Experimental investigation of solar powered vaccine chillers in the field

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Abstract

Ensuring the cold chain in areas without connection to the power grid, especially for essential vaccines and medication, is a major challenge in many developing countries. Especially in subtropical and tropical regions, the generally high ambient temperatures lead to further difficulties. "Solar Direct Drive" (SDD) refrigerators are an environmentally friendly way to meet this challenge. The devices are subject to a strict test protocol and approval procedure of the World Health Organization (WHO), which is reviewed and renewed annually. However, there is little data available on the actual system behaviour in the field. As part of an international cooperation project, several of these devices from different manufacturers have been installed in three countries in different climate zones and equipped with monitoring systems. The paper includes a corresponding evaluation of the data and a comparison of the system behaviour under varying boundary conditions.

Keywords:
Solar cooling, Solar Direct Drive, Natural refrigerants

1 Introduction

Currently, more than one billion people live in regions without reliable electricity supply [1]. In these regions, the provision of a secure "cold chain" is often very challenging, making it difficult or even impossible to supply food, medication and vaccines.

Since many vaccines are very temperature-sensitive, their storage is particularly challenging. Vaccines against cholera, hepatitis B, flu or tetanus, for example, must also be protected against freezing in addition to high temperatures. The required temperature range for storage in these cases is 2°C to 8°C. In the past, absorption refrigerators, which were mainly operated with propane or kerosene, were used for this purpose in regions without sufficient power supply. Due to insufficient controllability, however, this often resulted in freezing and thus destruction of the vaccine agents. In addition, the necessary combustion of the above-mentioned substances produces exhaust gases that are harmful to health.

In this context, the "SolarChill" project was launched in 2001, founded by a consortium of several international partners, including the United Nations Environment Programme (UNEP), the Deutsche Gesellschaft für Technische Zusammenarbeit GmbH (GTZ, now GIZ), Greenpeace, the World Health Organization (WHO) and the United Nations Children's Fund UNICEF, as well as the Danish Technological Institute (DTI). The purpose of this project was to develop solar-powered, environmentally friendly cooling systems for off-grid regions. A first prototype was already presented in 2002 and received its first certification in 2006 through the WHO's "Performance, Quality and Safety" (PQS) programme, which defines the performance requirements for vaccine chillers in several test protocols (see also Section 2.1).

The WHO website lists the approved SDD vaccine chillers, the number of which has increased in recent years. In January 2019, there were 40 chillers from eight different manufacturers. To be approved the devices must prove that they meet the strict WHO test protocol and the certification must be renewed annually. However, in order to meet the test requirements, photovoltaic (PV) systems are often oversized (mainly to overcome the inrush current) - a practice that is functional and accepted, but which is wasteful for a large number of operating hours.

Despite this oversizing, in the absence of data, there is a lack of information on whether the devices in the field meet WHO requirements and to what extent the installed PV power, which is available beyond the actual consumption of the devices, can be used elsewhere. Within the "Global Environment Facility" (GEF) project "GEF SolarChill", a data basis is to be created that shows the real performance of the devices in the field and determines the potential of the surplus power.

2 Technology and project countries

Hereinafter, the WHO requirements for the devices and the laboratory test necessary for certification are discussed, which forms the basis for the evaluation of the data. Subsequently, an overview of the equipment, the monitoring systems used and the three project countries is given.

2.1 WHO specifications

Refrigerators for vaccines to be listed in the WHO catalogue must meet specific test criteria of the WHO's "Performance, Quality and Safety" (PQS) procedure. The WHO PQS catalogue lists different types of refrigerators, e.g. absorption refrigerators. The cooling of the SDD devices presented in this study, is generated by a compression refrigeration machine, which is operated directly by photovoltaic current. In addition, the public invitation to tender for the PQS process allows different manufacturers to apply for this qualification. Since the member states and UN purchasing agencies primarily purchase PQS-qualified products, this process in turn promotes the development of a competitive market [2].

The WHO performance specification [3] requires full compliance with all performance requirements laid down in an independent test protocol [4]. The test protocol for SDD devices contains eight tests on the operating behaviour of the devices. The acceptance criterion is always the compliance with the internal temperature range according to the specified criteria. The required temperature range for vaccine cooling is +2°C and +8°C and deviations from this range are only permitted under certain conditions. The cooling units must comply with this in seven of the eight tests at an ambient temperature of +43°C. In two of the eight tests, compliance is also tested at a minimum ambient temperature of +10°C.

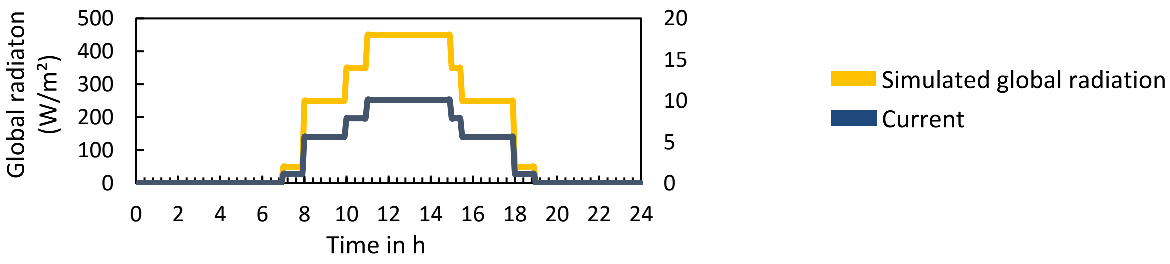


Figure 1: Daytime variation of global radiation 3.5 kWh m-2 d-1 according to IEC 62124 and exemplary maximum available current during the laboratory test

The laboratory tests are performed at a minimum average solar radiation of 3.5 kWh m^{-2} d^{-1} using an external power source simulating the course of the day. Figure 1 shows the daily course of solar radiation (yellow) and the available current (blue). The latter is shown in figure 1 based on an exemplary selected power of the PV modules of 540 Wp and an output voltage of 24 V.

In order to be included in the PQS catalogue, all conditions mentioned must be fulfilled. The main criterion is always compliance with the temperature band of +2 to +8 °C.

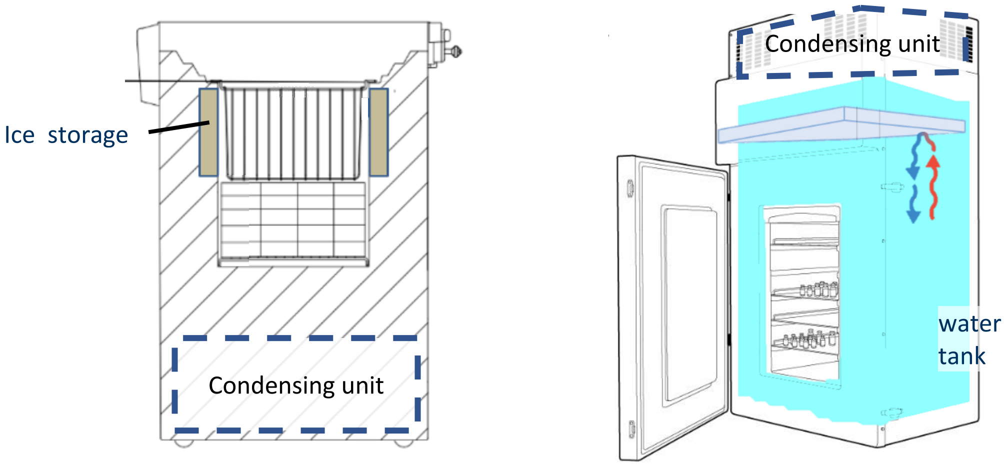
One of the most important tests is the autonomy test, in which, after a stabilisation phase, it is tested how long the devices can maintain the temperature within the required range with minimum power supply (5% of the actually available). The minimum requirement for this test is 72 hours at 43°C ambient temperature.

2.2 Tested devices

A total of 113 vaccine chillers from various manufacturers are being tested in field trials in three countries. For this report, the devices are categorized according to their operating principle. In principle, a distinction is made here between two different types of device:

1) **Type 1: Ice storage technology:**
   Type 1 equipment uses ice storage technology to bridge periods of low sunlight. The ice storage (and/or other PCM materials) is installed inside the walls of the refrigeration unit or in a special compartment near the evaporator. A schematic of this type of refrigerator is shown in Figure 2. These units are often designed as chest freezers with the condensing unit installed below the refrigerated compartment.
   34 of the 40 SDD vaccine chillers on the WHO list in January 2019 are based on this technology; 86 units of this type were installed in the GEF SolarChill project.

2) **Type 2: Water tank technology:**
   Devices of the second type have an upright design - similar to a household refrigerator. The tank surrounding the vaccine compartment is based on a mixture of ice and water. Figure 2 shows this type of refrigerator on the right. The water tank is indicated in light blue in the illustration. The evaporator of the refrigerant circuit is located in the upper part of this tank and in its surroundings, ice is formed during operation. The associated condensing unit is located in a compartment at the top. The water circulates inside the tank by natural convection and due to its maximum density at 4°C it is ensured that no freezing of the vaccine can occur. The temperature of the water at the bottom of the tank, which is in thermal contact with the vaccine compartment, is always around +4°C, which is ideal for storing vaccines.
   This technology is used in six of the 40 SDD vaccine chillers on the WHO list of January 2019. Within the GEF SolarChill project, 34 refrigerators of this type are tested.



Chiller in chest design (Type 1) Chiller in upright design (type 2)

Figure 2:: Layout diagram of the refrigerator types used

The following Table 1 provides an overview of the five different models used in the GEF SolarChill project. It shows the nominal output of the solar modules in Watts (Wp = Watt peak), the outdoor temperature application range (temperature zone) specified by the manufacturer and the autonomy period. It also shows the device type (refrigerator type).

Table 1: Overview of the SDD devices installed within GEF SolarChill

Manufacturer	Model	Nominal capacity of the PV system (W_p)	Temperature zone (°C)	Autonomy period (h)	refrigerator type
B Medical	TCW 40	400 @ 12V	5-43	81,9	Type 1
Haier	HTCD 90	720 @ 24V	5-43	114,9	Type 1
Zero Appliances	ZLF 30	540 @ 24V	5-43	77,05	Type 2
Vestfrost	VLS 024	360 @ 12V	5-43	81,7	Type 1
Godrej & Boyce MFG. Co. Ltd	GVR 50DC	500 @ 24V	10-43	134,8	Type 2

2.3 Monitoring systems

Within the scope of the field test, monitoring systems are installed which use the GSM mobile phone network for data transmission and thus provide continuous data from the moment of installation. Table 2 shows the recorded values of the different measuring systems, the deviations of the respective sensors are summarized in Table 3.

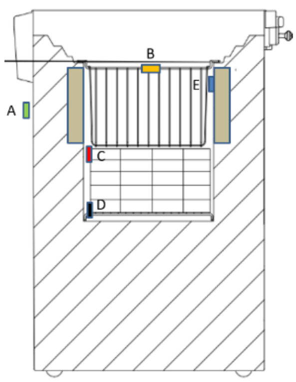
Table 2: Number of sensors within the used monitoring systems

Sytems	Indoor temperature	Outdoor temperature	Rel. humidity	Solar radiation	Door openings	Voltage	Amperage
HOBO	4x	1x	1x	1x	1x	1x	1x
Nexleaf	4x	1x					
Tologg	1x	1x			1x		

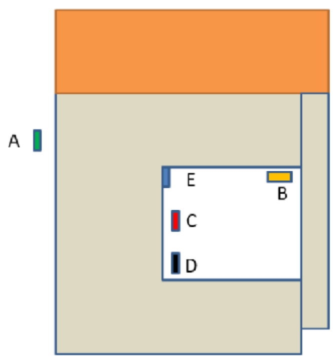
Table 3: Deviations of the individual measuring sensors

System	Measured variable	Measuring range	Deviation
Onset HOBO	Temperature	-40 to 100 °C	± 0.2 K
	Rel. air humidity	0 to 100 %	± 0.1%
	Solar radiation	0 to 1280 W m^{-2}	± 10 W m^{-2} or ± 5%
	Door opening	n.a.	n.a.
	Voltage		± 0.6 mV (± 0.2 %)
	Amperage		± 0
Nexleaf Coldtrace	Temperature		± 0.5 K
BMedical Tologg	Temperature	-30 °C to 60 °C	± 0.4 K
	Door opening	n.a.	n.a.

The measuring systems were implemented on site after the installation of the cooling units. The temperature sensors are installed in the respective device types as shown in Figure 3.



Chest type (Type 1)



Upright type (Type 2)

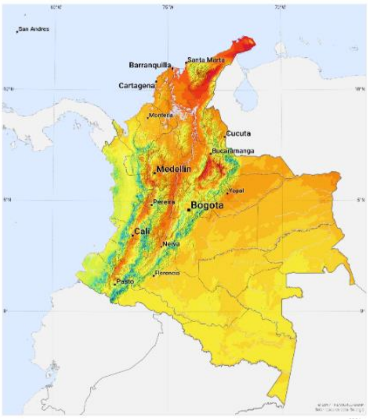
Point	Temperature
A	Ambient / Room
B	Top of the vaccine compartment (VC)
C	Mid of the VC
D	Bottom of the VC
E	Surface near the evaporator/ ice storage

Figure 3: General position of temperature sensors for the two cabinet types

The sensors are arranged in such a way that they map the internal temperature in the entire vaccine compartment and especially at critical points, such as near the evaporator or the ice compartment or in the upper area of the refrigeration compartment. The humidity sensors of the Onset HOBO systems are mounted as integrated temperature-humidity sensors at position C

2.4 Project countries and locations

In order to provide a good representation of the functionality of the devices, they were installed in three countries in different climate zones. The project countries are Colombia, Kenya and the Kingdom of eSwatini (formerly Swaziland, hereinafter referred to as eSwatini).
According to the WHO, the installation of an SDD refrigerator is recommended from an average solar irradiation of 4.8 kWh $m^{-2} \cdot d^{-1}$ [5]. Figure 4, Figure 5 and Figure 6 show a map of the country with information on the average monthly or annual Global Horizontal Irradiance (GHI), the number of SDD refrigerators installed in this country and the number of measuring systems installed. It can be seen that, with exception of a few examples in mountainous regions of Colombia, solar irradiation is sufficient in all three countries. It should be mentioned that the average solar irradiation in Germany is between 2.6 and 3.42 kWh m^{-2}.

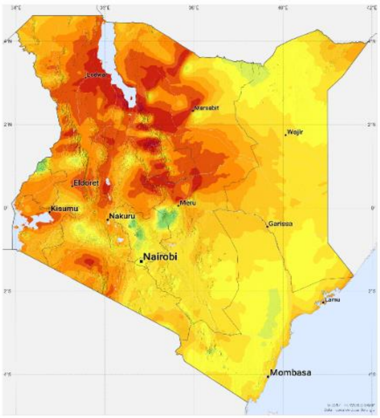


Colombia	
Number of installed units:	37
Type 1	31
Type 2	6
Measuring systems:	
Onset HOBO ©	6
Nexleaf	2
Tologg	12

Long-term averaged values of the GHI, 1994- 2015 kWh/m²

Per day	3.2	3.6	4.0	4.4	4.8	5.2	5.6	6.0
Per year	1168	1314	1461	1607	1753	1899	2045	2191

Figure 4: Colombia - map with mean solar irradiance [6] and information on tested devices



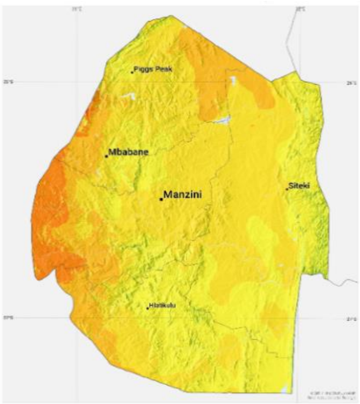
Kenia	
Number of installed units:	36
Type 1	20
Type 2	16
Measuring systems:	
Onset HOBO ©	9
Nexleaf	12
Tologg	

Long-term averaged values of the GHI, 1994- 2015

Per day	5.0	5.4	5.8	6.2	6.6	7.0
Per year	182	1972	211	226	2410	2556

kWh/m

Figure 4: Kenia - map with mean solar irradiance and information on tested devices



Kingdom of eSwatini	
Number of installed units:	40
Type 1	35
Type 2	15
Measuring systems:	
Onset HOBO ©	8
Nexleaf	6
Tologg	4

Long-term averaged values of the GHI, 1994- 2015

Per day	4.6	4.8	5.0	5.2
Per year	1680	1753	1826	1899

kWh/m²

Figure 5: eSwatini - - map with mean solar irradiance and information on tested devices

3 Evaluation

The analysis of the field test of the devices was primarily based on the compliance with the required temperature band and the comparison between available power and power consumption. Table 4 below provides an overview of the measured values in the field test and their evaluation.

Table 4: Relevant measured values and evaluation criteria

Measured value	Evaluation
Internal temperature(s)	Compliance with the temperature band
Outdoor and indoor temperature	Behaviour under different climatic conditions
Voltage, current, solar radiation	Power consumption and potential estimation of additionally available energy

3.1 Temperature range +2°C to +8°C

Maintaining the required temperature range between +2°C and +8°C is of highest priority, as failure of compliance can destroy the vaccines and, in addition to the financial loss, endanger the supply of vital vaccines to the population. Freezing is the major risk of vaccine destruction.

Short-term temperature fluctuations are also permitted within the PQA tests (see section 2.1) as long as the temperature returns to the required temperature band within a certain period of time. The internal temperature of the refrigerator, for example, must not fall below 0°C for more than one hour and must return to the permissible temperature range within two hours after it has fallen below 0°C. Under no circumstances may the temperature exceed +20°C or fall below -0.5°C. The temperature of the vaccine compartment was therefore measured and recorded at several points.

Figure 7 shows an example of the temperature curve within a type 2 refrigerator in the first half of 2019. The diagram shows the curve for three of the four internal temperature sensors. The temperature band is marked with green lines and the critical 0°C limit in red. It can be seen that the temperature varies within the vaccine compartment.

Short-term deviations from the required temperature band are marked with red circles in the diagram of the temperature curve of sensor B (top left).

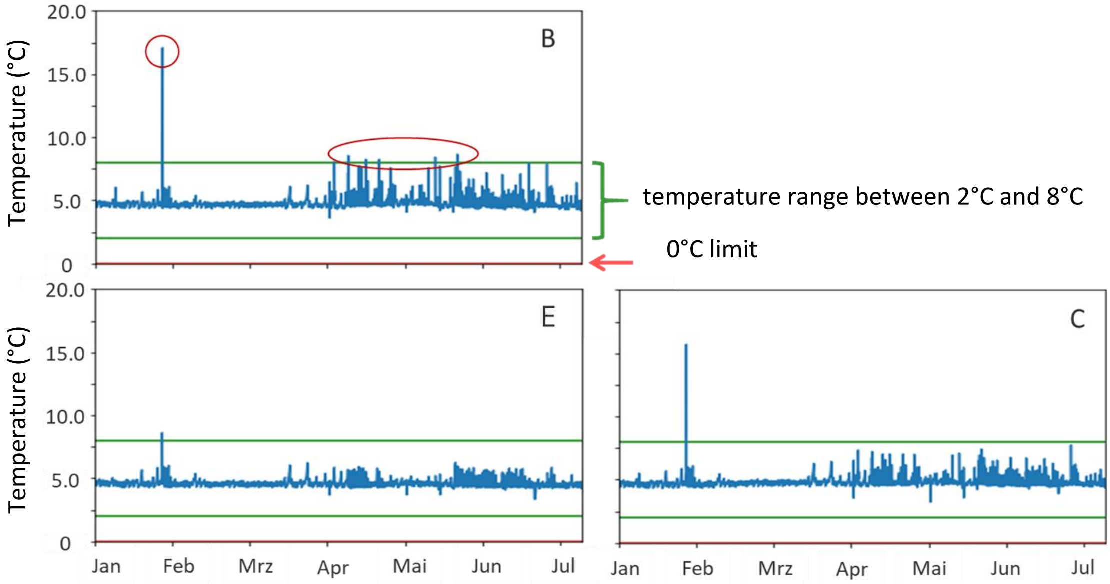


Figure 7: Temperature curve in the first half of 2019, exemplary shown for a type 2 device

Figure 8 shows the same course for a type 1 device. For both sensors B and C it remains within the temperature band up to a point, for sensor E it can be seen that the temperature exceeds the 8°C limit several times.

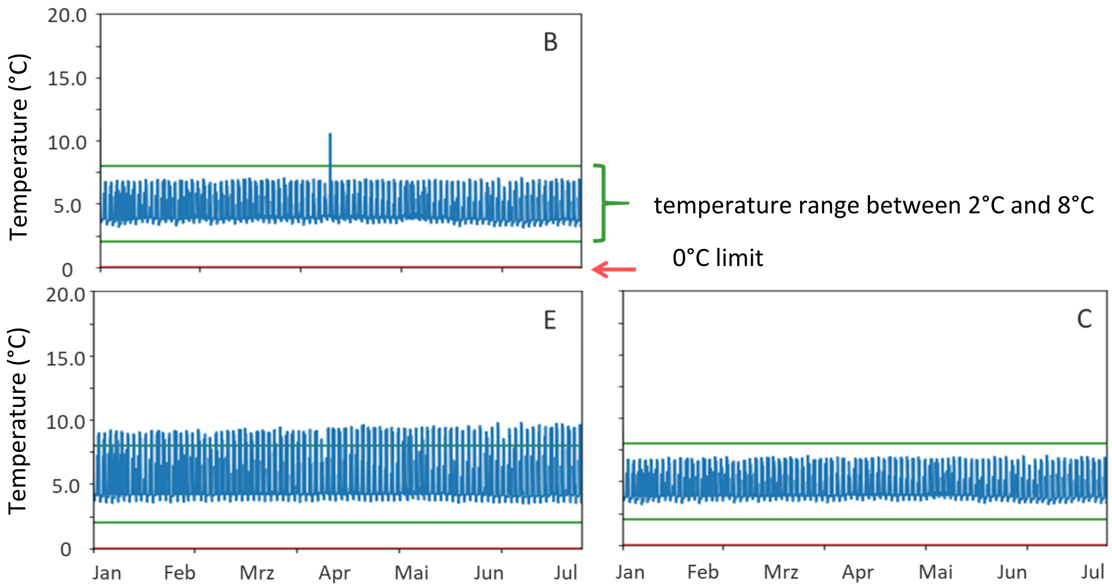


Figure 8: Temperature curve in the first half of 2019, shown as an example for a type 1 device

It can be observed that the temperatures for both types remain largely within the temperature band. An exact analysis shows that the temperatures are back within the temperature band within the required time.
In order to obtain the most meaningful statistics possible on the general behaviour of the refrigerator types, all measured values for the first half of 2019 were evaluated. Table 5 shows the percentage temperature distribution of the different refrigerator types according to the temperature band of the PQS requirements.

Table 5: Temperature distribution of all systems according to the PQS requirements

Refrigerator type	<0°C	<2°C	2°C - 8°C	>8°C	>10°C	>20°C
Type 1	0,7%	2,84%	88,04%	0,64%	0,62%	7,80%
Type 2	0,00%	0,00%	90,14%	6,72%	2,10%	1,05%

The analysis shows that all models used, with one exception, successfully maintain the internal temperature within the required temperature band. All deviations determined for the other models are within the permitted limits. As prescribed in the PQS test, the required temperature band is reached again after one hour at the latest. Correspondingly, long-term functionality has been proven in the field. The exceptional model, on the other hand, shows frequent and strong deviations from the required temperature band. In three of the eight refrigerators evaluated in this model, the critical temperature of -0.5°C was also undershot, which can lead to freezing of the vaccines.

The temperature fluctuations that occur must also be considered. The mean kinetic temperature (MKT) is suitable for this purpose. It is defined as a temperature to which a substance is exposed, which is equivalent to a thermal load from a series of higher and lower temperatures. It is a simplified way of determining the influence of temperature variations during the storage of drugs and is based on an approach by Haynes [7]. The MKT is calculated according to formula (1).

$$T_K = \frac{\frac{\Delta H}{R}}{-\ln \frac{\sum_{k=1}^{n} e^{-\frac{\Delta H}{RT_n}}}{n}} \tag{1}$$

The following applies:

T_K	Average kinetic temperature in K	
ΔH	Activation energy in kJ mol^{-1}	
R	Gas constant in kJ mol^{-1} K^{-1}	(8.31447 kJ mol^{-1} K^{-1})
T_n	Temperature measured values in K	

The activation energy ΔH is a substance-specific value, which is assumed to be 83.1447 kJ mol^{-1} as the average value for drugs. The activation energies of many active pharmaceutical ingredients lie in a range between 42 and 125 kJ mol-1. [8] According to the PQS test [4], the internal temperature must remain within the required limits at all measuring points during the measurement period and the MKT of none of the sensors must lie outside +2°C and +8°C.

Table 6 shows the calculated MKT for three of the four internal temperature sensors, as well as the minimum and maximum temperatures. The different models are generically marked with the Roman numerals I to V for this study. The last column shows the respective refrigerator type for orientation.

Table 6: MKT of interior temperature sensors, as well as minimum and maximum values

Model	B	C	E	Min	Max	Refrigerator type
I	3,54 °C	4,06 °C	3,17 °C	-1,56 °C	24,34 °C	1
II	4,68 °C	6,00 °C	4,47 °C	3,19 °C	19,75 °C	1
III	4,22 °C	4,79 °C	5,3 °C	1,04°C	24,82 °C	1
IV	5,75 °C	5,57 °C	5,03°C	3,75 °C	19,25°C	2
V	5,74 °C	6,04 °C	4,71 °C	3,22 °C	20,94 °C	2

3.2 Available and consumed power

In order to determine the additional power available through the oversized PV modules, the devices were individually averaged over half a year. The calculation of the energy available via the solar panels was based on formula (2) and the actual power used by the devices was determined via logged current and voltage values of the devices from P=U·I.

$$P_{max} = P_{nom} \cdot \frac{E_G}{1000} \cdot f_S \qquad (2)$$

For this purpose, the maximum power P_max of the solar panel in W is calculated from the nominal power P_nom of the solar panel given by the manufacturer with global radiation E_G in W·m-2 and nominal irradiance under clear skies (1000 W·m-2) and a general derating factor f_S, which is assumed to be 0.9.
Figure 9 shows this daily course of events for two devices of type 1 (left) and type 2 (right) installed in Kenya. The values shown are averaged over half a year from January to July 2019. It is clearly visible that the available power during the day far exceeds the power used.

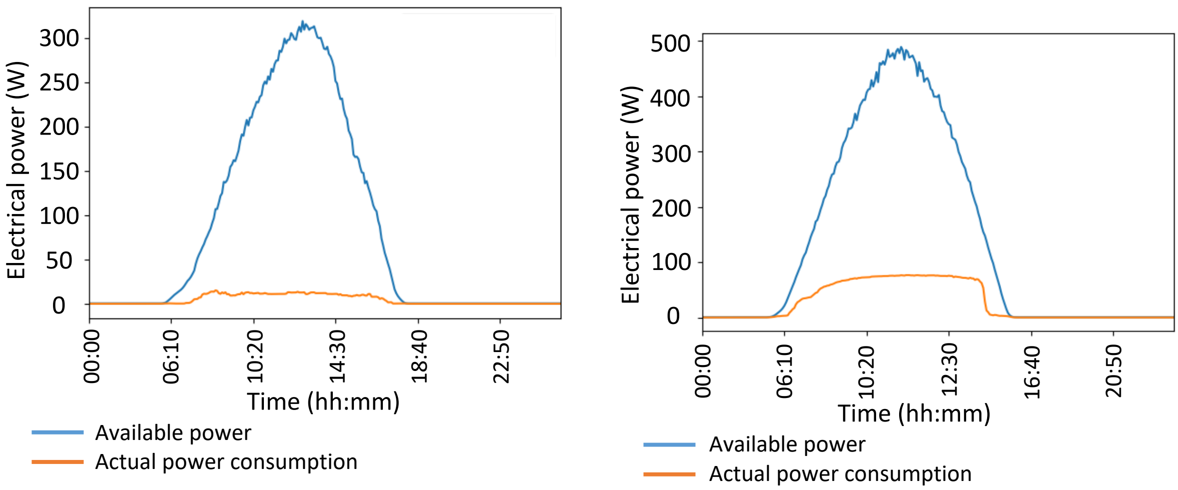


Figure 6: Available and consumed power over the course of the day, exemplarily shown for a device of type 1 (left) and type 2 (right)

In these exemplary cases, the electricity consumption for the type 1 device is 0.107 kWh per day, whereas 2.019 kWh per day could be provided by the PV module. Within one year, this corresponds to an unused work of 697.8 kWh. The second type 2 device consumes 0.654 kWh per day, whereas 3.303 kWh could be provided by the PV system. This means that almost 1000 kWh remain unused over the year with this device.

An examination of the electrical power consumed by the compressor of all devices shows that in all recorded cases, these devices consume a maximum of 20% of the available power. There is therefore a considerable potential to make this energy usable through suitable control technology and storage.

3.3 Further assessment criteria

As shown in Table 2, the Onset HOBO measuring devices record not only temperatures and performance data, but also the relative humidity within the vaccine compartment. The analysis of the data shows that for each sensor, this is over 98% and therefore consistently at the dew point of the air. This was also confirmed by random user surveys. There was sporadic mould growth within the compartment and on the packaging, which is mostly made of cardboard. In order to counteract this, regular wiping of the units with dry cloths is part of the preventive maintenance of the units, as they usually do not have a condensation drain.

4 Summary and outlook

Within this study, the GEF SolarChill project, the SDD technology and the requirements of the WHO-PQS were presented. Furthermore, the intensive monitoring of 43 vaccine chillers in Colombia, Kenya and the Kingdom of eSwatini was presented. Within the project a total of 113 devices from different manufacturers will be tested.

The results of the analysis of the first field tests show a frequently stable operation of the refrigerators within the required temperature range of +2°C to +8°C. After short term deviations from this temperature band, the devices reach this again within the required times. Only a model of type 1 is conspicuous with regard to too low temperatures. The project partners are also in contact with the manufacturers in the project to discuss such deviations.

Within the analysis of the consumption data of the devices it could be confirmed that the PV-modules of the devices reliably supply sufficient power for a constant compressor operation and that in addition there is surplus energy, whose further use has to be discussed. The devices use on average 5 to 10 % of the available power. The additionally available energy remains unused so far and there is a considerable potential for a utilization of this energy.
The three project countries were also selected within the project in such a way that a statement can be made about the behaviour of the devices under different climatic conditions. The three countries have a different annual temperature profile and the devices were also installed in climatically different areas within the countries. Within the measurement period considered, outdoor temperatures between a minimum of 8°C and a maximum of 38°C could be mapped.

The field test will be continued in 2020, so that a final evaluation in January 2020 will provide a well-founded statement about the actual behaviour of SDD refrigerators in the field over a complete year.

The GEF SolarChill project includes the presented field test of SDD vaccine chillers as well as a transfer of the technology to household and commercial refrigerators. Within this second part of the project, 45 solar-powered refrigerators will be tested in the three countries, which will also be equipped with the corresponding measurement technology.

Nomenclature

Symbols

E	Solar irradiance $(W\ m^{-2})$
f	Correction factor $(-)$
I	Amperage (A)
P	Performance (W)
T	Temperature (K, °C)
U	Electrical voltage (V)
W_P	Nominal power of the PV modules

Indices

max	Maximum
nom	Nominal, rated

Acknowledgement

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