Solar cooling modelling utilising for cooling agro-products cold store under Rwandan environmental conditions

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Abstract. Solar-driven cooling systems can be considered as a sustainable solution for the weak cold chain. Transient Simulation System (TRNSYS) offers component-based 0D modelling capability of different engineering systems. TRNSYS has been employed to model a year-round performance of a PV solar-driven electric chiller to meet the cooling demand of post-harvested foodstuffs under Rwandan metrological data. Various PV module sizes and batteries storage capacities have been investigated to examine their effect on the solar energy fraction powering the electric chiller to maintain the room at the desired temperature. In addition, two different arrangements of chilled water loop, namely one-loop with 3 KW chiller capacity and two-loops with 6 KW chiller capacity have been compared to investigate their effect on the chiller performance and solar fraction. Results revealed that the later arrangement exhibits a higher solar fraction compared to one loop despite the addition of another pump. For 35 PV modules, the two-loops arrangement requires 42 kWh battery capacity to provide about 90% solar fraction, while one-loop needs 66 kWh to deliver the same solar fraction. Accordingly, the battery storage capacity is reduced by a factor of 0.36 which justifies the increase in the chiller capacity from 3 KW to 6 KW. This study provides a selection map to choose between the number of PV panels and batteries capacity required to power the chiller and meet the cooling load.

1.Introduction

Food wasting is a substantial issue that escalates concerns about food security around the world. The word-wide amount of wasted food is about one-third of the total produced food. Subsequently, a huge amount of pollutants is emitted, and a wide area of arable land and a substantial amount of edible water are wasted [1]. Food wastage in sub-Saharan African (SSA) countries is mainly caused by the lack of food cold chain. To address this, it is crucial to develop and deploy sustainable cooling packages at scale to preserve perishable foodstuffs and maintain their market value [2]. The energy poverty and the limited access to the national grid are major impediments to the development of secured cold chains [3].

Solar energy is abundant in SSA countries and can be an alternative sustainable energy source to drive cooling systems. Many researchers evaluated the suitability of PV solar collectors to drive the vapour compression chiller. Huang et al. [4] concluded that the PV solar-driven Vapour Compression Chiller (PV-VCC) can be completely run by PV panels if the total average daily solar radiation greater than 13 $MJ.day^{-1}.year^{-1}$ and the PV collector power yield three folds the load power. Hartmann et al. [5] performed a cost comparison between a grid-connected PV-VCC and a Solar Thermal-Driven Chiller (STDC) under Freiburg and Madrid climate and reported that the former has less primary energy saving cost than that for the later. The same conclusion has been drawn by Eicker et al. [6] at Palermo, Madrid and Stuttgart sites. Fong et al. [7] compared the performance of five different solar-driven cooling systems, PV-VCC, mechanical compression, absorption, adsorption and solid desiccant cooling systems at Hong Kong site climate condition; PV-VCC exhibited the highest performance compared to other chillers. An extensive review study concerning a comparison of different solar-driven cooling systems has been carried out by Allouhi et al. [8]. Thermal-driven chillers were competitive, although the PV-VCC has the highest COP.

TRANSYS is a powerful, flexible, component-based environment which is used to model the behaviour of transient energy systems. It is a widely used and valid to analyse solar-driven systems such as a standalone residential lighting PV system and battery energy storage system-based PV charging station [9, 10]. The energy-saving performance of an electric chiller driven by PV solar energy with battery storage and phase-change cold storage has been investigated to meet residential cooling loads at three different sites, Madrid, Shanghai, and Brisbane using TRNSYS [11, 12]. It is found that higher energy saving is achieved using battery storage compared to cold storage approach and the system with energy storage option provides a considerable energy saving compared to no energy storage one, (battery storage 2.8 times and cold storage 1.9 times that for no storage option). Luerssen et al. [13] compared the performance of PV-driven off-grid cooling systems deploying various energy storage strategies, battery, cold water storage and ice storage to determine their life cycle cost under 7 different connection arrangements. Results showed that coupling only PV with the diesel generator as a baseline case decreases the life cycle cost by 9-10% whereas adding battery storage to all the arrangements reduces the cost by 14-17% compared to the diesel generator alone. In addition, the highest fuel saving of 51-77% is achieved by combining battery and thermal storage, but the investment cost rises by 27-50% while employing battery storage alone provides 39-48% fuel saving compared to diesel-powered option. They also reported that the fuel prices and their inflation and the discount rate have a significant effect on the life cycle cost of the investigated systems.

Limited research work has been carried out to investigate a year-round standalone PV-driven cooling system for cooling agricultural products under the effect of a real cooling load. Sizing of the main components of such systems under certain sites metrological data need to be considered to investigate their suitability to meet the cooling demand of a certain cold store. Also, the development of the food cold chain requires more attention in SSA countries to address the issue of food waste [2]. Therefore, the current study aims to investigate the performance of a year-round 24/7 off-grid solar PV- driven cooling system to meet the cooling requirements of a cold room used to cool crops under Rwandan climate conditions. Subsequently, different PV panel sizes and battery storage capacities have been examined to supply the required electrical power to run an electric chiller used for cooling the cold store. Besides the effect of two different arrangements of the chiller-cooling coil loop on the cooling system performance and hence on the PV panel and battery size has been investigated.

2.Model description

TRNSYS 18 was employed to model the hourly dynamic operation of the PV-driven cooling system throughout the year. An existing cold room of 12.5 m^2 used for cooling dairy products in Rwanda was adopted as a case study in this work. In the current study, the cold room was proposed to be used as a cold store to preserve different post-harvested foodstuffs such as banana, potatoes and tomatoes at farm level before marketing to remain perishable and keep their nutrition and market values.

TRNBuild model with zone module (Type56) is employed to simulate the thermal behaviour of this room using Trnsys3d integrated with SketchUp software to determine the actual time-dependent cooling demand [14]. Multizone building simulation allows users to input different building characteristics such as orientation, building materials, internal gains, infiltration rate, ventilation, time-schedule and building set temperature and humidity to calculate the cooling demand according to the site weather data. Consequently, Type 56 zones generate outputs to be used as inputs to the cooling system which in turns generates outputs to be connected to the building inputs. Moreover, crops daily loading and respiration rate cooling loads need to be added as internal energy gain to the room model. Therefore, an internal gain of 1383 kJ/hr is added corresponding to the cold room capacity of 10 tonnes and crops daily loading rate of 500 kg/day. The resulting required total cooling load and ambient air and room temperatures are shown in figure 1 and figure 2, respectively.

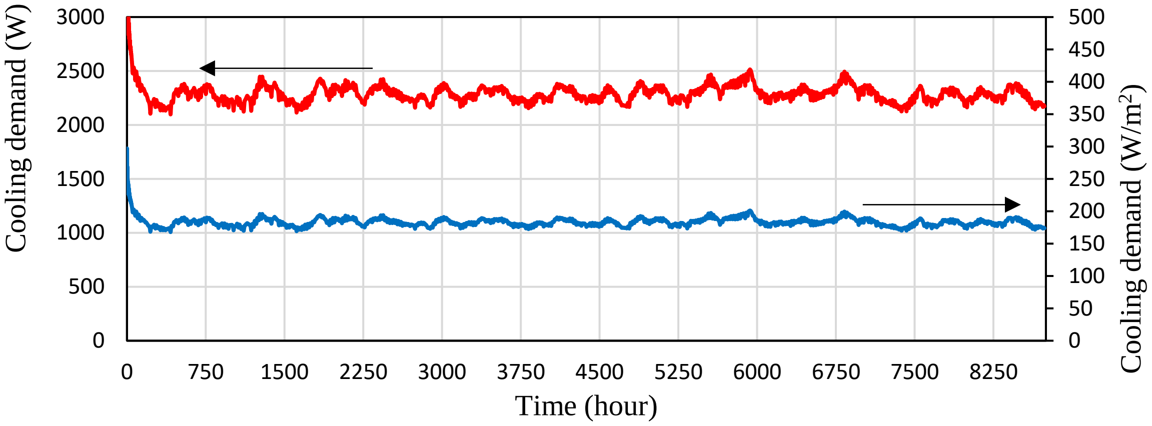

Figure 1. Hourly variation of cooling demand throughout the year

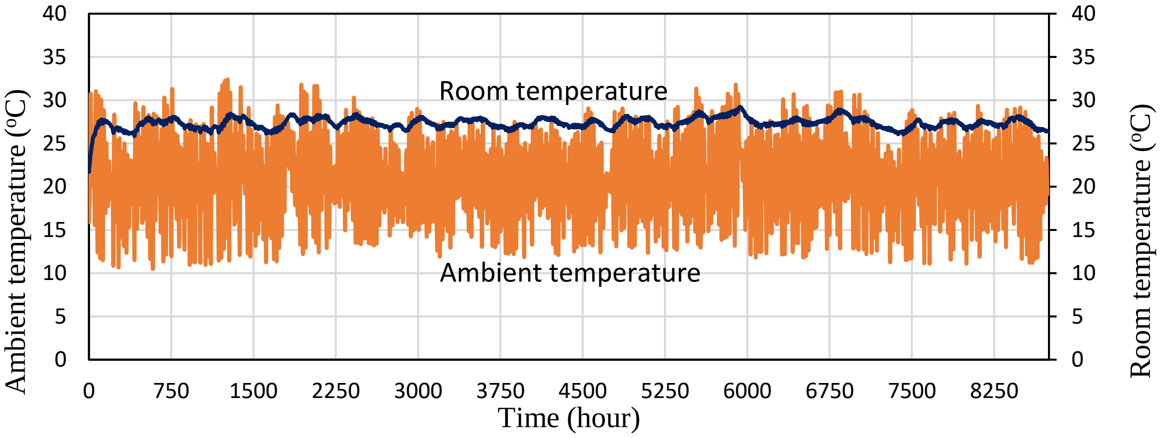

Figure 2. Hourly variation of ambient and room temperatures throughout the year

Typical Meteorological Year (TMY) weather file is used to obtain weather data every hour around the year for a certain geographical site which is selected from hourly collected data for a long period, typically more than 10 years. Therefore, the TMY weather file for Kigali is directly chosen from TRNSYS database using TRNSYS weather component named Type15. Type15 reads and interpolates the data from the TMY file regularly at each time step providing all required environmental data to be used with all relevant components [15].

PV panel simulation module (Type94a) was employed, which proved its validity to simulate the performance of mono and polycrystalline PV module [15]. The parameters of Type94a are adopted from PEIMAR polycrystalline solar panels and are presented in table 1.

For conditioning the generated PV power among PV panels, battery storage and the load, inverter with power controller module (Type48b) is used. It models a regulator to control the power from the PV and the battery charging / discharging processes; it also models an inverter to convert the output DC power into AC power as an input to the load. The regulator and inverter efficiencies used in Type48b are 78% and 96%, respectively which are the TRNSYS default values for this module. The operating mode for this type is Maximum Power Point Tracking (MPPT) which tracks the PV power rather than the voltage, and monitoring of state of charge of the battery. The high and low limits on Fractional State Of Charge (FSOC) are set to 1 and 0.3, respectively. This makes the priority for battery charging and prevents discharging at FSOC lower than 0.3. Moreover, the battery storage module (Type47) is used to operate conjunctionally with the PV array and power conditioning component (regulator and inverter) with a default efficiency of 90%. The energy storage capacity is calculated by multiplying three inputs, cell energy in Wh unit, the number of cells in parallel and the number of cells in series [16].

Table 1. PV panel parameters.

Parameter	Value
Peak power Wp	280 W
Area	1.6 m^2
Voltage at peak power V_{mp}	31.2 V
Max open circuit voltage V_{oc}	37.3 V
Current at peak power I_{mp}	8.98 A
Max short circuit current Isc	9.7 A
Temperature coefficient of I_{sc}	0.04 A/k
Temperature coefficient of V_{oc}	-0.079 V/k
Number of cells wired in series	60

Electric chiller module (Type655) was employed to model the air-cooled vapour compression chiller to predict its performance relying on a catalogue data lookup approach. At every time step, Type655 interpolates the capacity, COP and part load ratios at different outside ambient temperatures and chiller set point temperatures to determine the chiller capacity, COP, required electric power, chiller load and inlet chilled water temperature.

All components were integrated using the TRNSYS model to investigate the chiller performance and accordingly its required driven power under a direct cooling load of the cold room. Subsequently, a different number of PV modules and battery storage sizes were examined to meet the chiller power providing different solar fractions.

Two different chilled water loop scenarios were modelled: one-loop and two-loops to investigate their effect on the cooling system performance and the size of the PV system (PV panel and battery storage). For the one-loop option, chilled water from the chiller passes through the storage tank to the cooling coil and is pumped back to the chiller where the chiller capacity, in this case, is 3kW as shown in figure 3. However, for the two-loops option, there are two separated loops, in the first one, chilled water is circulated between the chiller and the storage tank using pump2 while in the second loop, the cold water is circulated between the storage tank and the cooling coil using pump1 as shown in figure 4. For this arrangement, the chiller capacity was double that for one-loop arrangement, 6 kW, and accordingly the flow rate of the first loop is 2 times that for the second loop.

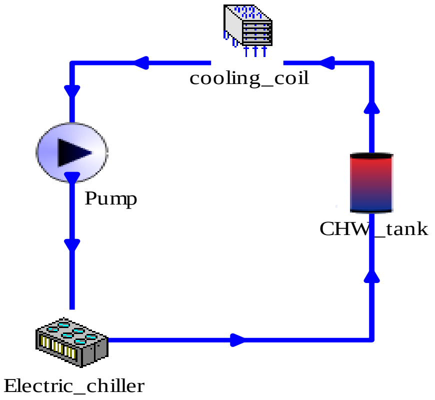

Figure 3. One-loop arrangement

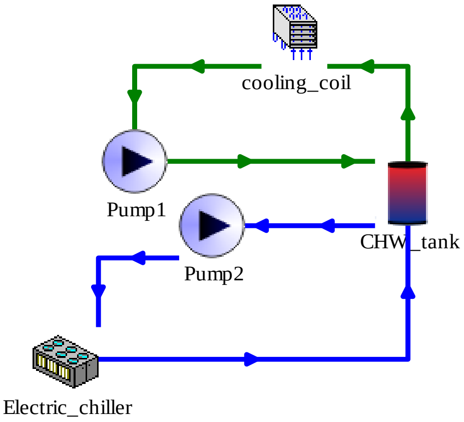

Figure 4. Two-loops arrangement

3.Results and discussion

A standalone PV-driven cooling system was modelled to investigate its year-round performance and the component sizes to meet the cooling demand of the cold room used for cooling a range of perishable foodstuffs. The solar fraction which represents the power provided to the load from the PV solar system divided by the load power is used as an indicator of the required PV and battery sizes. Figure 5 shows the variation of the solar fraction with the number of PV modules at a battery storage capacity of 48 kWh for the two arrangement, one-loop and two-loops. For the system to run 24/7, the solar fraction has to be higher than 90% while the rest 10% can be provided by the cold storage for about two hours without running the chiller. It is noticed that to obtain about 90% solar fraction at the same battery storage size, 30 PV modules are needed when the two-loops is used, while 50 modules are needed in the case of one-loop. Accordingly, about 67% extra PV modules are required for the one-loop compared with the two-loops to meet 90% of the chiller input power.

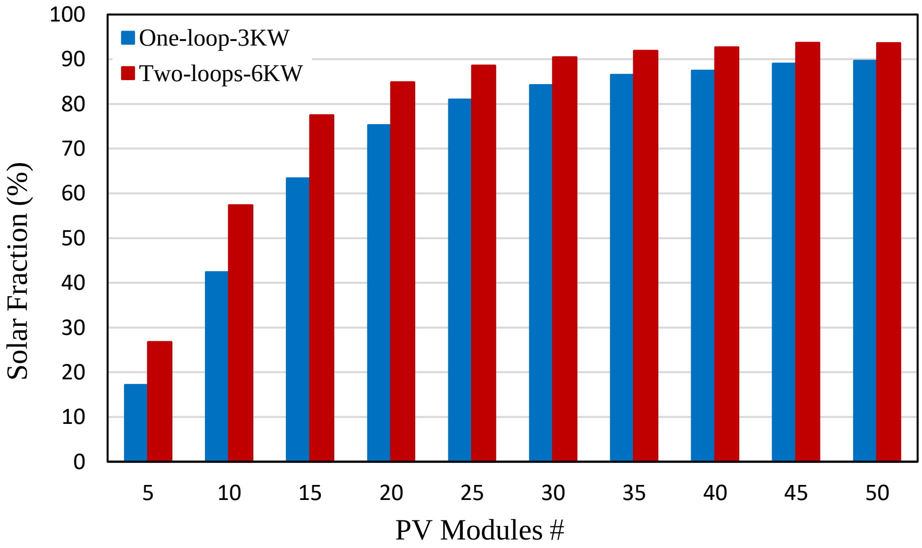

Figure 5. Solar fraction variation with number of PV modules

Change of the solar fraction with the battery storage capacity in kWh at different PV module sizes for one-loop and two-loops arrangements are presented in figure 6 and figure 7, respectively. They show for one-loop, the solar fraction increases sharply at battery capacities of 6 and 12 kWh while for two-loops, there is a sharp increase only at a capacity of 6 kWh. The sharp increase indicates that the battery capacity is considerably lower than that required capacity at a certain PV module number. Also, using 15 PV panels provide a solar fraction of about 64% for one-loop and 80% for two-loops at a battery size of 60 kWh, whereas 40 PV panels deliver about 89% and 96% at the same battery capacity. It is also observed that to achieve 90% solar fraction using 35 PV modules, 66 kWh and 42 battery capacities are needed for one-loop and two-loops scenarios, respectively. Therefore, employing the two-loops option decreases the required battery storage size by 24 kWh to achieve the same solar fraction which represents a 36% reduction in the battery capacity needed. Considering 8 years the life cycle time of the battery and electric chiller, a capital cost of 469 USD/kW$_{th}$ for the chiller and 380 USD/kWh for the battery, an annual maintenance cost of 10.78 USD/kW$_{th}$ for the chiller and an annual maintenance cost of 11.3 USD/kWh for the battery [13]. Carrying out a cost calculation for the increase in the battery size from 42 to 66 kWh (an increase of 24 kWh) against the increase in the chiller capacity from 3 to 6 kW results in a total cost of 11290 USD for the extra 24 kWh battery capacity and 1666 USD for the extra 3 kW chiller capacity. Therefore, using an extra 3 kW chiller capacity exhibits a much lower cost than that of increasing the battery storage size by 24 kWh.

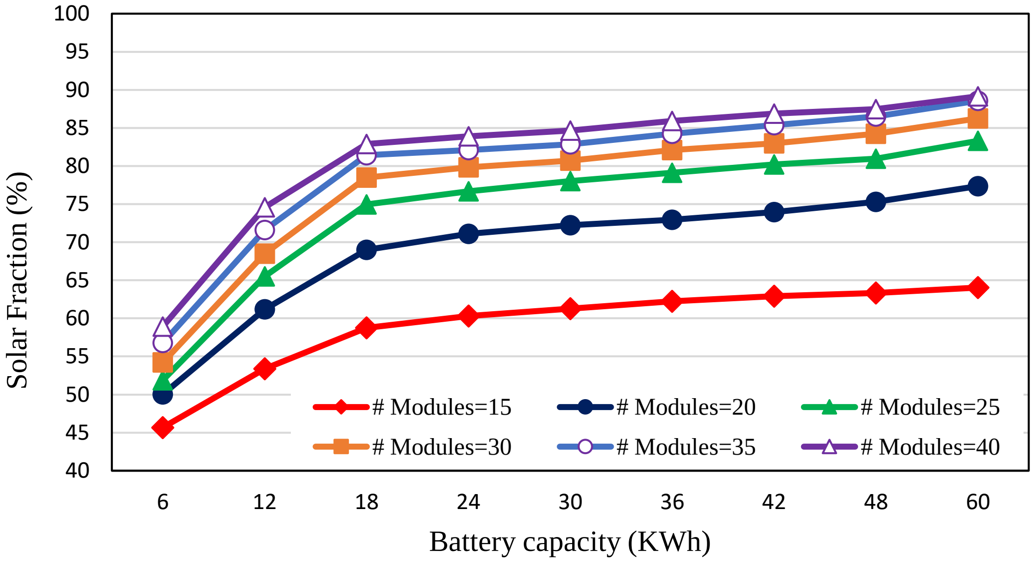

Figure 6. Solar fraction versus Battery capacity for chiller capacity of 3 kW-one-loop

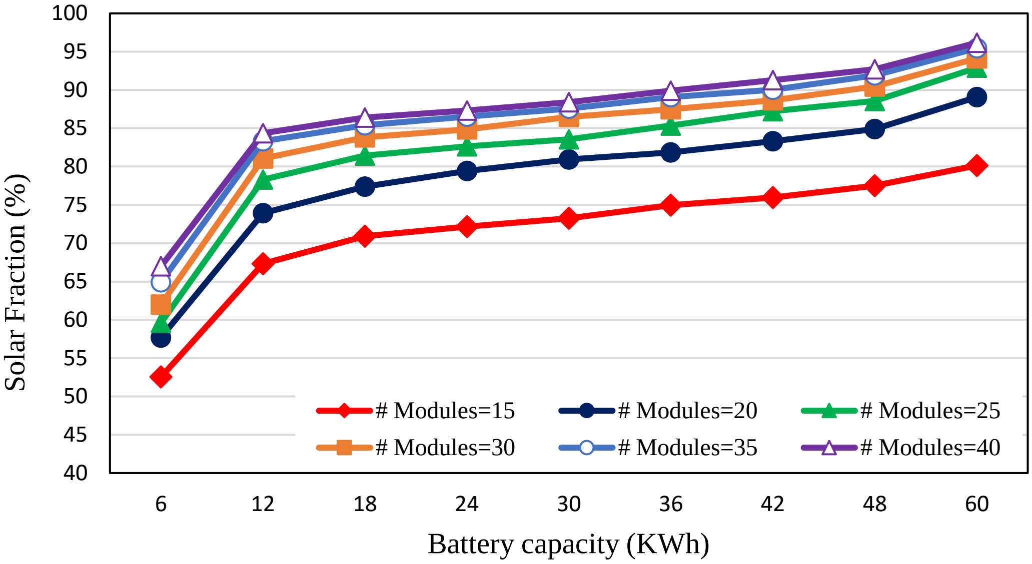

Figure 7. Solar fraction versus Battery capacity for chiller capacity of 6 kW-two-loops

The increase in the solar fraction in the case of two-loops compared with one-loop is due to the significant increase in the chiller COP at the same cooling load and accordingly the same chiller load as shown in figure 7. It presents the hourly change in the chiller COP around the year for both arrangements. The fluctuation in the COP is due to the change in the ambient air temperature where the ambient air is directly used as a heat sink for the system. It is noticed that the difference in the COP between the two arrangement is higher than 1.5. The increase in the COP is attributed to the noticeable reduction in the chilled water return temperature in the case of the two-loops compared with the one-loop as shown in figure 9. This is because of doubling the chiller capacity in the case of two-loops results in doubling the chilled water flow rate of the first loop compared to the flow rate of the second loop which decreases the rise in the returned chilled water temperature to the chiller.
The increase in chiller COP decreases the required chiller inlet power as shown in figure 10 which increases the solar fraction in the case of the two-loops scenario.

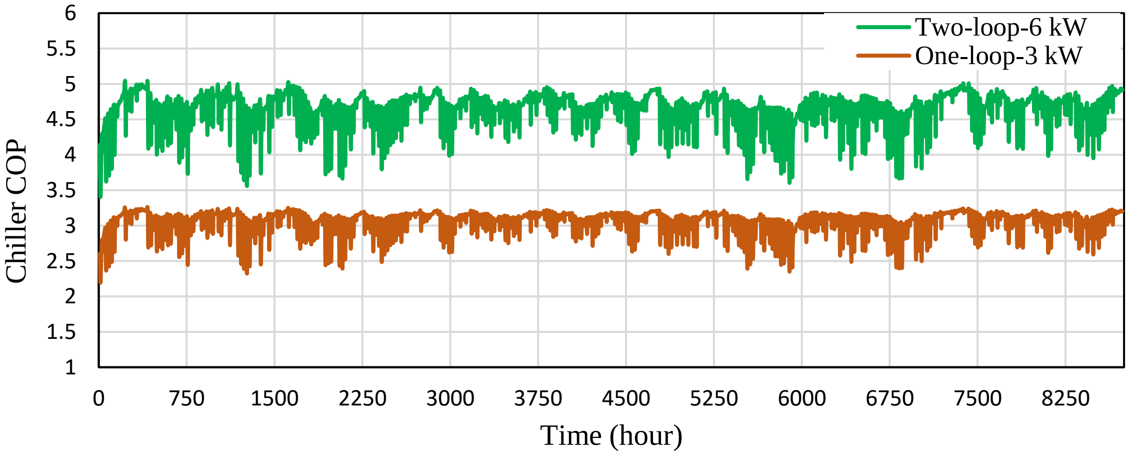

Figure 8. Hourly variation of chiller COP throughout the year

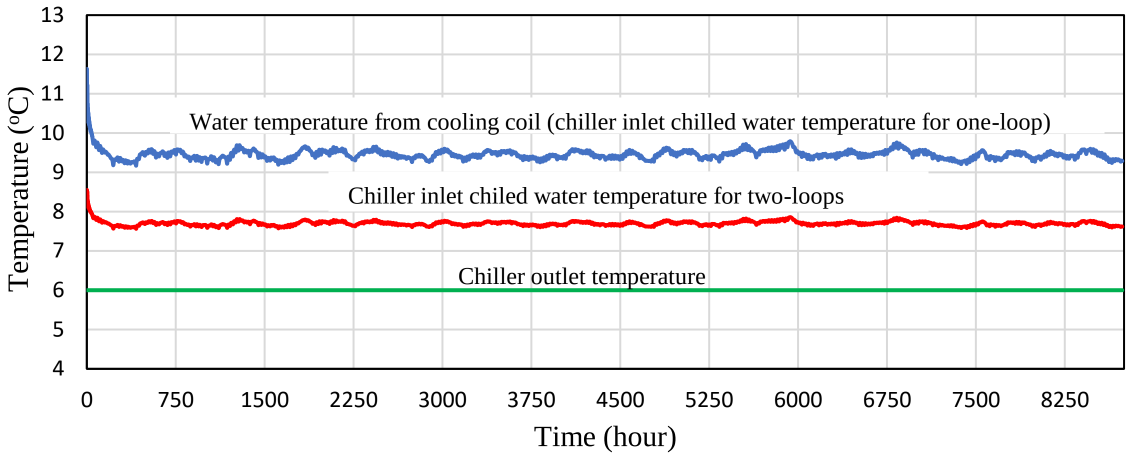

Figure 9. Hourly variation of chilled water inlet and outlet temperatures

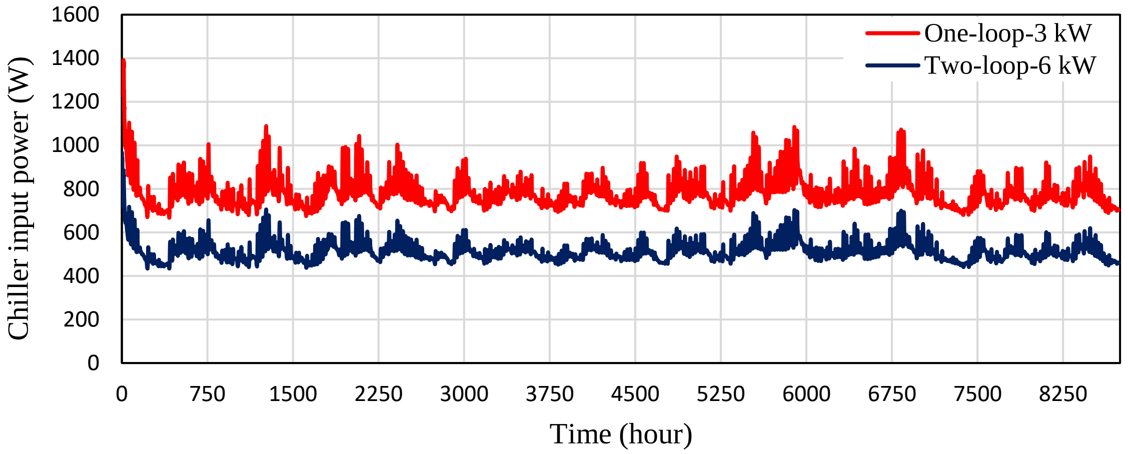

Figure 10. Hourly variation of required chiller input power

Figure 11 presents the outside ambient and room temperature change at each hour throughout the year. It shows that the room temperature is almost maintained at 10 ºC which is the required optimal temperature to preserve the specified fruits and vegetables.

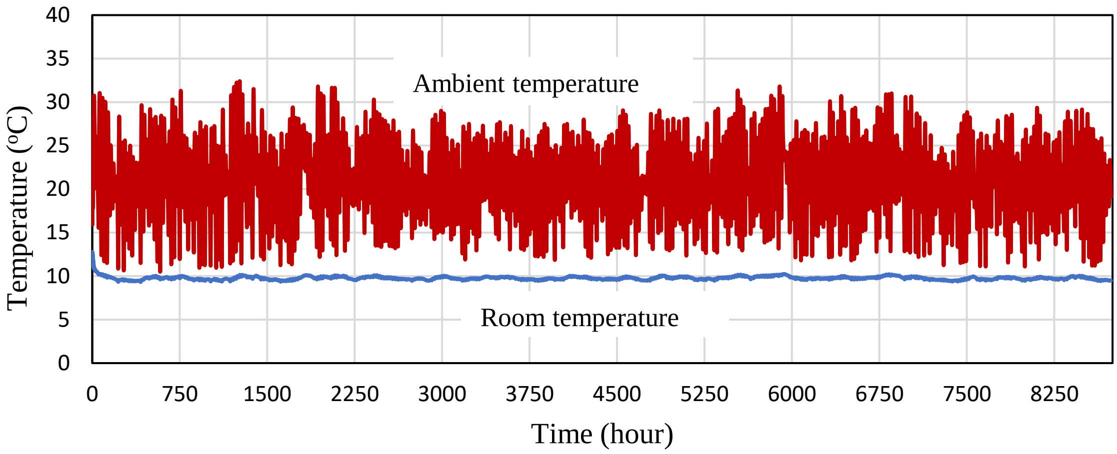

Figure 11. Hourly variation of ambient and room temperatures

4.Conclusions

A year-round dynamic performance of a PV-driven cooling system was simulated using TRNSYS to meet the cooling demand of a cold room employed for cooling fruits and vegetables in Rwanda. The model was employed to investigate the effect of two different arrangements of chilled water loop on the chiller performance and accordingly on the sizes of PV modules and battery storage capacity. The chiller performance increased significantly in the case of two-loops arrangement with a chiller capacity of 6 kW which increased the COP of the chiller by more than 1.5 compared to one-loop with a chiller capacity of 3 kW. Accordingly, the required chiller input power was reduced considerably which increased the solar fraction. To achieve 90% solar fraction with 35 PV panels, 24 kWh less battery size is obtained when the two-loops is employed compared to one-loop. This reduces the system cost by about 9600 USD despite doubling the chiller size which justifies the increase in the chiller capacity from 3 KW to 6 KW.

The study also provides a selection map of different PV modules and battery sizes to drive the electric chiller and maintaining the cold store at the desired temperature. If for example, a limited area is available for installing the PV panels, larger battery capacity can be used to provide the same power and vis versa.

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