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Research Article

Photovoltaic-Thermoelectric Power for Sustainable Cold Chains Needed for Covid-19 Vaccine Delivery and Use in Niger

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Abstract

In areas where the access to an off-grid electricity is not possible or not reliable, the transport and conservation of vaccine and medicines is not possible. Nevertheless, these areas need and have right to access medicine. This need is much more critical nowadays since preservation of COVID-19 vaccines require cold-chain at some level of degree. Solar energy can be used to power the refrigerator destined to keep the medicines and vaccines cool. Even tough stand-alone photovoltaic (PV) is already used to power these coolers, our work shows that the use of a Photovoltaic-Thermoelectric hybrid generators could allow a great improvement of the autonomy. The output power of the PV alone and the hybrid are investigated under Niger meteorological conditions. These two systems coupled with a medical cooler are investigated. The results show that the hybrid system produces considerably more power to be stored in the battery, indicating much longer autonomy. Under the same conditions, when the PV reached its lowest efficiency of 12.24% , the hybrid was at his efficiency peak 19.62%. Thus, a rise of 5.88% was achieved. Our work presented here is important for giving a message to the international organizations that sustainable cold chains needed for equitable COVID-19 vaccine distribution is clearly possible with solar PV/TE driven DC refrigerators.

Keywords: COVID-19 vaccine cooler, DC refrigerator, Niger, PV/TE power, Solar PV, Efficiency

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1. Introduction

Electricity is one of the most important assets in the development of a country. Electricity can be made using charcoal, uranium, petroleum, renewable energy, and so on. Niger is the fourth country worldwide to produce uranium, it also possesses a lot of gas and petroleum deposit (90000 barrels/day could be produced by the country), the sun irradiation is also non negligible, and it also has hydraulic potential due to its river.

Noting that Niger is rich in all these energy sources, it comes as a surprise that the country is not electrically independent. Indeed, in 2017, 73.8% [1] of the electricity used in the country comes from Nigeria. Noting that electricity is used for water production, the lack of power also influences the access to water. In 2018, only 12.93% [1] of the population had access to the electricity, and 72% [1] of that rate is from the population of Niamey, the capital city. The rural population, which represents 80% [1] of the population, has an access rate to the electricity of 3.14% [1] in 2016.

In these conditions, in rural areas it is difficult to access medical attention, mostly when it comes to vaccines and preservation of medicines that require a certain temperature. Since the electricity in those areas is not accessible, to extend the medical care to the furthest village, we should be able to conserve the medicines, vaccines, and other supplies under the best conditions possible. The use of generators would be quasi impossible due to the cost and availability of the fuel.

Solar energy could be the solution to the problem in a world where the research of new eco-friendly energy sources is the focus. The solar energy is a very promising type of energy to be exploited in the country. The average time of irradiance is of 9 hours per day in the capital city in 2019. The irradiance is in between 5.1 kWh/m2 and 6.3 kWh/m2 [2].

The solar energy can be used as a stand-alone power for a DC refrigerator in order to keep the vaccine under a temperature range of 2 ℃ to 8 ℃, which is within the standard of the world health organization (WHO). This temperature range is suitable for most of recently-developed Covid-19 vaccines (i.e., AstraZeneca, Janssen, Sinovac and Novavax), excepting that BioNTech require cold storage at -70°C.

A solar-powered refrigerator is a refrigerator that is powered by solar energy. The system can either use a photovoltaic (PV) or a thermal energy module. This type of refrigerator is used to keep perishables good in places where electricity is not available or to reduce the uses of fossil fuels. The solar powered refrigerator can be both used in houses or in the medical field. Vaccines need to be kept under some conditions for them not to turn bad. In some countries where the electricity is neither available nor reliable, the solar refrigerator comes as the best solution.

PV panel have already been used to power refrigerators destined to vaccines storage. Nevertheless, even if this type of system is the best answer for an access of the rural areas to the vaccines and medicines, its implementation and use is challenging, especially in terms of making an important investment at once. Also, the PV panel efficiency is affected by the sun. In a country like Niger, where the temperature reaches 45 under shade, the efficiency of the panel can reach it lowest and the panel can deteriorate quickly. As it was demonstrated, adding a thermoelectric generator (TEG) to a PV module to create a PV-TEG hybrid is a good way to improve the overall efficiency.

The idea would be to implement the hybrid in the back of the PV panel to have an PV-TEG hybrid refrigerator system. The PV-TEG hybrid has a higher efficiency than the PV panel alone. The increase of the efficiency means that the hybrid produces more power output than the PV stand alone. This increase in power means that more energy could be saved by the battery, thus increasing the autonomy of the refrigerator in case of lack of irradiance or a low production of power due to cloudy days. Also, due to the fact the power output of the hybrid is higher, a smaller PV panel could be used compare to a PV stand-alone powered refrigerator. The reduction in the size of the PV panel will lead to a reduction in the overall size of the system.

All in all, this research can serve as a support for others studies in the improvement of the efficiency of PV systems, but also lead the way for more investigation, application and improvement of PV module in Niger.

2. Working principle of the system

A PV refrigerator is basically a refrigerator which is powered by a PV panel. The PV panel produces the electricity necessary for the refrigerator to function. The main important thing is to make sure that the refrigerator and the PV array the electrical characteristics are a match. The PV array should be able to cover the need in voltage and electric current of the refrigerator. These values are usually given by the manufacturers for both modules.

The solar refrigerator uses a PV-TEG hybrid to collect and transform the sun into electricity and batteries to store energy, a battery charge regulator, and a controller.

The hybrid should preferably be able to provide more than the power necessary to run your refrigerator. This should ensure that your refrigerator will not have less than
the required power for it to function.

The refrigerator part works as a normal refrigerator powered with fuel-based electricity. Nevertheless, it has a higher insulation around the storage place.

Batteries are used to store the extra energy that is not used by the refrigerator. This energy will be used to keep the vaccines cool when the sun will not be available: night-time or cloudy days. The battery will allow us to provide our refrigerator with stable power. Depending on the batteries used, the system could keep keeping cool for five days in the absence of sun. Mostly a lead battery with a long life and a deep cycle are chosen. The battery characteristics are given by its voltage and ampere-hours. The latter allow you to know how much current is used through a certain amount of time. For example, a 50 amp-hour can supply a current of 2 A for a duration of 25 hours. Thus, choosing the best battery for your refrigerator the ampere needed by the latter and the autonomy you would expect your system to have.

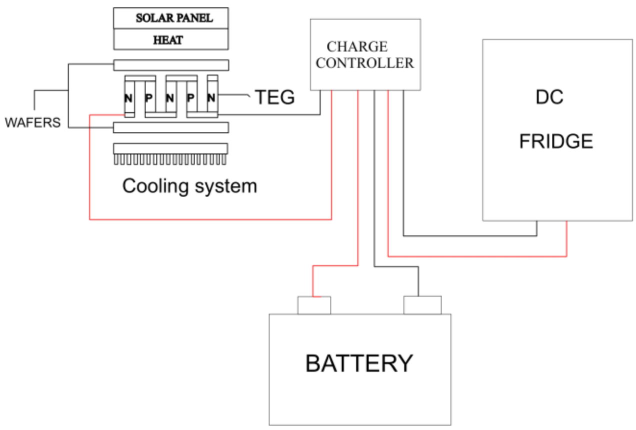

Figure 1. Simple schematic of a DC fridge powered by a PV/TEG hybrid

Charge regulator are not only used to control the current and the power delivered to the refrigerator in order not only to exceed its tolerated range but also to avoid overcharging the battery. The power output of the PV panel's output changes throughout the day because of different factors such as the temperature and irradiation. These changes can damage your system if not taken care and regulated. A charge regulator allows you to control these fluctuations and thus to protect your system and allow it to work under the best conditions.

Where you need an inverter to supply a normal refrigerator with an AC standard current taking in account that the PV panel and battery power output are in DC mode, using a solar refrigerator which is DC powered, you can skip the inverter. The DC powered refrigerators are also built to work with solar energy which make them more efficient. This type of fridge is usually built to operate with 12/24v, which make them safer.

The PV-TEG module size and characteristic are chosen to meet the requirement of the system.

2.1. Previous work

The feasibility of using solar power for vaccines refrigeration is not a new idea, and many research and approaches were conducted on this issue.

A small refrigerator's performances were investigated by Alshqirate et al. [3]. The results were satisfying and gave acceptable performance results when deep discharge batteries were used. The solar module was able to produce enough power for the refrigerator to work without interruptions or delay. The used batteries had a good charging and discharging alternance capacity.

In 2012, Henriques [4] and his team implemented a mobile vaccine refrigerator with a parallel photovoltaic system in Kenya, an African country. They aimed to allow the transportation of vaccine without any lost in the vaccines number. Their implementation was based on a mobile system and another one which was fixed to the car used to transport them. The system used a low DC vapor compressor refrigerator, a PV panel, battery, an inverter, and a charge controller. The selected refrigerator was able to maintain the temperature between the requirement of 2 °C to 8 °C. The mobile system (fixed on the truck) could ensure an autonomy of 3 days and the stationary system (present at the located hospital) was able to go reach 10 days of autonomy.

It was proved that a PV system efficiency was not affected by the addition of load [5]. The efficiency of the PV system when connected to a fridge was not affected. Hence, it can be safe to combine the two system without having a drop in the efficiency of the PV panel.

A thermoelectric refrigerator was used as load for a PV system by Saidue et al. [6]. They used a PV system, a battery bank, a thermoelectric fridge, an inverter, and a charge controller. Their system was able to produce an autonomy of 3 days in case there is no sun available. They could keep the fridge temperature at a degree ranging from 1-7 °C and in average 4°C. The thermoelectric fridge was used thanks to its low starting power and because it is environmentally-friendly and it does not produce noise. Nevertheless, they report that this result can be improved by increasing the insulation of the fridge and improving the efficiency in term of heat exchange.

It was also proven by Modi et al. [7] that a normal domestic fridge can be powered by solar panel without any problem. The refrigerator worked normally as if it was connected to electricity grid. For the chosen refrigerator, they used a 140 Wp PV module and a battery bank composed of 2 batteries of 12 V-135A-H. However, they advised to choose a PV module with higher power output and a larger battery capacity in order to run the system sustainably. The forehand system was able to maintain the temperature to a range of 0-8°C, which is the range approved by World Health Organization for vaccine refrigeration.

The system discussed by Siddarth and his colleagues [8] consisted of a PV panel of 150 W with a voltage of 12 V, a battery of 75 Ah with a voltage of 12 V, which will allow a 50 W vapor compression refrigerator to be run smoothly. They demonstrated theoretically that their system has an autonomy of 12 hours. They also discussed that by introducing ice as a phase change material (PCM), they can reduce the size of the PV module, which will reduce the overall cost of the system.

The performance analysis of a vapor compression refrigerator and a vapor absorption refrigeration was conducted [9]. The two of them were powered and as a result they found that the vapor compressor refrigeration needs more time to cool the cabinet, but it does use less power than the vapor absorption refrigerator. The vapor absorption refrigeration coupled with the PV array is found to be the best system for rural areas to conserve medicine or food. The latter system could hold a temperature range of 6-10°C. Another positive point is that this system investment and maintenance cost less than the one with a vapor compressor, and also produce less noise.

A new system made of a portable refrigerator powered by PV array was presented in a study conducted by Buitendach et al [10] . The system was made of a well isolated refrigerator unit using an air thermoelectric cooling module, a control system for checking the temperature in and out of the cooler but also the voltage and capacitor of the battery. Their system was able to maintain a temperature range of 2-8 °C. This system can keep cool up to 250 vaccines and the temperature could be controlled with an accuracy of 1°C. In addition, the temperature, battery voltage and remaining capacity are being shown and it can keep the vaccines up to 3 days.

A solar powered refrigerator was assembled by Hossain [11] et al. using local materials in order to keep vaccine in a range of -15°C to 30°C. A solar panel was used along with an evaporator, a compressor, an inverter and an expansion valve. The system was tested under different weather temperature. They proved that it is compatible and the best solution in rural areas and refugees' camps, where the electricity is not sustainable.

A system [12] made of a solar powered DC refrigerator, a microcontroller to monitor the temperature, two PV panel connected in parallel was implemented. Their experiment showed that this type of refrigerator can be powered by using renewable energy, in this case solar energy. A DC refrigerator needs less power leading to the minimization of the loss. This will allow to reduce the cost and make the system more affordable to install in countries under development.

An experiment was conducted in Marrakesh, Morocco making in a PV powered refrigerator system under temperature and irradiance recorded trough winter, spring, and summertime. The PV module used a maximum power point tracking controller to produce the maximum power possible, a battery which was used along with Luenberger charge estimation, a converter, and a refrigerator. These components were chosen taking in account that the system should be light, strong and be the less expensive as much as possible. This system proposed by Doubabi et al. [13] is found to be compatible for keeping vaccines under a 4°C temperature, which meet the requirement of world health organization (WHO) for the storage of vaccines. The system could keep the vaccine cool up to 15 hours.

The superiority of the efficiency of the hybrid compared to the efficiency of the PV stand alone was demonstrated by many researchers. The TEG would use the extra heat of the PV cell to create electricity, thereby increasing the efficiency of the PV panel. The use of a thermoelectric generator with a dye sensitized solar cell (DSSC) get the efficiency goes from 9.39% to 13.8% [14]. Many types of solar cells were tested with a TEG, it was found that the copper indium gallium selenide photovoltaic has shown the highest efficiency, but the cost of the solar cell make its use difficult [15]. Beeri et al. [16] found that the hybrid made of a multi junction PV and TEG gave an efficiency of

32% and they predicted that in the future, this efficiency could reach 50%. Also introducing a PCM into the PV-TEG showed a good improvement in the efficiency [17]. Dallan's team [18] proved that indeed the addition of the TEG to the PV panel is beneficial and the electric efficiency could be increased to 39%; however, a drawback system is needed to counter the reduction of the fill factor. A rise of 3% in the efficiency of the system made of a concentrating photovoltaic and a TEG was reached [19]. A roof integrated PV-TEG system presented a 23% efficiency [20]. An experiment was conducted not only for 24h but also on the long term, (one year) [21]. It was found that the temperature of the PV-TEG under the maximum irradiance was of 44.2°C while the temperature of the stand alone was of 57.1°C. A rise of 1.65 % and 1.72% respectively in the electrical and energy efficiency for the PV-TEG compared to the stand alone. The use of a PCM and TE at the back of the solar cell allowed Luo et al.[22] to reduce the cell temperature from 79.72°C to 57.39 °C. The cell temperature of the simple PV-TE was of 73.62°C. The efficiency of the PV-PCM-TE module had an increase of 17.57% compared to the PV stand alone and a 2.37% increase compared to the PV-TE module. The efficiency increase was more considerable in summer (3.53 %) than in winter (0.6%).

3. Mathematical modelling of a PV-TEG

A PV-TEG is made of a PV module and TEG. The PV module uses the sunlight to produce electricity. However, the more the panel gets heated, the less it is efficient. The heat could reduce the efficiency of the PV panel by 25%. A TEG uses temperature difference between its two side (hot and cold side) to create electricity. The TEG is joined to the back of the PV module to use the heating of the PV panel to create more electricity. The PV temperature will be considered as the temperature of the hot plate of the TEG. Thus, the hybrid will present a better efficiency than the stand-alone PV panel.

The temperature of the PV device is given by:

$$T_{PV} = T_a + c.G \tag{1}$$

$$c = (T_{noct} - 20)/800 \tag{2}$$

where T_a represents the surrounding temperature, G irradiance of the sun and C is a parameter that differ from one installation to another and it is calculated using the capacity of the heat exchange between the PV cell and the surrounding.

The efficiency of the PV module is given by

$$\eta_{PV} = \eta_{PVref}.\left[1 - \beta.\left(T_{PV} - T_{ref}\right)\right] \tag{3}$$

where β represents the coefficient of the temperature efficicency, η_{PVref} represent the efficiency of the device under the standard test conditions, T_{ref} represent the temperature reference, usually taken as 25°C.

The equation of the power output of the is:

$$P_{PV} = \eta_{PV}.G.A \tag{4}$$

A is the area of the cell that the irradiation is falling on

The power output of a TEG is given by:

$$P_{TEG} = Q_{hs} - Q_{cs} \quad (5)$$

$$Q_{hs} = n * (S \,.I.T_{hs} + \overline{K}.(T_{hs} - T_{cs}) - (1/2)\,.R_{te}.I^2) \quad (6)$$

$$Q_{cs} = n * (S.I.T_{cs} + \overline{K}\,.(T_{hs} - T_{cs}) + (1/2)\,.R_{te}.I^2) \quad (7)$$

$$P_{TEG} = n(S.I.(\,T_{hs} - T_{cs}) - R_{te}.I^2) \quad (8)$$

$$I = S.(T_{hs} - T_{cs})/R_{te} + R_L \quad (9)$$

Where R_L is the load resistance

For matching purpose, let's consider that R_{te} and R_e are sharing the same value.

The efficiency of the TEG becomes:

$$\eta_{TEG} = P_{TEG}/Q_{hs} \quad (10)$$

The power of the hybrid is given by:

$$P_{HY} = P_{PV} + P_{TEG} \quad (11)$$

Its efficiency is:

$$\eta_{HY} = P_{HY}/G.A \quad (12)$$

$$\eta_{HY} = \eta_{TEG} + \eta_{PV} \quad (13)$$

For our simulation, we used the mono-crystalline Silicon PV panel and TEG specified below

Table 1. PV specifications

Size	$40 * 40\ mm^2$
Number of couples thermoelement	128
Thermoelement cross section(W * D)	$1{,}4 * 1{,}4\ mm^2$
Maximum temperature	320 C
L_{TE} (length of thermoelement) (mm)	1,6
S ($^{\mu V}/_{K}$)	282
$\overline{K}$	1.20 W/(m·K)
Number of TEG used in series	615

Table 2. TEG's specifications

Size	1480mm*665mm*35mm
Maximum power (Pmax)	150W
Optimum operating voltage (Vmp)	17.2V
Optimum operating current(Imp)	8.72A
Open-circuit voltage(Voc)	21.6V
Short-circuit current(Isc)	9.92A
Isc temperature coefficient	(0.065 ±0.015)%/°C
Voc temperature coefficient	-(80 ±10)mV/°C
Peak power temperature coefficient	-(0.5 ±0.05)%/°C
Operating temperature	-40°C to 85°C

Table 3. Refrigerator's specification

Gross / Net volume (l)	52 / 45
Set temperature (preset)	+5°C
Set temperature (setting range) can be adjusted in steps of 0.1°C	+4°C to +15°C
Temperature cold / warm alarm limit	+3°C / +7°C
Hold over time (+5°C to +10°C)	1 h 15
Climate class (ambient temperature range)SN	(+10°C to +32°C)
Defrosting technique	Natural
Refrigerant type	R600a
External dimensions H x W x D (mm)	670 x 495 x 575
Inner dimensions H x W x D (mm)	470 x 375 x 350
Supply voltage (V)	220-240
Frequency (Hz)	50/60
Power (W)	100
Energy consumption (kWh/24h)	0.42/0.45
Heat emission (Kcal/h)	12
Compressor running time (%)	32
Noise level (dB(A)) (at 1m height & 1m distance)	35/36

4. Results and Discussion

In order to conduct our research, we implemented our model using Matlab. Our calculations were conducted using average data of the months of January and September. A specific day, 7th May was chosen because it represented the hottest day in the country during the year 2019. The data used were the irradiance and temperature collected from the Meteorology Center of Niger, nevertheless the irradiance for the 7th May were accordingly approximated, and for the other months the daily average data were used. The figures 2 and 3 given below show corresponding irradiance and temperature data.

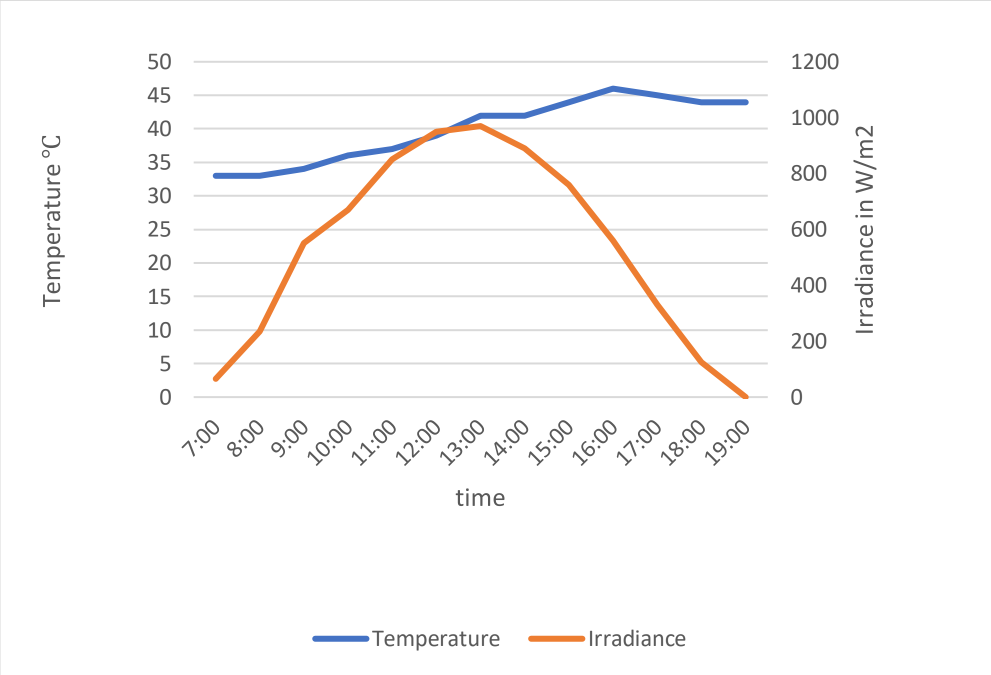

Figure 2. Curves of the average irradiance and temperature on 7th May 2019 in Niamey

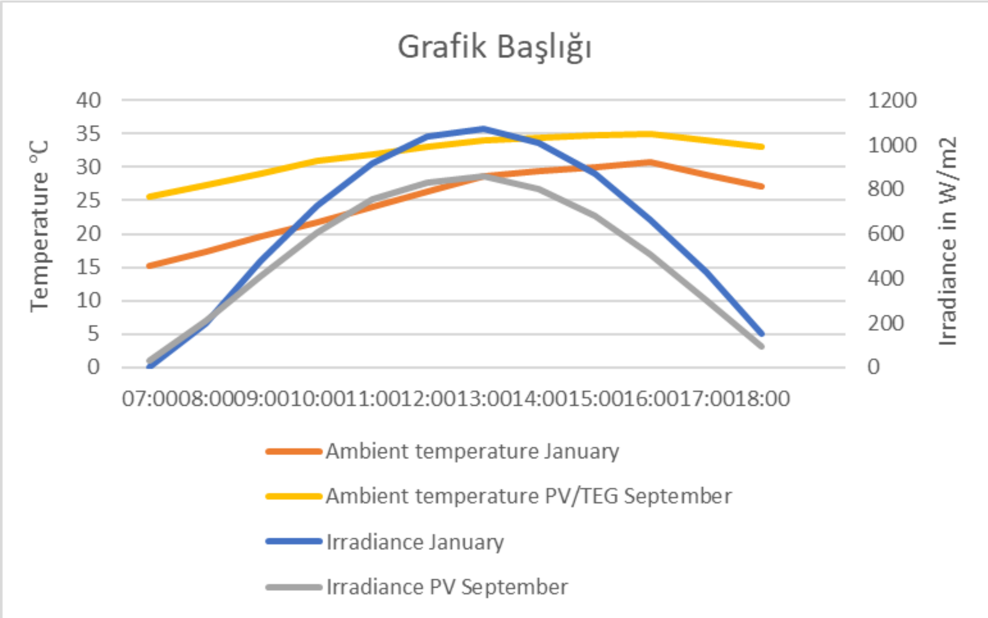

Figure 3. Curves of the average temperature and irradiance in January and September 2019 in Niamey

From the figures 4, 5, 6 and 7 given below we can see the power output and efficiency of a PV panel when used alone and when used with a TEG. The PV-TEG has shown a greater performance than the stand alone and this regardless of the day.

For example, on the 7th of May, the hybrid showed a peak of 186.9 W while at the same point the stand-alone's power was of 117.13W (see Fig.4). In addition, at the same date, when the efficiency of the hybrid is of 19.62% , at the same point the stand alone presented an efficiency of 12.24% (see Fig.6).

The results obtained with the data in January and September are here to correlate and support the results obtained the 7th May. We can see on the curves a good improvement in the total power output and efficiency of the PV coupled with the TEG than when the PV is used alone. The highest power output in January is of 196.69 W for the hybrid against a 134.79 W (Fig. 5) for the stand alone in January, while the power was of a value of 153.224 W for the hybrid and 108.79 W in September (Fig. 5) . The efficiency went up to a highest value of 18.69% for the hybrid from 12.81 % (Fig. 7) for the stand alone under January's conditions which is a rise of 5.88%. Under September's conditions, a 18.29 % for the hybrid and an efficiency of 13.09% for the stand alone which is a total rise of 5.2% (Fig. 7).

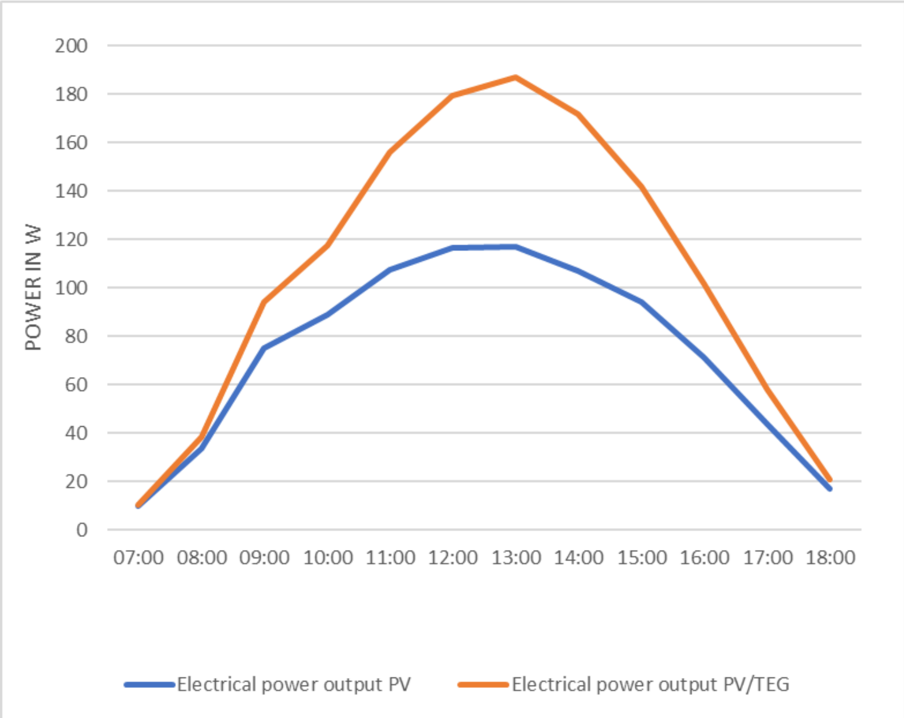

Figure 4. PV and PV-TEG power output in May 2019

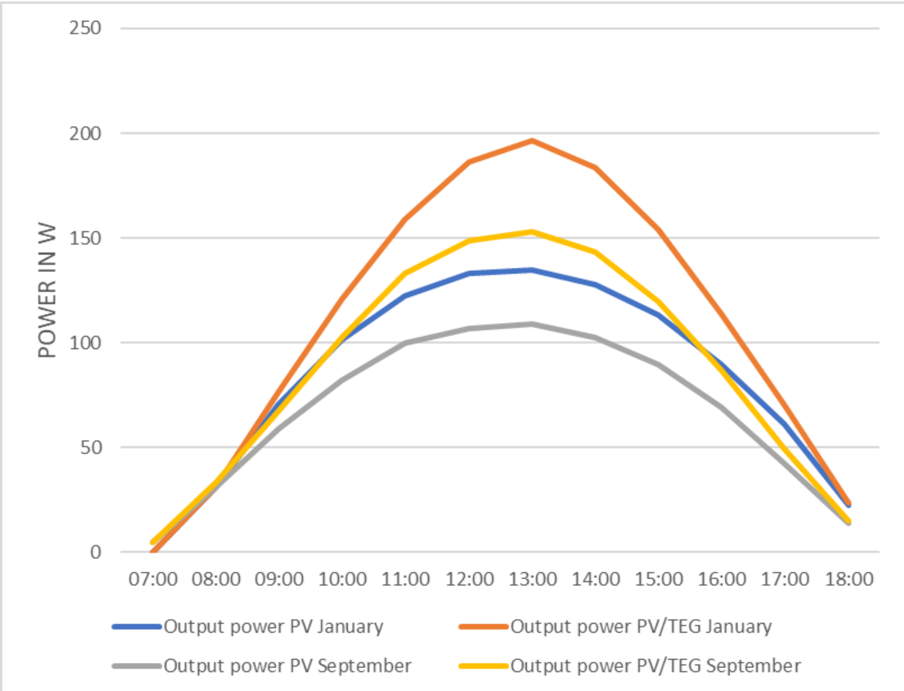

Figure 5. PV and PV-TEG power output in January and September 2019

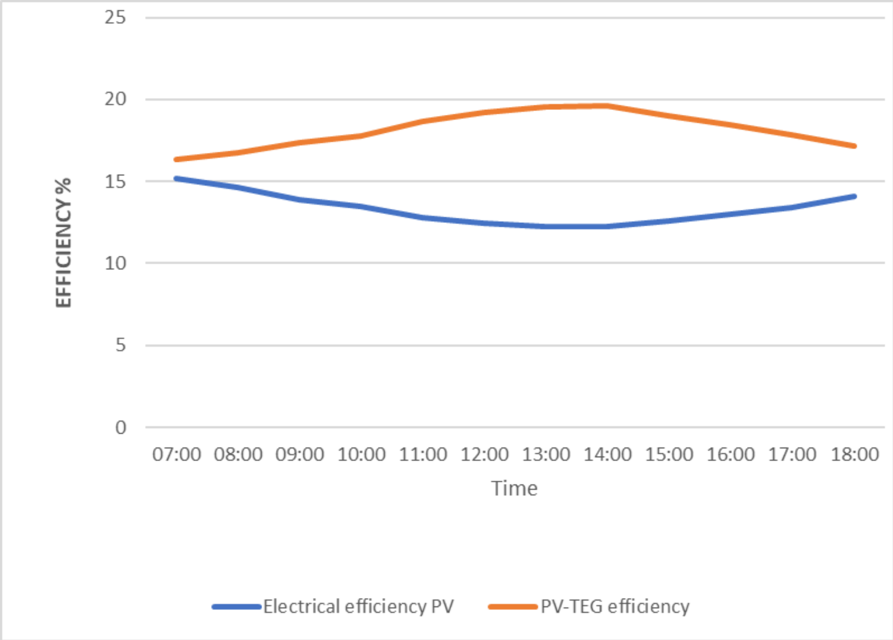

Figure 6. Efficiency of PV panel and PV/TEG on 7th May 2019

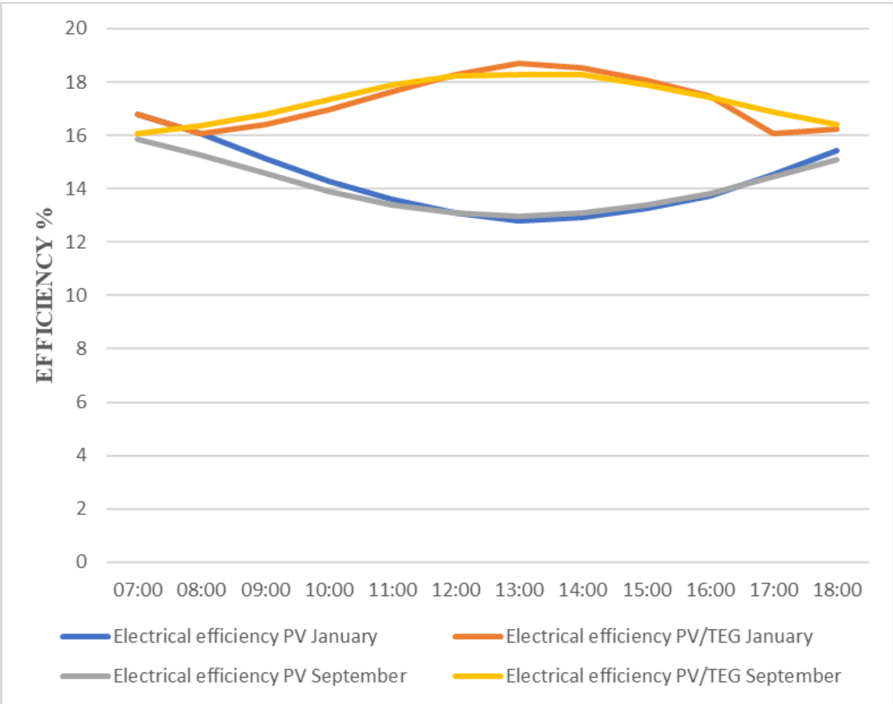

Figure 7. Efficiency of PV panel and PV/TEG in January and September 2019

A medical refrigerator manufactured by B-medical systems is used. Its technical specifications are given in Table 3. A refrigerator with a power consumption of 30 W is used with our hybrid and stand-alone system designs. For the 12 hours of irradiance throughout the day, a total of 882.56 Wh energy was produced by the stand-alone PV versus 1277.53 Wh for the hybrid. The same refrigerator with a power consumption of 30 Watt and a capacity of 52 L is used with these two different systems. Taking in account that the fridge consumption is 450 Wh/day, we would be able to store approximatively up to 827.53 Wh which would give us nearly 44 hours of autonomy, while with the stand-alone PV panel, we would be able to only store 432.55 Wh, which corresponds to 23 hours of autonomy. The autonomy provided by the hybrid powered refrigerator is almost the double of that provided by the PV stand-alone system.

The table 4 below is a recapitulative of the produced, stored power and the autonomy hours under the three different conditions. It can be seen from these results that the use of a hybrid is an important asset to be considered in vaccine refrigeration.

Table 4. Recapitulation of power and autonomy of the two different systems in January

	January		**7th May**		**September**	
	PV power	**Hybrid power**	**PV power**	**Hybrid power**	**PV power**	**Hybrid power**
Total output power	1007.93	1315.87	882.558	1277.53	810	1058.59
Saved output power	557.93	865.87	432.558	827.53	360	608.59
Days coverage	1.23	1.92	0.96	1.83	0.8	1.35
Autonomy hours	29.75	46.08	23.04	44.13	19.2	32.4

5. Concluding Remarks

The access to electricity is a real challenge in the rural areas in Niger, not to say in the whole country. The access rate to electricity is 12.93% in the whole country, and only 3.14 % of the rural population has access to the on-grid electricity. With most of the electricity imported from Nigeria, besides the numerous power sources available in the country, to extend medical care to the rural areas, solutions must be found. Indeed, vaccines and medicines need to be well stored for them not to perish. The potential of the country in solar energy is an interesting answer to be investigated. The country has a high irradiance and has an average of 9 hours of irradiance per day. Solar energy could be used to power the refrigerators destined to the storage of the vaccines and medicine.

To achieve better performance of such system solar powered fridge, the use of a Hybrid PV-TEG is considered. It was shown that the efficiency and power output of the hybrid is superior to the ones of the stand-alone PV panel. The efficiency of the hybrid was found to be 7.38 % higher than the stand-alone efficiency at the moment the cell temperature reached the highest point. That increase in the efficiency of the hybrid, will allow to create more power to be stored in batteries for times when sun will not be available. Thus allowing a rise in the autonomy of the solar powered refrigerator. For our designed system, the autonomy procured by the hybrid is almost the double of the one provided by the PV stand alone for the same refrigerator. The use of hybrid can also allow to reduce the size of the PV panel necessary to power the system, thus reducing the size of the overall system.

Our work comes as a support to the already existing base affirming that a thermoelectric coupled to a PV module is a very good mean to reduce the heating and hence improve the efficiency. This work is a first conducted under the Niger weather, which is in real need of an energetic solution.

We believe that PV-TEG system can be a good solution for sustainable cold chains for equitable delivery and use of Covid-19 in Niger and in most of the sun-rich African countries. The WHO can arrange such a campaign call for G7 or G20 countries to afford, provide and organize delivery of large amount PV-TEG refrigerator systems into the countries in need.

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