages are between – 1.5 and + 2.5 C and the temperature in air are between -2 and + 3.0 C. The hold-over time is about 2.7 days (food is warmed up to + 7 C) and after a little more than 3 days the testpackages are warmed up to + 10 C. It can be seen from the curves that the ice has melted after about 2.5 days.

The DTI has the opinion, that these results are very good. Both at +22 and + 30 C ambient we have surplus of cooling capacity, temperatures from -1.5 to + 3 C. By modifying the thermostat setting this might be a little warmer, if this is wanted. The hold-over time is about 2.5 – 3 days, which also is good.

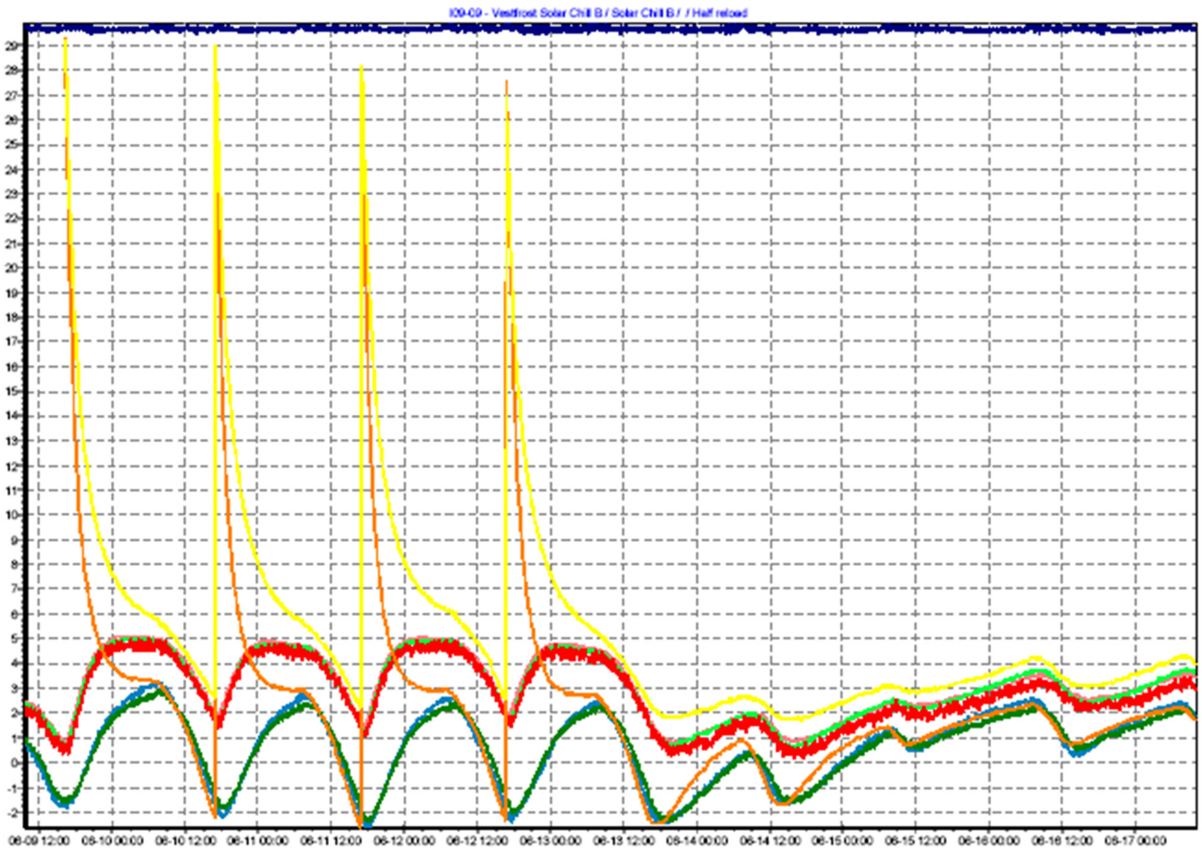
The cooler is intended for household and small commercial use, where the claims for temperature setting is not that big. It does not matter if the temperature is -1.5 or + 3 C. The coldest temperature is at the bottom of the cooler and the warmer is in the upper baskets, and if wanted this can be beneficial eg. by storing food in the bottom and drinks in the upper baskets.

Simulated use of cooler: "Half reload test".

The DTI again started the power supply, and the cooler vent into stable running at 30 C ambient. We then strted a simulated use of the cooler, by changing 20 cold cans with 20 warm cans (with temperature of + 30 C) at "sunset" which is supposed to be the most critical time. The cooler contains 40 cans, so we call the test a "half reload test".

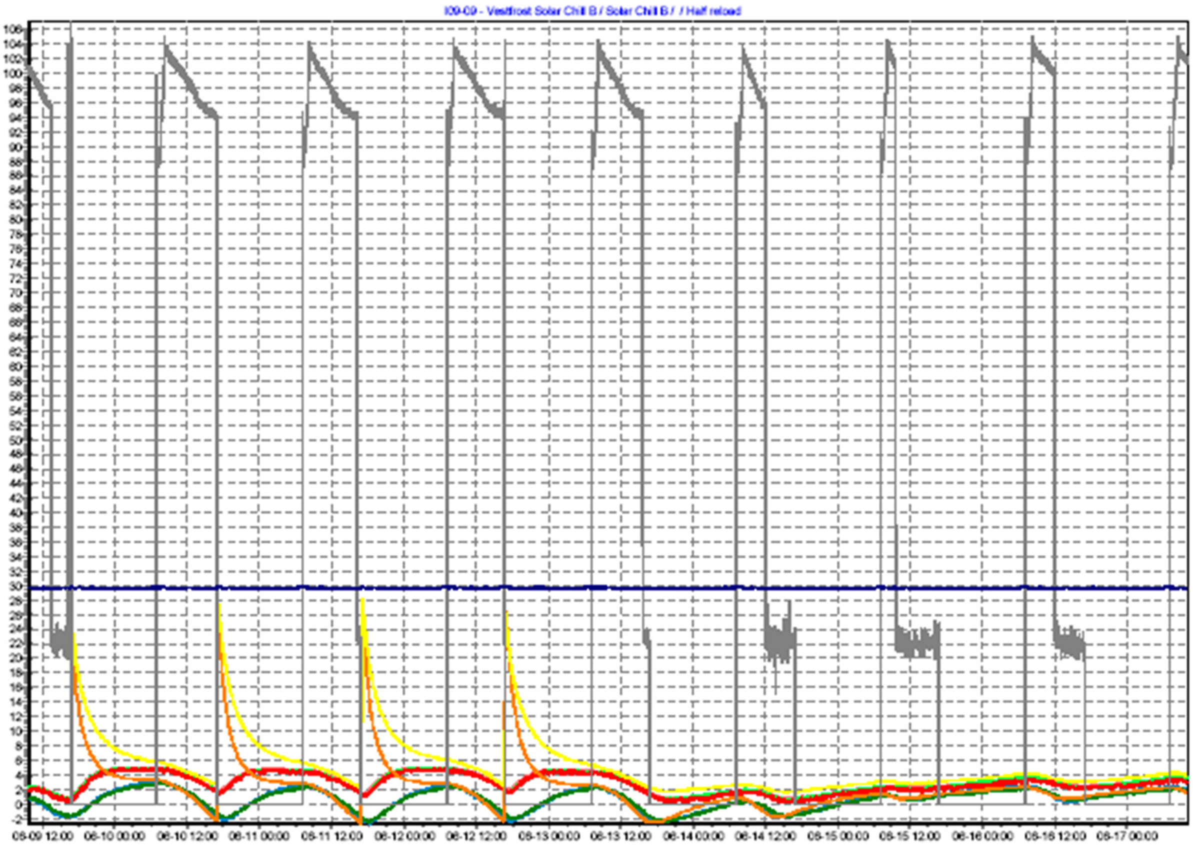
I each basket are 8 cans placed in the 4 corners. The upper cans are replaced every day, and the test was done in four days.

Two of the cans were equipped with termocouples for measuring the temperature, one in the upper row of baskets and one in the lower row.



Curve: Tempertures inside the SolarChill-B cooler during the half reload test. It can be seen that the warm soft drink cans are quite rapidly cooled down, and after about 8 hours the warmest can is below 7 ^{0}C.

It can be seen from the curve above that the warm cans are rapidly cooled down. It takes 8 hours for the warmest cans to be cooled down to +7 ^{0}C.



Curve: Half reload test with temperatures and the effect used by the power supply. It can be seen that the compressor is running almost all the time when power is available (10 hours a day) when the half reload test is ungoing. This reflects that we are close to the maximum cooling capacity by this test. The average temperature in the cooler is quite low (about + 2 ^{0}C).

The conclusion on the "half reload test" is, that the cooler works fine and can each day cool at least 20 soft drink cans (equal to 6,7 kg water) down from 30 ^{0}C to below + 5 C.

Annex 2. Abstracts of selected project references:

1) A refrigeration facility for milk cooling powered by photovoltaic solar energy

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Keywords
refrigeration • stand-alone PV systems • performance

Abstract
The use of renewable energy sources is usually a reliable alternative in rural areas and developing countries, where the grid line does not exist or is at a great distance. In this work, the characteristics and working conditions of a refrigeration facility designed for cooling down an expected daily production of 150 l of milk are analyzed. The facility is a stand-alone, direct-coupled system where 20 photovoltaic modules, 120 Wp each, power two permanent magnet, direct current motors of 24 V, 650 W. Each motor drives a separate cooling system compressor, which provides the flexibility to operate the equipment with one or two motors and with various interconnections of the PV modules, depending on the available irradiance level and the thermodynamic state of the system. The photovoltaic energy obtained during daylight hours is stored in the form of sensible and latent heat of frozen water in a tank surrounding a milk container.
Thermodynamic analysis of the system shows that the autonomy of the system is 2·5 consecutive cloudy days if the available stored ice energy is 80% of the nominal capacity of the water/ice tank. Results of the refrigeration efficiency are similar to those obtained by other commercial refrigeration facilities powered by a photovoltaic array, including batteries. Copyright © 2003 John Wiley & Sons, Ltd.

2) FP5 Project Record 528 . Development of a mobile solar-driven refrigerated container for rural areas

General Project Information
FP5 Programme Acronym: EESD

Project Reference: ENK6-CT-2000-35010 Contract Type: Exploratory awards
Start Date: 2000-07-06 End Date: 2001-07-05
Duration: 12 months Project Status: Completed
Update Date: 2005-05-03

Project Description
In countries with a high level of sunshine there is a considerable demand for cold supply. Statistics have shown that in sough Europe nearly 10% of fresh food become worse in quality due to the lack of sufficient refrigeration. This concerns in particular structurally weak rural areas in Southern Europe (Greece, Spain,

Portugal, etc.) which represent about 2/3 of the total territory in these regions. The main problems in these thinly populated areas are often the logistics and the lack of infrastructure. Against this background there is a major demand for new and innovative solutions for decentralised and combined cooling processes. Solar refrigeration plants are ideal for keeping foodstuffs fresh, since the solar radiation which "causes" the need for refrigeration is available in sufficient quantities. The COOLTAINER proposed here can be used for different applications such, for examples the storage of fresh fish, meat and vegetables and also of medicine. Prior to the project, the possibility of application on a large scale was tested by means of some basic system-related laboratory trials and the results were positive. The objective is to develop further and optimise the COOLTAINER in the framework of a research project so that upon complete

Coordinator
Organisation Type: Other

Organisation: CRYCLE CRYOGENIC DEVELOPMENT N.V.
PO Box 4056
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Contact Person:
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Participants

Organisation: COOLINGTEC INDUSTRIES (1993) LTD.
Ramat Hashron
47264 RAMAT HA-SHARON
ISRAEL
Contact Person: ARTSIELY, Yehuda

3) Vapour Compression Cooling System Powered By Solar PV Array for Potato Storage

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ABSTRACT
Refrigerated storage, which is believed to be best method for storing the fruits and vegetables in fresh form, is not available in rural or remote locations where grid electricity is almost not available. So, without having a conventional energy source at these areas, the present study was taken up to design and fabricate a solar PV powered vapour compression refrigeration system to attain favourable conditions for potato storage, and to evaluate its shelf life under different operating conditions. The system is designed and fabricated in the division of Agril. Engineering at IARI, New Delhi. It consisted of PV panel, lead-acid battery, inverter and the vapour compression refrigeration system consists of a drier-cum-filter besides the main components: compressor, condenser, expansion device, evaporator, exhaust and evaporator fans. The 2.50 m3 cold storage structure was constructed and insulated with proper materials. An evaporatively cooled storage structure (1.0 m3) was used for curing process. The cured potato cultivar (Kufri Chandermukhi) were stored for 5 months. The stored tubers were divided into two lots, one used as control (free sprouting) and the second was manually desprouted. Measuring of moisture loss, dry matter, sprouting, rotting, sugars content, starch and chipping quality reflected the shelf life

of potato. The average daily solar photovoltaic (SPV) energy output and energy consumption by the load were 5.65 and 4.115 kWh, respectively, under full load. The obtained results indicated that, the average daily actual COP for loaded and air circulated cold storage structure was 3.25. The average temperature and relative humidity maintained inside the loaded and air circulated storage structure were 283.13 K and 86 %, respectively. Solar panel can serve as an alternative source of energy for powering cooling system.

Keywords: Solar photovoltaic, cold storage, potato, curing.

4) EXPERIMENTAL EVALUATION OF A SOLAR PV REFRIGERATOR WITH THERMOELECTRIC, STIRLING AND VAPOR COMPRESSION HEAT PUMPS

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Houston, TX 77058
Et.al

ABSTRACT
Solar photovoltaic (PV) refrigeration systems which use batteries have existed for several decades but have only been used in limited applications. Recent technology developments and experimentation in the field are refining the “solar refrigerator." Coupled with the decreasing cost of PV, this is expected to lead to more wide-spread acceptance and use. Keys to the success of the solar refrigerator are a thermally efficient cabinet, thermal storage, and a high-efficiency heat
pump. These elements, which are also important for aerospace refrigerators, were combined in a successful demonstration of solar refrigerator technology at the Johnson Space Center. Three heat pump, or “cooler”, technologies (thermoelectric, Stirling, and vapour compression) were experimentally evaluated in the same vacuum insulated cabinet. Individual heat pump performance was quantified, and the entire solar refrigerator system was evaluated by defining a system
solar COP (coefficient of performance).

5) Wind-Powered Refrigeration - US Dept. of Energy

The National Renewable Energy Lab, a branch of the US Department Of Energy has funded YES to develop an innovative wind-powered refrigeration system. Much like clean drinking water was a major issue two decades ago for villages, reliable refrigeration (or ice) remains a need of most of the third world. The availability of refrigeration is in great demand both in terms of public health and for standard of living reasons. However high electrical energy costs and lack of distribution infrastructure keeps a refrigerator of the reach of most of the world's population.

If ice could be produced for free (or nearly free) for example, many of the world's fishing villages could then successfully transport the fish they harvest to market and convert it to hard currency. An obvious solution is to develop a renewable energy-based system to power refrigeration on a large, "village-wide" scale, much like shared water wells are setup today around the world. Everywhere but in the desert, wind handedly beats solar power in energy-recovered-per-invested-dollar. However, because wind availability generally tends to be erratic in most parts of the world, it is difficult to efficiently couple the needs of a static refrigeration cycle to a wind turbine. YES engineers are developing an adaptive electronic load-matching charge management system that will permit a large-scale commercial ice machine to be directly connected to a >10kW tower-mounted wind turbine.

6) Photovoltaic-powered cold store and its performance

J.Nagaraju & al.
Dept. of instrumentation, Indian Institute of Science, Bangalore
Published in: International journal of energy research 2001:25

A photovoltaic-powerd cold store plant, the first of its kind, has been developed to store 10 tons of frozen fish at -15 ^{o}C. It consists of a photovoltaic array (4 kWpeak), a battery bank (96 Vdc, 180 Ah), a vapour compression refrigeration system (1 ton), electronic controls for automatic operation of plant and an insulated cold chamber. Experiments were conducted on the system to evaluate its performance with no heat load (frozen fish at -15 ^{o}C) and with different heat loads. It is observed that the system can be operated with a maximum heat load of 2350 W to maintain the walk-in-cooler temperature below the freezing point of fish (-2 ^{o}C). The performance studies conducted on these subsystems viz., photovoltaic array and battery bank showed that their output has deteriorated in 5 years.

Annex 3. Existing products of interest for the project:

ILK Dresden
Solar-powered shelters for cold-storage of medicines at hand

Commissioning and operating them is really uncomplicated. And there is practically no need for maintenance. As they are around the- clock automatically operating systems, which are designed for use under high ambient temperatures and for rough operation conditions in full-year operation, they are very well suited for use as absolutely self sufficient cold-storage depots for central remote hospitals, refugee camps, vaccines supply networks and remote immunization stations.

Main features
• exclusively solar supplied cold room shelters
• for cold-storage of medicines and/or vaccines and/or blood conserves
• available as 10 ft-, 20 ft- and 40 ft ISO-versions
• three ranges of interior room temperature levels to be arranged in different combinations on demand
• room 1: 0 °C to 5°C; room 2: 10 °C to 15 °C and room 3: about 25 to 28 °C
At present it is an indisputable fact that special adapted photovoltaic based off-grid applications will be competitive in areas with unsafe or missing power supply. Especially in remote areas with high ambient temperatures, where demands for self-sufficient, islanding cooling systems coincide with high solar radiation rates, and where lacks of cheap mains supply or unreliability and high costs of decentralised, conventional energy supply systems are to state, special adapted PV supplied cooling systems for cold-storage of any type of medicines, vaccines or blood conserves may be suited well.
Bearing this in mind ILK Dresden has designed different types of so called Solar Cooling Containers for cold-storage of food-stuffs, which have started their market carrier two years ago. Following a two-year demonstration of the first units we are able to present now special adapted shelters as cold rooms or depots for medicines, vaccines and blood conserve.

Picture: ILK Container system for cold storage of perishable goods and foodstuffs

■ basic unit: 20 ft container
■ PV generator: 3.4 kWp
■ cooling power: 5.1 kW (-5°C/45°C)
■ cold storage room temperature: 0°C to 10°C (fan controlled)
■ cold storage room capacity: 23 m^3
■ special features: cold storage for 3 days, redundant design of cooling system and energy supply

According to recent communication with ILK, status of the ILK project is that the commercial production has not yet been realized, only a number of demonstration units.

Contact information:

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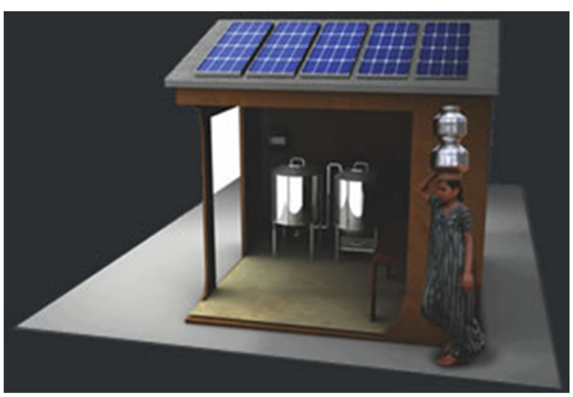
Promethean Power Systems, Massachusets, USA

http://www.coolectrica.com/
The product is under development, and consist basically of a PV powered Peltier element supplied by a generator.
Citation from web site:

Products Off-grid solar refrigerator: our product is an energy-efficient hybrid solar refrigerator system for food distribution networks that operate in off-grid or partially electrified areas. The system uses clean, quiet, solid-state technologies such as thermoelectric cooling modules and solar photovoltaic (PV) panels. A small generator is used during extended periods of cloudy conditions to backup the solar panels. By comparison, conventional refrigeration systems are not designed for efficient, off-grid operation. They use diesel-thirsty power generators and freon-based refrigeration compressors that require constant maintenance.

Lowest operating & maintenance cost: we've designed this product to achieve the lowest operating & maintenance cost. Our system takes advantage of increasing efficiencies and decreasing costs in solar and thermoelectric refrigeration technologies to reduce consumption of fossil fuels. In addition, the system includes a remote monitoring unit, which enables remote diagnosis that further reduces maintenance cost. As a result, our system can provide cooling power at an operating cost that is 66% lower than the operating cost of conventional units.

Complete, stand-alone rural refrigeration system: our vision is to develop a complete, stand-alone rural refrigeration system that stimulates businesses, reduces dependency on fossil fuels and increases the quality of life in emerging markets by enabling its users to reliably store food, vaccines and other perishable items.



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A refrigeration facility for milk cooling powered by photovoltaic solar energy
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Résumé / Abstract
The use of renewable energy sources is usually a reliable alternative in rural areas and developing countries, where the grid line does not exist or is at a great distance. In this work, the characteristics and working conditions of a refrigeration facility designed for cooling down an expected daily production of 1501 of milk are analyzed. The facility is a stand-alone, direct-coupled system where 20 photovoltaic modules, 120 Wp each, power two permanent magnet, direct current motors of 24V, 650 W. Each motor drives a separate cooling system compressor, which provides the flexibility to operate the equipment with one or two motors and with various interconnections of the PV modules, depending on the available irradiance level and the thermodynamic state of the system. The photovoltaic energy obtained during daylight hours is stored in the form of sensible and latent heat of frozen water in a tank surrounding a milk container. Thermodynamic analysis of the system shows that the autonomy of the system is 2.5 consecutive cloudy days if the available stored ice energy is 80% of the nominal capacity of the water/ice tank. Results of the refrigeration efficiency are similar to those obtained by other commercial refrigeration facilities powered by a photovoltaic array, including batteries.
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Langue / Language
Anglais

Editeur / Publisher
Wiley, London, ROYAUME-UNI (1999) (Revue)

Examples of large commercial low energy chest freezers

AFS 402-628 liter chest freezer

Description & Features:
Foam filled lid for efficient temperature preservation
Temperature control panel, simple design operation easily
Embossed aluminum inner with good conduction of heat, easy to clean
Strong all-direction wheels as feet, easy to move
With lock and drain hole
External condenser is available(optional)
Certifications: CE

Model(L)	AFS-402	AFS-512	AFS-628
Fridge Capacity(L)	402	512	628
Temperature range	d-18	d-18	d-18
Climate	N/ST	N/ST	N/ST
G.W/N.W(KG)	76/68	82/72	92/68
Unit dimension(mm)	1370x675x700	1660x675x700	1940x645x700
Packing dimension(mm)	1410x750x860	1700x750x860	1990x750x860
Refrigerant	R600a/R134a	R600a/R134a	R600a/R134a

Whirlpool Chest Freezers

Whirlpool Chest Freezer: Energy Star Qualified

Whirlpools makes a very energy efficient chest freezer, model number EH151FXR (similar models are EH151FXQ or EH150FXQ). This 14.8-cubic-foot freezer is rated at 354 kWhrs per year. The average cost to run this freezer for year is $29, according to Energy Star. Though it requires manual defrosting, it sport a number of other features including an interior light and a temperature alarm. Its key-eject lock means that the freezer can only be opened when the key is pushed in and turned — a safety feature helpful in homes with small children. Four baskets (two upper, two lower) make it easier to organize the contents — especially on the lower level.

It’s available from Amazon for $405.

Vestfrost

The Vestfrost SOE -215 cabinet is a highly insulated cabinet (100 mm PU-foam) equipped with a Danfoss BD-compressor for 12V or 24 V. The net volume is 213 litres and the dimensions are 1125*600*850 mm (L*D*H).
Two options are available: refrigerator (0 - + 10 C) and freezer (-10 - -18 C).
The existing coolers are likely equipped with HFC-refrigeration system (R134a), but would possible be modified to natural refrigerant (R600a).

Elcold XLE

Rated A+ Energy efficient, the XLE range of super low energy chest freezers will help to lower running costs. Features include temperature warning light, defrost drain and fitted lock. Made by Elcold.

Features and Benefits	**Technical Specifications**
100mm Insulation	Temperature Range: -18 / -22ºC
A+ Energy Rating	Refrigerant: R134A
Low Running Costs	Type of Defrost: Manual
Defrost Drain	Exterior Finish: White
Mains Indicator Light	Interior Finish: Aluminium
Temperature Warning Light	Power Required: 13 Amp Supply
Hammered Aluminium Liner	Energy Consumption at -18ºC: XLE30: 0.46 kwh / 24 hr XLE41: 0.57 kwh / 24 hr XLE51: 0.630 kwh / 24 hr.
Lock	
Adjustable Temperature	
Internal Light	

Annex 4. Presentations, SolarChill B

SolarChill TECHNOLOGY

Solar powered direct drive refrigerators with hydrocarbon refrigerants

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ABSTRACT

Solar powered refrigeration technology (SolarChill) has been developed in an international project involving Greenpeace International, UNEP, the World Bank, WHO, UNICEF, GTZ, PATH, industrial partners and Danish Technological Institute. The refrigerators can operate directly on solar PV panels, without batteries or additional electronics and therefore they are suited for locations where maintenance and reliable operation are in short supply. The main objective of the SolarChill project is to help deliver vaccines and to cool and store food and beverages in rural areas without grid power. SolarChill does not use any fluorocarbons in its cooling system or in the insulation.

SolarChill-A is a vaccine cooler with ice storage that keeps the vaccine cold for about 5 days without power. SolarChill-A units were used in field tests with good results and the cooler is now produced by one supplier. SolarChill-B is for domestic and small business applications, and this type of solar refrigerator is currently being tested in two different prototype versions. The units are suitable for cooling and storing food and beverages in areas where grid power is non-existent or unstable. The market potential for this type is enormous as almost 2 billion people live in areas without grid power.

SolarChill is made from mass produced cabinets and other standard components, which results in a favourable cost compared to other solar refrigerators.

SolarChill-A (as well as B) has a DC compressor with R600a and a special built-in controller for solar power, including adaptive speed control. A compressor manufacturer has developed the compressor for the SolarChill partnership.

1. INTRODUCTION

Refrigeration of vaccines and food is problematic in parts of the world where there is no electricity or where the electricity supply is unreliable. In those regions, vaccines are maintained by either absorption or battery-based solar refrigeration. Absorption refrigerators are also used for food preservation. There are concerns related to absorption refrigeration as well as to the existing generation of solar-vaccine coolers because of the constant need for fuel and new batteries.

The need for environmentally friendly and affordable solar vaccine coolers and refrigerators was realized in 1998-2000 through separate discussions between the United Nations Environment Programme (UNEP), World Health Organization (WHO) and Greenpeace International (GPI).

At about the same time, Danish Technological Institute (DTI) independently began the development of a new solar refrigerator that bypassed the use of batteries (funded by the Danish Energy Agency). DTI worked together with the Danish refrigerator manufacturer Vestfrost. The direct current hydrocarbon compressor was developed by the Danfoss Company.

The first meeting of the SolarChill Project Partners was hosted by GTZ Proklima in Eschborn, Germany, on 5 May 2001. With an initial decision to proceed with the project, Greenpeace International provided the funds for the development of the first SolarChill prototypes. These were exhibited at the World Summit on Sustainable Development in the fall of 2002 in Johannesburg, South Africa.

A second generation of SolarChill Vaccine Cooler prototype was field tested at the beginning of 2004 in Senegal, Indonesia and Cuba. 10 prototypes of the chest vaccine cooler were tested under a variety of climatic conditions, 3 units in each of the countries mentioned, and 1 unit at the DTI laboratory in Denmark. The field tests were coordinated by DTI, and overseen in Senegal and Indonesia by PATH, and in Cuba by GTZ. The governments and Ministries of Health of the host countries were active participants in the field tests.

Following the experience from the field tests and the implementation of new standards from WHO (PQS, Performance Quality Safety) specifying required vaccine storage temperatures, a third generation of Solar Vaccine Cooler prototype was tested and the unit was marketed. Prototypes of SolarChill B for domestic and small commercial businesses were developed and tested with help from GTZ and the Danish Energy Agency. In 2009, the World Bank joined the SolarChill partnership. SolarChill technology is free of charge and accessible to everyone. With substantial funding from the Global Environment Facility, SolarChill Project will conduct, with the SolarChill-A, extensive demonstration and technology transfer projects in Colombia and Kenya. In addition, the project plans to complete the development, field testing and commercialization of the SolarChill-B refrigerators.
More details about the partnership can be found in Ref. 1.

2. ICE STORAGE VERSUS BATTERIES

It has been a wish from the relief organizations to avoid lead batteries as the main source of energy to keep the vaccine coolers cold during night-time and during periods with minor solar power. Previous experience has shown that additional costs are related to the batteries because frequent decharging results in a fast degradation of the batteries. That is one reason why the solar powered coolers have been more expensive compared to kerosene or LPG-powered absorption refrigerators.

In the SolarChill project, ice batteries have been developed as an alternative source for energy storage, and the SolarChill refrigerators use ice batteries in different versions. In the following, a comparison is carried out between the energy storage in a typical lead battery and in ice:

One major supplier of batteries informs the following about its 12 V, 50 Ah batteries:

Dimensions: $0.175*0.190*0.221 = 0.00734\ m^3$

Weight: 13.6 kg
Energy storage: 2,160,000 J and the specific energy storage is 0.159 MJ/kg or 294 MJ/m^3.

If we assume a COP value of 1.49 of the refrigeration system (Danfoss BD35K, - 10 C, 2000 RPM, CECOMAF-data, Ref. 2) then the specific cooling energy in the battery is 0.23691 MJ/kg or 438 MJ/m^3.

The similar figures for ice are 0.333 MJ/kg or 333 MJ/m^3.

The conclusion is that the cooling capacity for ice storage is of the same order of magnitude as for a lead battery on volumetric and mass basis. The cooling capacity is app. 40% higher (for the ice storage) on weight basis and app. 30% less on volume basis. In this comparison, a 100% discharge of the battery is assumed, which should not be carried out in reality as that would harm the battery. Another point that disfavors lead batteries is the risk of lead pollution at the end of the lifetime of the battery.

Future commercialization of batteries with high energy density for electric vehicles might change the role of battery storage in solar refrigeration. But so far, the project partners believe that ice storage in SolarChill is the preferred solution. A disadvantage when using ice storage is that the ice has to be stored inside the insulation in the cabinet and therefore part of the volume inside the refrigerator is used.

3. CONCEPT FOR SOLARCHILL

The philosophy behind SolarChill is that the coolers must be as cheap as possible and affordable for people living in areas without grid electricity.

The SolarChill coolers are based on existing well-insulated cabinets, which are mass produced. The SolarChill-A vaccine cooler has a small chest cabinet with 100 mm polyurethane insulation (blown with cyclopentane gas), the SolarChill-B-chest-type is based on an “ice-liner” refrigerator produced for other purposes and also with 100 mm insulation and the SolarChill-B-upright prototype is based on a small well-insulated upright household freezer cabinet with 80 mm insulation.

It is important for the SolarChill partnership to use natural refrigerants and a compressor manufacturer entered the project as industrial partner and developed a DC compressor for isobutane refrigerant (R600a). The displacement is 3 cm^3. The compressor manufacturer also developed a new integrated electronic control for the compressor, which ensures that the photovoltaic panels can be connected directly to the compressor without external control. The electronic control also ensures a “soft start” which is important when no battery is used.

The electronic control is equipped with an adaptive speed control (Adaptive Energy optimizer – AEO). By using that control, the compressor will stepwise speed up from low speed to maximum speed in 12.5 RPM/min. If the photovoltaic panels cannot provide sufficient power, the compressor will stop and after a short while it will try to start again. The compressor will try to start every minute and once the power from the panels is sufficient the compressor will start at lower speed. The first start in the morning is at app. 2500 RPM. After a compressor stop the compressor will start up at the latest speed minus 400 RPM. The speed range is from 2000 to 3500 RPM.

The controller accepts a voltage between 10 and 45 V. The voltage from photovoltaic panels can vary and that is a good feature for solar powered refrigerators and freezers. When using 12 V modules, the compressor starting current is less than 3 A. The compressor runs continuously at about 3 A at low speed (see figure 1). Using normal electronic control the start current would be much higher, requiring much bigger PV-panels or require the use of a capacitor to help start the compressor.

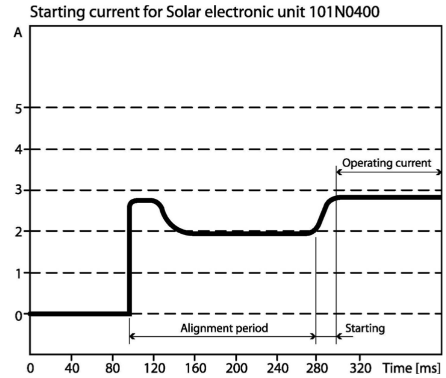
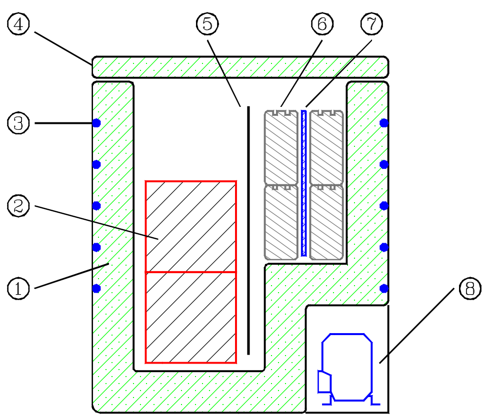


Figure 1: Starting current using the solar electronic control, 12 V.

The expansion device is a capillary tube with heat exchange to the suction line. In the chest type cabinets integrated skin condensers are used as in most chest freezers.

The evaporator in the SolarChill-A vaccine cooler is a wire-on-tube-type placed in the ice storage as shown in figure 2. The evaporator in SolarChill-B chest-type is an integrated skin-type as in most chest freezers. The evaporator in SolarChill-B-upright-type is a box-type roll bond-aluminum evaporator as known from old refrigerators with a small freezer compartment. The refrigerant charge in the SolarChill-A vaccine cooler is 48 grams of R600a and the charge in the SolarChill-B-chest-type is 60 grams. The charge in SolarChill-B-upright is 48 gram.



1 – Cabinet with 100 mm insulation	2 – Vaccine compartment
3 – Skin condenser	4 – Lid
5 – Internal wall, insulated	6 – Ice storage (26 „ice packs“, 600 ml)
7 – Evaporator, wire on tube	8 – Compressor

Figure 2a: Figure with basic principles for the SolarChill-A vaccine cooler. Figure 2b: Photo of the solar DC compressor. The integrated solar electronic control is placed at the left-hand side of the compressor.

4. SOLARCHILL-A VACCINE COOLER

The basic principle of the SolarChill-A vaccine cooler is shown in figure 2a. The evaporator is placed in the ice storage in the right-hand side of the figure, and natural and forced convection ensures the temperature of the vaccine stored in baskets as shown in the left-hand side of the figure.

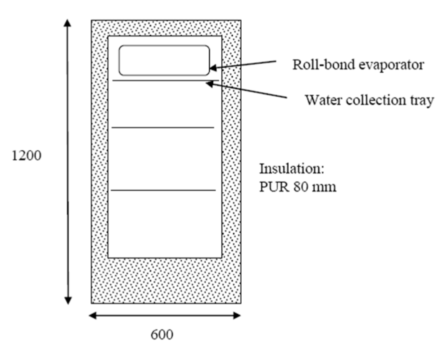
Pedersen and Maté (2007) explain how the field test of this vaccine cooler took place in Indonesia, Senegal and Cuba using 180 W photovoltaric panels (3*60 W peak) and tests show the hold-over time of about 5 days without any energy available. The field test lasted about one year and the ice banks were never totally melted except when the connections to the PV-panels were disconnected intentionally.

WHO has now developed specifications for battery free vaccine coolers, and tests are ongoing to validate that the SolarChill-A can fulfill the specifications. About 200 SolarChill-A vaccine coolers have been manufactured by Vestfrost A/S and installed in many countries, and an even greater implementation rate is expected with approval by the new WHO specifications and the involvement of the World Bank. The present price is in the range of app. 1000 Euro for the cabinet and a little less for the photovoltaic panels depending on the size of the panels for the specific location. The price for both cabinet and panels is expected to decrease in the future.

5. SOLARCHILL-B UPRIGHT TYPE

SolarChill-B is a refrigerator for domestic and small commercial use. The purpose of SolarChill-B is to help people cool and store food and drinks in small scale. Almost 2 billion people live in areas without grid electricity and the potential need for the product is enormous. The problem is that only part of the potential users at present can afford to buy a cooler.
The first customers to buy SolarChill-B are expected to be the more wealthy people in areas without grid electricity and small businesses that can profit from selling cooled products. When the coolers come into mass production the cost will decrease and more people will be able to buy them.

Danish Technological Institute built a prototype upright SolarChill-B cooler in 2004 and after laboratory tests the cooler was placed at DTI and has been powered by 3*60 W PV-panels. Except for in mid-winter (from November to February) at this high latitude (56 degrees north) the coolers have been working well since 2005. The net volume of the cooler is about 100 litres.



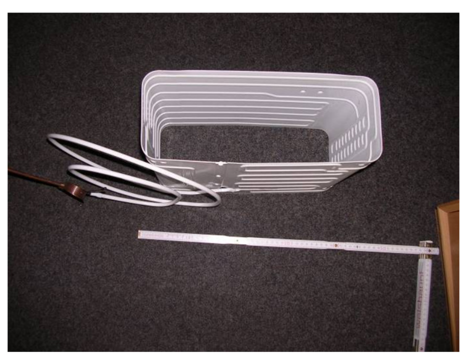


Figure 3a: SolarChill-B upright prototype built in a well-insulated freezer cabinet with 80 mm PU-insulation. Figure 3b: The box-type roll-bond evaporator in the cooler.

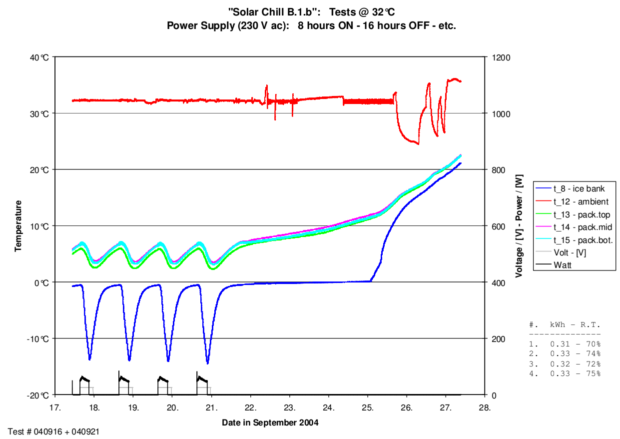


Figure 4: Lab test of SolarChill upright at 32°C ambient temperature. Power is available 8 hours a day, but the compressor runs less (about 6 hours a day). The temperature inside the compartment is between 2.5 and 7.5°C which is good for food storage. Hold-over time is 3.1 days (75 h) defined until the temperature rises to +10°C. The compartment contained 10 kg of test packages.

The ice storage is placed inside the box evaporator and natural convection ensures the temperature inside the cooler compartment. The shelves have to be open grill type to ensure convection. The compressor is of the same type as for the SolarChill-A vaccine cooler. So far, no manufacturer has been found for this type of SolarChill, but discussions are taking place with a potential manufacturer.

6. SOLARCHILL-B CHEST-TYPE

The development and laboratory test of a chest-type SolarChill-B took place at Danish Technological Institute in 2009. The cooler is based on an existing cabinet used for other purposes ("ice liners").

Figure 5: SolarChill-B chest-type prototype based on a 160 liter ice liner cabinet. The cooler is equipped with 5 baskets (3 upper baskets and 2 lower baskets). The photo shows that the cooler is tested with 12.5 kg test packages and 13.3 kg soft drinks (40 cans) simulating food and drinks.

The cabinet has been installed with the solar DC compressor of same type as in SolarChill-A. An ice bank of about 17.5 kg is placed in the wall between the evaporator and the interior cabinet. The cooler is controlled by a mechanical thermostat and tests were conducted in the laboratory at DTI.

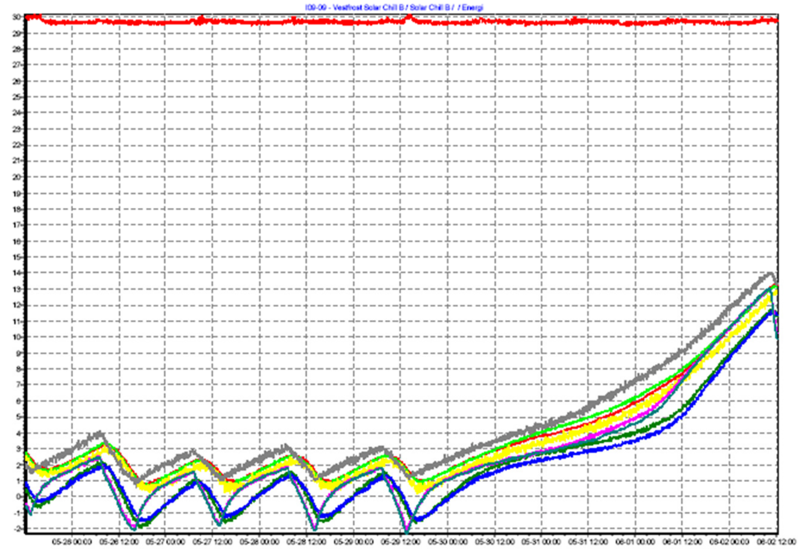


Figure 6: Test at ambient temperature of 30°C. The compressor runs about 6h 40 minutes per day and the temperature of the test packages is between -1.5 and 2.5°C. The air temperature is between -2 and +3 ^{0}C which is relatively cold for a refrigerator. The hold-over time is 2.7 days (up to +7°C) and 3 days (up to + 10°C).

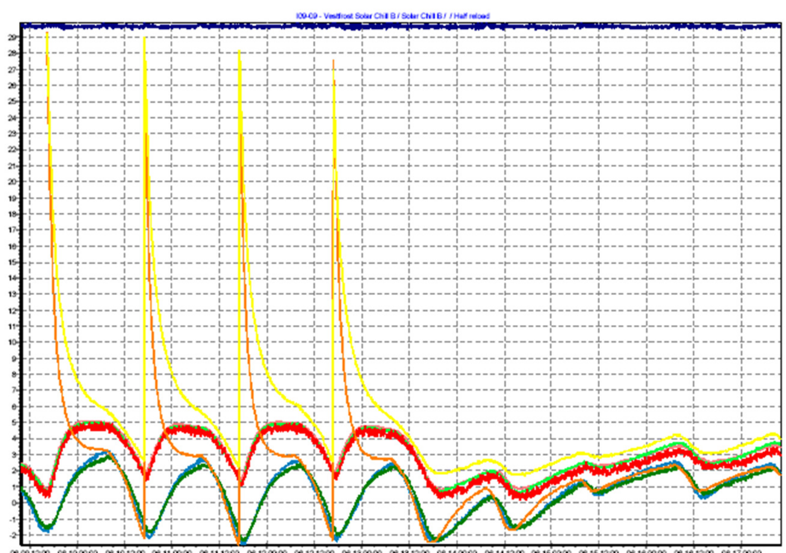


Figure 7: "Half reload test". 20 warm soft drink cans were inserted inside SolarChill-B chest-type when taking out 20 cold cans. That was done at "sunset" four days in a row. Power is available 10 hours a day, temperature is measured in one can in an upper basket and one can in a lower basket and the test shows the cooling capacity is sufficient to cool 20 cans a day. However, the cooling capacity is limited for this type of cooler.

7. DISCUSSION ON FUTURE TYPES OF SOLARCHILLS

The next step for the SolarChill partnership is the commercialization of the existing coolers mentioned above. However, in future it will be possible to develop other types.

If greater cooling capacity is needed, a compressor with higher cooling capacity is needed and so is a larger photovoltaic area. It will be possible in the future to develop coolers for cooling a greater number of drinks and food (e.g. 50 soft drinks a day). The technology and the components are more or less available today.

Danish Technological Institute has been involved in discussions concerning the development of a milk cooler for farms with only a small number of cows. Milk has to be cooled down to about +4°C in less than 2 hours and that can take place quickly by building up ice storage and thus having sufficient cooling capacity for fast cooling of the milk. The existing prototype of SolarChill-B chest-type might be used by inserting the milk in small containers, but a more efficient cooler would probably need another design.

Finally, it should be mentioned that freezer type SolarChills would be useful for freezing and conservation of fish, meat and vegetables. A freezer type would need eutectic ice storage with a melting point around -20 ^{0}C, which could be a saturated solution of salt and water.

ACKNOWLEDGEMENTS

The authors would like to thank Greenpeace International, GTZ and the Danish Energy Agency for financial support during the process.

The authors also would like to thank the Danfoss Company and the Vestfrost Company for providing components, cabinets and advice during the project.

Finally, the authors would like to thank the project partners from UNEP, the World Bank, GTZ, PATH, WHO, UNICEF and Greenpeace International for good discussions and support during the project.

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Annex 4. Milk Cooling

Teknologisk Institut
4. februar 2009/Per Henrik Pedersen

Solcelledrevet mælkekøler bygget ind i isoleret kumme

I samarbejde med Karise Kleinsmedie har Teknologisk Institut fået den idé, at benytte et kabinet fra en kummefryser til at lave en billig mælkekøler til mindre kvægbesætninger i visse u-lande. Karise Kleinsmedie (KK) har i samarbejde med Danida og lokale samarbejdspartnere en virksomhed i Uganda, som leverer rustfrie stål-produkter til mejeriindustrien.

Derfor er Teknologisk Institut i samarbejde med ovennævnte virksomhed i gang med at løbe et nyt projekt i gang, og vi håber at Vestfrost kan have interesse i at deltage.

Groft sagt går princippet ud på, at nedsænke et rustfrit stålkar i en kummefryser. Karret er mindre end inderkabinettet, således at der er plads til en vandreservoir (is/vand-blanding) i hulrummet imellem stålkar og inderkabinettet. Karret skal monteres, således at det sidder fast og ikke flyder ovenpå. Der skal endvidere være afløb i bunden med et to tommer rustfrist rør (51 mm ydre dimension).

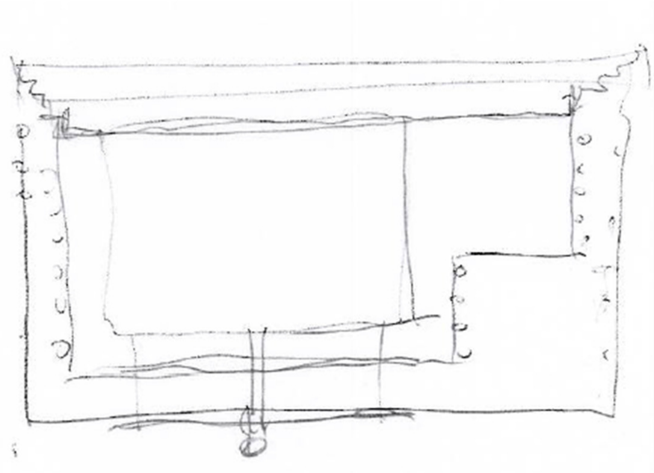
Samarbejdet skal gå på, at KK laver de rustfrie emner (+ omrører) og Vestfrost (i samarbejde med Teknologisk Institut) laver prototype af kabinet, køleanlæg og styring. Vi tager udgangspunkt i eksisterende kabinet.

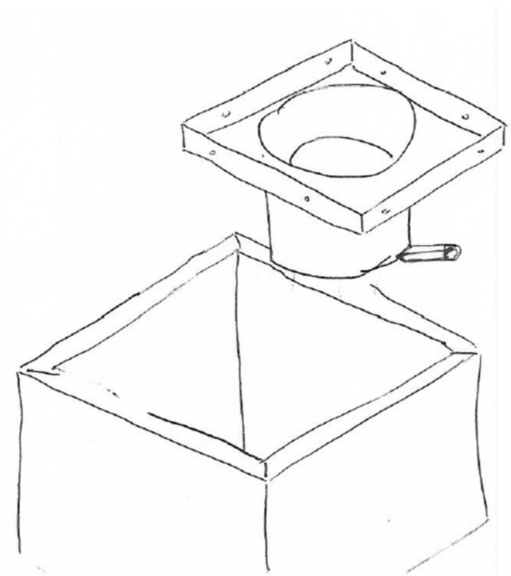
Den første prototype testes på Teknologisk Institut i Taastrup.

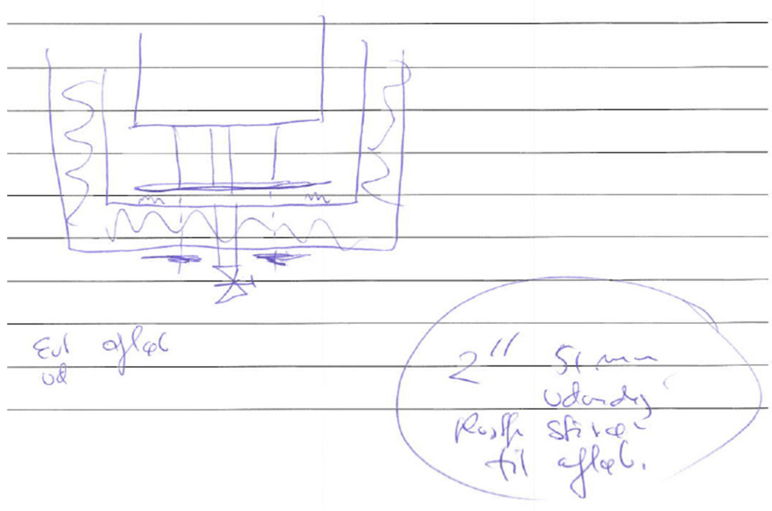
Karise Kleinsmedie satser på i første omgang at lave en prototype, som kan køle 150 liter mælk fra 29 C til 4 C i løbet af max. 2 timer. Det er meningen at den skal kunne køre med energi fra solceller, og gerne opbygge et islager i løbet af dagen.

Sekundært kan man forestille sig et 300 liter anlæg til netdrift (eventuelt ustabil netdrift).

På de næste sider er tre grove skitser fra KK, og disse giver ide om, hvordan det måske kan principopbygges.







Kabinettet kunne måske være Vestfrost Function SW284C med bruttovolumen på 296 liter eller måske det professionelle kabinet HF396 med et bruttovolumen på 373 liter ?

Nedkølingsprocessen
Her kommer en beregning af nedkølingsprocessen m.m.:

Kølekapacitet i nedkølingsfasen på max 2 timer:
Der skal nedkøles 150 liter mælk fra 29 C til 4 C. Vi regner på vand:

Q_{cm} = (M*DeltaT*C_p)/Delta TID = (150 kg*25K*4186(J/kgK))/(2*3600s) = 2180 W

Det svarer til smeltning af et ismængde på:

M_{is} = (Q_{CM}*DeltaTID)/smeltevarme = (2180W*2*3600s)/335000(J/kg) = 46,85 kg is

Af to grunde vil det være godt, hvis fordamperrørene ligger et stykke nede i kummen:

- Det gør det muligt, at sætte støtteskruer på karret (jf. tegning)
- Det vil være godt, hvis isopbygning sker lidt nede i vandreservoiret. Det vil medvirke til god cirkulation (konvektion) samtidig med, at der er plads til is, som måtte løsrive sig og flyde overpå.
- Der vil i øvrigt være luft foroven i reservoiret, og der skal kunne ske passage af luft ind og ud af reservoiret – evt. igennem et trykudligningshul på bagsiden.

Nedkølingsprocessen for system A: Køling med direkte solkraft
Ved kørsel med køleanlæg i 7 timer kan dette genereres med en køleeffekt på:

$Q_{coolcapacity,SC}$ = 2/7 * 2180 W = 623 W.

Dette kan klares med følgende kompressortyper (propan R290):
Antagelse: t_o = - 10 C, t_c = + 45 C (måske for lavt?)

SC10CNX (lige akkurat !)
SC12CNX
SLV15CNX (variable speed, - kan måske neddrosles til 12 eller 10 cm^3)

Det vil nok være mest naturligt og passende at vælge SC12CNX i første omgang.

Nedkølingsprocessen for system B: Køling med batteridrift
Ved kørsel i 20 timer kan man klare det med 2/20 * 2180 W = 280 W køleeffekt.
Det kan klares med en noget mindre og i kølemøbler mere almindelig kompressor.
Det vil måske være oplagt at benytte NLE15KTK, som Vestfrost i forvejen benytter i flaskekølere (M200 R600a) og impulskølere (POS72 R600a).

Der findes også en Danfoss jævnstrømskompressor, som kan klare det. Det er en BD350GH, som dog er til R134a.

Hvis det skal være med naturlige kølemidler kan en twin-løsning med BD100CN tænkes.

Konklusion: I første omgang benyttes en NLE15KTK i den første prototype. Kapillarrør og intern varmeveksler fra flaskekøler kan måske benyttes.

Varmeovergangsforhold på vand- og mælkesiden

Det antages, at der er omrøring i mælketanken i nedkølingsperioden. Herved får et meget stort varmeovergangstal i størrelsesordenen 1000 W/m^2K.

På vandsiden er der opbygget is langs fordamperrør i svøbet, og de er måske også is i toppen af vandbeholderen, mens der er vand længere ude mod mælketanken.
Vandtemperaturen vil være omkring 0 C i den øvre del af vandtanken, mens det vil være ca. + 4 C helt i bunden. Der vil i nedkølingsprocessen være naturlig cirkulation på vandsiden, og varmeovergangstallet vurderes til at være ca. 100 W/m^2K (eller mere) i det meste af nedkølingsprocessen, men når mælketemperaturen reduceres til omkring 4 – 5 C, vil den blive mindre idet den naturlige cirkulation af vandet går i stå ved + 4 C (hvor vandet er tungest). Der vil dog stadig vare varmeledning over et stort overfladeareal.

Det vurders at det varmeoverførende areal er mindst 1,5 m^2.

Med 1,5 m^2 vil den varmeoverførende effekt være ca. 3750 W i starten af nedkølingsperioden, ca. 1875 W, når halvdelen af energien er overført og noget mindre i slutningen af perioden. Hvor meget mindre ved jeg ikke lige nu, men i det helt ekstreme tilfælde:
1,5 m^2, stillestående vand, deltaT=4 K, 2 cm tyk lag vand:
Q = Lambda/delta*deltaT*A = 0,57 W/mK/0,02m*4K*1,5m^2 = 171 W
Dette ekstreme tilfælde nås aldrig, idet der altid vil være omkring 0 C i reservoiret foroven og dermed konvektion på vandsiden i den øvre del af mælketanken.

Hvis det i praksis viser sig at blive et problem at få afkølet de sidste par grader på grund at, at vand har maksimal densitet ved + 4 C, så kan man komme sprit (eller andet) i vandet.
Lad os se, hvad en nedkølingstest med 150 liter vand vil vise.

Styring
Hvordan skal køleanlægget styres ?
Her er et bud:

<u>Batteridrift:</u>
Hvis vi vælger batteridrift skal køleanlægget køre indtil ismængden er tilpas stor / istykkelsen er tilpas stor. Herefter skal køleanlægget slukkes for ikke at nedfryse hele vandreservoiret og mælken.

Hvordan kan vi gøre det med en almindelig termostat:
Hvis der benyttes en almindelig termostatlomme (som i kummefrysere) kan denne måske benyttes sammen med en termostat, som afbryder ved f-eks. – 15 C ?
Når der er en tilpas islag i reservoiret vil fordampningstemperaturen krybe nedad og termostatføleren vil blive koldere.

<u>Direkte soldrift:</u>
Som udgangspunkt skal køleanlægget køre, når der er kraft (det må Ivans strømforsyning (solceller + lille batteri + styring hertil klare).

Når ismængden er tilstrækkelig stor, skal køleanlægget stoppe. Det kan måske gøres som vist ovenfor under "batteridrift".

Indpasning af mælketank:

- Kan KK placere et 2'' stålrør igennem bunden ?
- Kan de ligeledes bore støtte-stænger igennem bunden?

- Er kummen vandtæt (udover KKs gennemboringer)?
- Hvor højt sidder de øverste fordamperrør. Kan KK montere støtte-skruer foroven (som vist på tegningen)?
- KK skal have tegning for den kumme, som vi vælger

Afgivelse af varme:
Normalt afgives varmen igennem svøbskondensatoren i en fryseboks. Vi har her med større varmeeffekter at gøre; - især hvis der satses mod af benytte SC12CN-kompressoren og brug af direkte solkraft.

Batteridrift:
Hvis vi benytter NL15KTK.2 vil den afgivne effekt være ca. 600 W.
Det kan måske klares med svøbskondensator + overhedningsfjerner m. blæser ?
Det svarer lidt til en stor iscremefryser.

Direkte solkraft:
Her har vi med større effekter at gøre. Her skal vi af med 1,3 kW, og det er måske nødvendig med ekstern blokkondensator m. blæser.

Markedspotentiale, notat udarbejdet af Karise Kleinsmedie, Palle Maag:

Mælkekøler 150 l – vurdering af afsætningspotentiale i Uganda.
Karise Kleinsmedie Aps. (KK) har taget initiativ til udvikling af et mælkekøleanlæg drevet af solenergi med henblik på afsætning i Uganda og nabolande.
I samarbejde med Danmarks Tekniske Institut (DTI) vurderes det, at et anlæg i størrelsesordenen 150 l vil være økonomisk og teknologisk forsvarligt at producere.
KK vurderer afsætningsmulighederne for et 150 l anlæg således :

1. I oktober 2008 deltog Karise Kleinsmedie Uganda Ltd. (KKU) i den årlige messe, Kampala International Trade Fair .
   KKU havde på messen en større stand med udstilling af et udvalg af forskellige produkter fremstillet i rustfrit står, herunder flere forskellige typer mælketanke.
   Interessen for ikke mindst mælketankene var overvældende, men et stadigt tilbagevendende spørgsmål drejede sig om køling – kunne KKU ikke levere tanke med køleanlæg ?
2. Der findes i Kampalas omegn og i det sydvestlige Uganda store landbrugsområder, hvor mange især mindre farmere holder malkekvæg, der producerer mælk, som finder afsætning i lokalområderne og leveres til større mejerier i Kampala og Mbarara. Inden mælken kan afhentes, er det nødvendigt at få den kølet ned, og da der i stor udstrækning er tale om småfarmere, er der hovedsageligt behov for mindre køleanlæg, som oven i købet vil kunne betjene et fællesskab af flere farmere.
3. Dairy Development Aythority (DDA), der har den overordnede føling med og indsigt i produktion og forarbejdning af mælkeprodukter i Uganda, er ikke i tvivl om behovet for mindre køleanlæg til småfarmere i Uganda, især anlæg, der kan drives af solenergi, hvilket vil gøre anlæggene anvendelige også i områder uden offentlig strømforsyning (der i øvrigt ofte er ustabil) og overflødiggøre brugen af generatorer, der øger omkostningerne ved køling af mælken både hvad angår investering og drift.
4. Mht. afsætning af mindre køleanlæg i regionen, skal man holde sig for øje, at det ikke blot gælder Uganda, men også omliggende lande, dvs. Rwanda, Kenya, Congo og Sudan, der i øvrigt alle havde besøgende gæster på Kampala Trade Fair.
   Endelig må det formodes, at et mælkekøleanlæg drevet at solenergi og fremstillet til en konkurrencedygtig pris, vil kunne afsætte i mange andre udviklingslande.

   Den afsluttende konklusion er, at vi ser et absolut lovende afsætningspotetiale for en mindre mælkekøler drevet af solenergi og fremstillet til en pris, der kan matche traditionelle anlæg drevet at el.
   Det er meget svært at sætte et præcist antal på, hvor mange vi vil kunne afsætte , men vi forventer inden for det første år at kunne afsætte mindst 100 stk. Herefter tror vi at de gode erfaringer fra anlæggene vil sprede sig blandt farmerne og dermed få efterspørgslen til at accelerere.

   Karise Kleinsmedie Aps. 16.02.2009