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SIMULATION-BASED ASSESSMENT OF HYBRID PV/T SOLAR SYSTEMS FOR HEALTHCARE STERILIZATION AND POWER SUPPLY

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Abstract

The healthcare industry urgently needs a reliable energy source to meet both electricity and high-temperature heat demands for sterilization processes. This paper simulates hybrid photovoltaic-thermal (PV/T) systems to serve a healthcare facility in Santhia, paring its performance with a conventional photovoltaic (PV) system with battery storage. Both configurations were simulated using Polysun under the same climatic conditions. The 97.2 kWp PV system achieved 53.6% electrical self-sufficiency and generated excess electricity (116,871 kWh/year) sent to the grid. The PV/T system, with a 1.3 m² collector, contributed 15.3% to the thermal load and produced ancillary electricity. Environmental analysis showed notable CO2 reduction; 75,501 kg/year for the PV system and 555 kg/year for the PV/T system. While large-scale PV systems optimize carbon-emission reduction and financial gains, the hybrid PV/T system offers a small but valuable alternative for energy resilience, particularly in providing renewable thermal power for sterilization services.

Keywords: Hybrid PV/T System, Solar Energy, Healthcare Sterilization, Energy Resilience, Polysun Simulation.

1. INTRODUCTION

The healthcare sector in the world is marked by a considerably high level of energy consumption that calls upon the constant availability of energy in electricity to energise the medical devices and thermal power needed to run the necessary processes such as sterilisation. This necessity is a major issue particularly in the areas where the grid infrastructure is unstable and this requires energy resilience as a community health necessity (Yadav et al.,2025). The solar energy has received a viable solution but the conventional method of installing them by utilizing a number of photovoltaic (PV) modules and solar thermal (ST) modules tends to meet one significant limitation, and that is the amount of space available on the roof of the hospital or its grounds (Franco et al., 2017). This has been a space constraint which has heightened the rate of interest in integrated solar technologies. One innovation that can provide a solution to this has been hybrid photovoltaic-thermal (PV/T) system. A PV/T collector shown in Fig.1 is a combination of a thermal absorber and a PV module, which offers co-generation of heat and electricity on the same area (Chow, 2010). This design addresses a significant source of inefficiency with traditional PV panels where a small percentage of the absorbed solar energy is used to heat other parts of the system therefore raising cell temperatures and reducing the electrical efficiency by approximately 0.4-0.5 per ^{0}C (Chow, 2010).

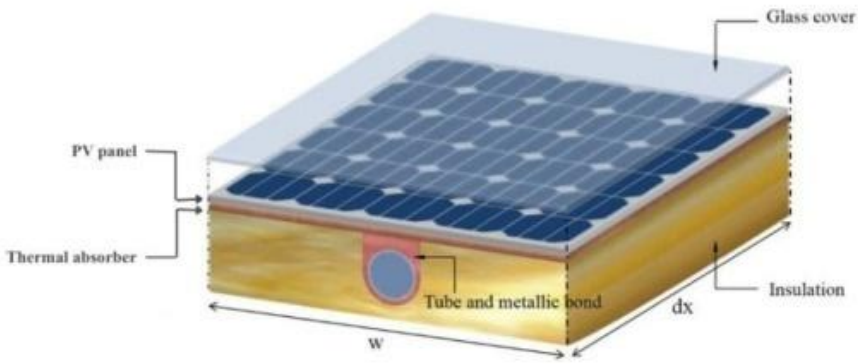

Fig. 1. PVT Collector

PV/T systems can capture this thermal energy fairly effortlessly, cooling the PV cells to ensure electrical output is optimised and can supply useful heat and therefore maximise overall energy collections per square area and also offer a more compact alternative to side-by-side PV and ST systems

(Skoplaki & Palyvos, 2009). Despite the significantly large number of literature on PV/T technology, most of the studies are on residential or general commercial deployment of PV/T technology in domestic needs when it relates to hot water (Ibrahim et al., 2011). These systems have never been tested at high detail, in simulation-based tests, which are distinct to the critical and concurrent electrical-thermal demands of healthcare institutions. This is the gap that this paper aims to fill. The overall objective of the study is to conduct a simulated performance analysis of a hybrid PV/T system which is designed to meet the electricity and sterilisation requirements of one of the healthcare centres. The functioning of the PV / T system is very much contrasted with that of the conventional and large-scale PV-only system that has battery storage. The environment under which this comparative analysis is conducted is the Polysun simulation software that is a proven platform when it comes to designing and simulating solar energy system (Witzig et al., 2010). Polysun will enable the accurate modelling of the system behaviour under a realistic climatic condition in the real world, which will provide reliable data of the key performance indicators. To determine the degree of self-sufficiency, self-consumption fraction, and total useful energy production, this paper will be used to show the feasibility and relative merits of the PV/T system. The outcome of the study will assist in the proper planning of the energy use in the medical sector through the promotion of more efficient and resilient solar energy systems (Ordoñez-Díaz et al., 2021).

2. LITERATURE REVIEW

The fact that the solar energy system is on its way into the building, especially the healthcare facilities, has prompted an array of academic studies, which has resulted in the increasing body of literature that bears testament to its viability, effectiveness and many other benefits. The latest research has been about the opportunities of photovoltaic (PV) systems to meet the electricity demand of hospitals. As an example, Ganguly, and Ghosal (2020) have documented effective application of PV technology in saving power in hospitals, as the solar panels are implemented as a reliable and non-polluting power source (Agrawal & Tiwari, 2011). The use of solar radiation to generate power by PV systems lowers the dependence on the grid and high savings in the operating costs. Additionally, since it was determined by Khan and Muneer (2017) that hospitals which are situated in regions with high solar irradiance, they can fulfill 40%-60% of their electricity demands with the help of PV stations (Kumar et al., 2015). Even though the PV systems can effectively meet the electrical requirements of the hospitals, the hospitals require thermal energy like water heating, sterilization processes, and spaces heating. Conventional thermal generation usually relies on fossil/grid power that makes it more expensive to operate and more harmful to the environment. This contributed to the invention of photovoltaic-thermal (PVT) hybrid system whose objective is to integrate photo-voltaic generation of electricity with thermal energy harvesting system in one integrated unit. Kumar and Baredar (2018) rationale were that PV/T systems can reuse and use the heat generated outside the photovoltaic panels to either heat water or air and therefore fulfill electricity and thermal needs simultaneously (Pang et al., 2020). Also, Siddiqui et al. (2020) emphasized that PVT systems reduce the necessity of installing different systems for solar electricity and thermal ones, make maximum use of spaces, and enhance the overall efficiency of the systems in healthcare facilities (Michael, 2015). Besides energy conservation, the hybrid PV/T systems have been put in place to deliver environmental benefits. PV and PVT systems will reduce the carbon footprint of health care facilities by reducing the consumption of fossil fuel as the energy source in the generation of electricity and heat. As an illustration, Sustainable Energy for All (2020) wrote that the adoption of renewable energy technologies in hospitals could potentially cut emission. Despite the listed advantages, the practical application of PV and PVT systems must also have a high level of consideration to factors like the climate conditions at the area, the spatial sources at hand and the economic feasibility of the application, and the energy usage trends. In the series of research, simulation tools have been employed to consider the performance of PV and PVT systems in several research that are essential to optimizing the design of the system and its effectiveness. Examples of such a tool are Polysun, a popular simulation software that is used to model a solar energy system (Riffat & Cuce, 2011).

3. METHODOLOGY

3.1 Introduction to Integrated System Design

The PV/T System is a hybrid system that is the synthesis of two key renewable energy technologies Photovoltaic (PV) and Thermal (T) system into one hybrid system that produces electricity and thermal energy to a healthcare facility. The system developed in the present study will be used to meet the power needs of a hospital of a total capacity of 97.2 kWp in Santhia, Pabna. The hospital has special energy requirements in the sterilization units and water heaters in addition to the overall electricity that the hospital consumes. The electricity consumption (39,832.45 kWh/year), thermal consumption (6262 kWh/year), and the intention of improving sustainability, energy self-sufficiency, and efficiency of the operations in the hospital will be solved using the hybrid PV/T system. This system will integrate electricity generation and thermal generation requirements in the health care facility. An integration of a hybrid PV/T system in a healthcare organization like a hospital has several major benefits. To begin with, it is environmentally friendly because it reduces fossil fuel and grid electricity. The renewable source of solar energy can also be incorporated in the global agenda in the field of environmental conservation since having a long-term solution can help in reducing carbon emission. The hospital will be operating in a more effective manner with such renewable resources. The hybrid system is the most energy efficient system because it uses PV panels to generate electricity and at the same time, it uses PVT to get thermal energy. The thermal energy plays a very crucial role in the operation of the hospital and in activities that are energy-consuming like sterilization and water heating. In this respect, the hospital will be in a position of experiencing a significant reduction in its energy bill. The ability to generate electricity and thermal power through one mechanism will help the hospital save on its operations cost leading to financial savings in the long run.

3.2 PV and PVT System Overview

3.2.1 Photovoltaic (PV) System

This hospital has 540 solar panels of 180 W capacity that offer 97.2 kWp installed capacity. Such panels are placed where there is strategic position on the rooftop of the hospital and the gross area of this amount is 756 m². The panels are positioned at 0° south to the greatest extent in order to achieve maximum exposure to the sun where the tilt is 45° to achieve the maximum amount of solar energy that the panels would capture throughout the year. The reason behind this design is to ensure that the panels are not receiving less solar radiation, particularly when the sun is at its optimum time and this increases the efficiency of the system.

3.2.2 Photovoltaic-Thermal (PVT) System

Concerning this project, the hospital operates on PVT modules, the nominal power of which is 170 W, and the aperture area is 1.3 m². The nominal power of each of the PVT modules is 0.17 kW (170 W). These modules will greatly convert solar energy into electrical and thermal energy, and this will be a long-lasting solution to the hospital requirements. The heat energy that is gathered is largely used in facilitating the sterilization procedure, and to provide hot water that the hospital operates within its daily operations. Another important inverter in regulating the energy produced by the PVT modules made by Enphase Energy is a PVT inverter (C250-72-2LN-S2-5). The inverter has an AC output of 507 kWh/year, and this is allocated to the supply of electricity to the hospital to have the electricity and thermal power when it is required. In the instance of thermal energy storage, the hospital uses 300-liter hot water storage tanks that consist of stainless steel which are used to stabilize the thermal energy produced by PVT system which is then stored to be utilized at a later stage (Fig 2). In addition, there will be the installation of a continuous flow electric heater whose output is 25 kW, as a supplementary heat generator, that ensures all times there is adequate thermal energy even when solar energy is not sufficient.

It is attributed to the solar pump that must circulate the solar loop fluid that in this instance is a mixture of propylene glycol of the concentration of 40% which enables the circulation of heat. The solar pump will have a flow rate of 105 liters/hours and the consumption of 11.9 kWh/year which is valuable in maintaining the circulation of the heat of the PVT panels into storage tanks and the effective flow of thermal energy. The solar loop fluid is crucially important in guaranteeing the process of heat transfer and the absence of a possibility of freezing or overheating during the operation of the system.

3.3 Site, Load, and Thermal Workflow

The hospital is in Santhia, Pabna (23.966°N, 89.473°E). This area is characterized by tropical monsoon conditions along with wet and dry seasons, and the amount of solar radiation received is 4.5 kWh/m²/day. This is why it is a perfect place to use solar power facilities. This site has a yearly sunshine of about 2,500 hours making it favorable to both Photovoltaic (PV) and Photovoltaic-Thermal (PVT) systems.

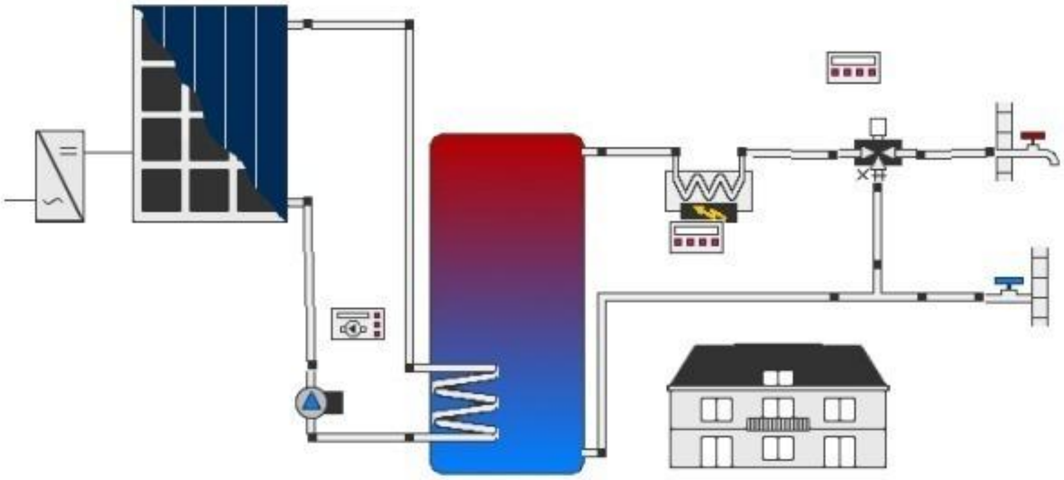

Fig. 2. Photovoltaic-Thermal (PVT) System

Fig. 3. Pabna district, Bangladesh

The resulting energy of these systems will help immensely in meeting the electricity and thermal energy demand of the hospital, which will help with environmental sustainability and energy self-sufficiency.

Nevertheless, there are some site-specific limitations which should be considered. It is most likely that the roof of the hospital shown in Fig. 4 is flat providing the flexibility of placing solar panels. However environmental conditions like dust, temperature changes and rain could cause efficiency of the system to degrade with time. The panels might have dust on them reducing their production and thus need to be cleaned periodically.

Fig. 4. UHC building Santhia

Also, the high temperatures in summer are usually between 32 °C and 38 °C and could affect the performance of the panels adversely leading to losses in the efficiency of the panels.

3.4 Load Requirements

The electrical load of the hospital cuts across a variety of areas, covering the lighting to the more important medical equipments and HVAC systems. The electricity consumption per day is 109.13 kWh which is equivalent to 39,832.45 kWh/year. A large part of this energy is used in lighting with 100 light bulbs (20 W each) running on average of 7.5 hours a day, which equals 15.00 kWh/day. Other contributors to energy consumption of the hospital include medical equipment including vaccination refrigerators, suction machines, and autoclaves. e.g. the autoclaves that use 2000 W take 0.5 hours/day which is 2.00 kWh/day.

The HVAC systems and particularly the air conditioners (5 units, 1500 W each) use approximately 15.00 kWh/day for 2 hours per day. Such systems play an important role in ensuring the comfort and safety of the environment of patients and healthcare staff. To sustain these high energy requirements, the hybrid PV/T will be required to generate enough electricity which will lessen the dependence on the external grid and will provide cost savings.

3.5 Sterilization Load

Sterilization is a key activity in any medical facility, and sterilization workload in the hospital is high. The hospital has 3 sterilization units that utilize 1000 W each, and the total is 17.16 kWh/day. These sterilization units play very significant roles in making sure that medical equipment and supplies are safe to be used. Considering the significance of keeping a hospital in a sterile condition, the units must be efficient. This demand will be fulfilled through the thermal energy produced by the PVT system.

3.6 Thermal Workflow

The PVT system will be used to capture the thermal energy that will be utilized in sterilization and heating of water. The PVT modules generate thermal energy that warms the solar loop fluid that is pumped around the system to provide heat to the hot water storage tank and the sterilization units. The solar pump provides the efficient flow of fluid so that the thermal energy movement without interruptions is ensured by the PVT modules through the fluid to the point of need. The 300-liter hot water storage tank is used to store thermal energy used to supply both medical and non- medical applications in the hospital. There is a constant flow electric heater that can be used as the backup, when there is not enough thermal energy generated, particularly at the times when there is low sun radiation or when the demand is high. The hospital can fulfill its electrical as well as thermal energy requirements by incorporating a PVT system. Not only does this minimize the reliance of the hospital on non-renewable sources of energy but it also acts to reduce the energy bills and promote the sustainability agenda. Finally, the hybrid PVT system is a very effective and efficient measure towards addressing the electrical and thermal energy requirements of the hospital. According to Table 3 Solarzentrum Allgau produces the PVT panel under the name 165p and it is compatible with Trina Solar PV panels delivering 180 W in each.

Table 1. Electrical Load Requirements

Load Description	Quantity	Power (W)	On time (h/d)	Daily-Energy (kWh/d)
Vaccine Refrigerator[a]	2	200	24	9.60
Light[b]	100	20	7.5	15.0
Suction	3	300	0.5	0.45
Ceiling Fan	30	70	8	16.8
Autoclave[c]	2	2000	0.5	2.00
TV/DVD	1	150	6	0.90
Refrigerator	3	300	24	21.6
Centrifuge(large)	1	500	1	0.50
Microscopes	4	50	2	0.40
Laptop	3	65	4	0.78
Blood chemical	1	200	2	0.40
Computer desktop	6	150	6	5.40
Printer	3	100	2	0.60
Exhaust fan	5	80	12	4.80
Air conditioner[d]	5	1500	2	15.0
Surgery spotlight	2	500	4	4.00
Ventilator	2	300	4	2.40
Anaesthetic machine	2	400	3	2.40
Cautery diathermy	1	1000	2	2.00
Pulse oximeter	5	20	2	0.20
X-ray machine[e]	1	2000	1.2	2.40
Water pump	1	1000	1.5	1.50
			Total	**109.13 (kWh/d)**

[a]Operates continuously for vaccine preservation.
[b]Lighting includes indoor and essential operational areas.
[c]Autoclaves operate intermittently based on sterilization demand.
[d]Air conditioner usage reflects average daily operation.
[e]X-ray machine operates intermittently depending on patient load.

Table 2. Sterilization Load

Load Description	Quantity	Power (W)	On-time (h/d)	Daily Energy (kWh/d)
Sterilizer Equipment [a]	3	1000	3.28	9.84
Water Heater [b]	2	1500	2.44	7.32
				Total 17.16 (kWh/d)

[a]Sterilizer equipment operates intermittently depending on daily medical procedures.
[b]Water heater is used for preheating and supporting sterilization processes.

The system is also fitted with battery Varta storage GmbH, 6.1 kWh total energy storage and inverter model PVS300-TL-3300W-2-[5681] made by ABB. This enables the reliable provision of the energy requirements of the hospital, thus making the facility more sustainable and energy independent, as well as decreasing the operational expenses and carbon footprint of the hospital.

3.7 Introduction to Polysun Simulation Software

Polysun is an advanced dynamic simulation software, specifically designed to model, design and optimize a renewable energy system, including hybrid photovoltaic-thermal (PV/T) system. In this research, version 11.28.27 was used. Its primary advantage is the use of simulation as a method that incorporates a combination of detailed component behavior, site-specific weather conditions and definition of load profiles to predict the behavior of the system with a very high level of reliability. Polysun was selected in the current study because it has a high capability of simulating electrical and thermal performance of a PV/T collector in an integrated system setting. The representation of the most important components, including the specific PV/T collector, the storage tank, pumps, and the backup electric heater, was also possible due to a large set of tested elements in the software.

Table 3. Components price

Component Name	Manufacturer	PV System (USD)	Hybrid PV/T System (USD)
PV Modules (97.2 kWp @ $0.25/Wp [a]	Solarzentrum Allgäu	$24,300	$24,300
Battery Storage (6.1 kWh) [d]	Varta Storage GmbH	$3,660	$3,660
Inverter & Protection [c]	ABB.	$20,776	$20,776
Thermal Unit (PV/T Additional Cost) [d]			$30,240
Balance of System (BoS) & Installation [e]		$21,027	$21,027
Subtotal [f]		**$69,763**	**$100,003**
Contingency (5%) [g]		$3,488	$5,000
Total Initial Investment [h]		**$73,251**	**$105,003**

[a]Cost includes photovoltaic modules based on installed capacity.
[b]Battery system used for backup and grid support.
[c]Includes inverter, protection devices, and associated accessories.
[d]Additional cost for thermal collectors and related components in the PV/T system.
[e]Includes mounting structures, cabling, and installation labor.
[f]Subtotal before contingency allowance.
[g]Contingency included to account for unforeseen expenses.
[h]Total capital investment required for system deployment.

According to Fig 6 the software gave a virtual test bed to experiment with the real functionality of the system by introducing the correct climatic data on the city of Santhia and defining the special electrical and sterilization thermal load in the healthcare facility. Key performance indicators such as the PV AC yield (Q_{inv}), solar thermal energy sent to the system (Q_{sol}), solar fraction (SF_n) and self-consumption were obtained as the annual results of the simulation. It is an intensive comparative analysis of the technical

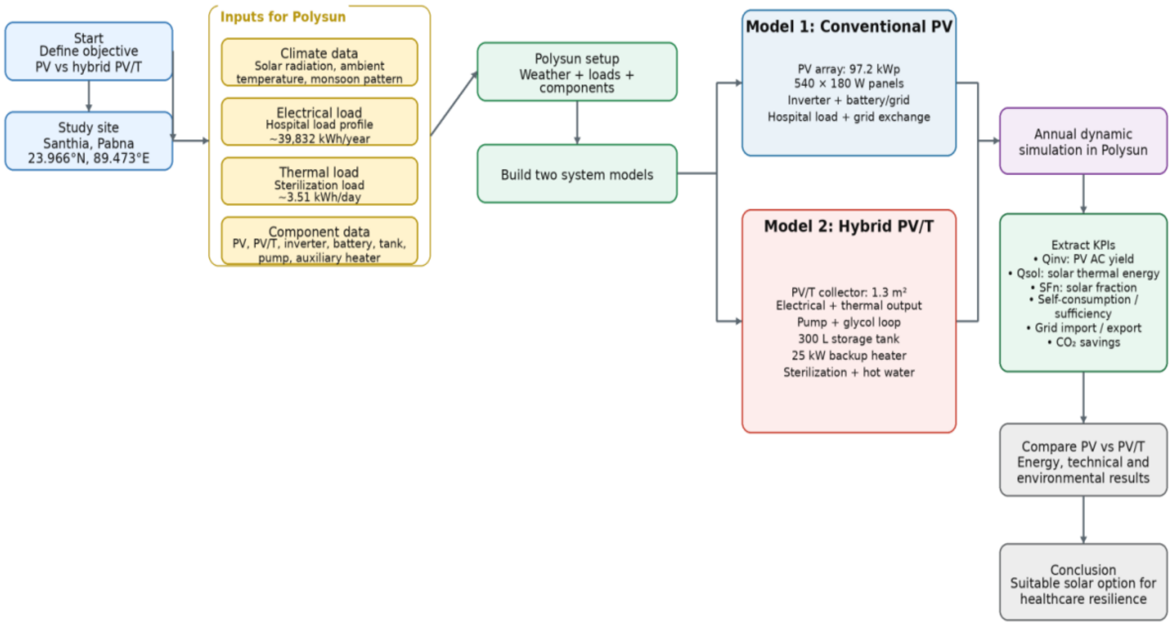

Fig. 5. Polysun Simulation Workflow for PV and Hybrid PV/T System Assessment

The methodological workflow entailed designing two comparisons of system architecture of a PV system and hybrid PV/T system in a software set up. feasibility and energy of implementing a hybrid PV/T system to enhance the energy resilience of healthcare infrastructure, founded on simulated and data-driven information. The simulation used a location-specific hourly weather dataset for Santhia, Pabna, including solar irradiance and ambient temperature data. The system components were modelled using the selected component specifications, including the Solarzentrum Allgäu 165p PV/T collector, Trina Solar PV modules, a Varta 6.1 kWh battery storage system, and an ABB PVS300-TL-3300W-2-[5681] inverter. The system was simulated using an hourly time step to capture variations in solar resource, electrical demand, thermal load, and component operation throughout the year. The simulation was considered converged when the annual energy balance was achieved within the numerical tolerance of the Polysun solver, with no unresolved calculation errors or unstable component states.

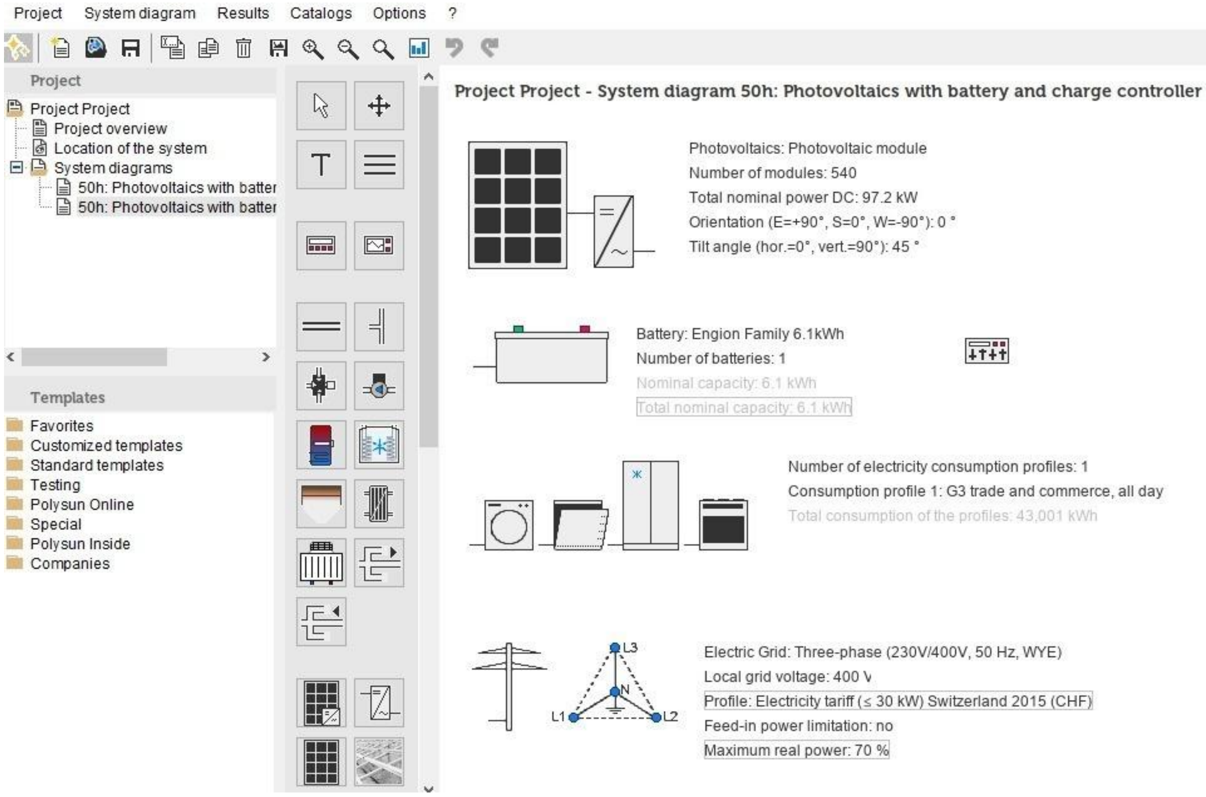

Fig. 6. PolySun Interface

4. RESULT

4.1 Total Electricity Consumption of the Healthcare Facility

The medical institution has a consistent rate of 3,500-3,700 kWh of energy consumption every month, which is typical of 24/7 facilities (Fig.7). This constant demand generates a basic discrepancy between the variable generation of the PV system and the requirement of a consistent demand, leading to a low 17% self-consumption rate because the facility is unable to absorb peaks in production.

Such dynamic requires grid imports not only at periods of low generation, but also in times of high export in periods of surpluses, which characterizes the bi-directional nature of the system as an energy consumer and a decentralized producer of power

4.2 PV System AC Energy Production (One-Month Detail)

According to Fig 8. the PV system of 97.2 kWp has a specific seasonal pattern of generation, with the annual AC output reaches a peak of 13,685 kWh in March and the minimum of 7,528 kWh in July. The system has been shown to have an ideal performance in spring (March-April) and autumn (September-October), when the solar radiation is

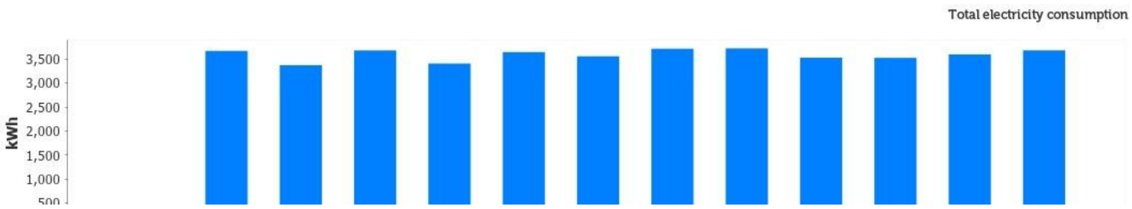

Fig. 7. Total Electricity Consumption

good and the temperatures are not too high or too

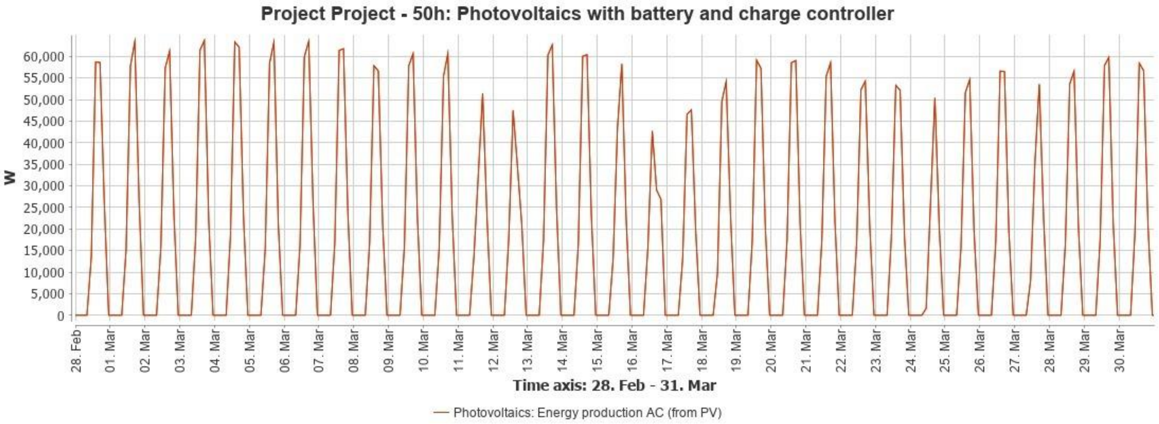

Fig. 8. PV System AC Energy Production

low. Noteworthy, however, is a great drop in production during summer monsoon months (June-July), as much lower solar irradiance to continued cloud cover lowers production by about 45% of the spring levels.

This seasonal fluctuation causes the need to have strategic energy management whereby excess capacity during high-yield periods is used to export power into the grid, and the huge reduction in the generation during the monsoon periods demands a higher level of grid reliance, making the provision of a complementary energy storage or backup systems to maintain the continuous power supply to the healthcare facility.

4.3 PV System Annual Energy Balance

According to Fig 9. there is a demonstration of the net-energy export profile whereby its high 146,811 kWh annual DC energy output greatly exceeds the

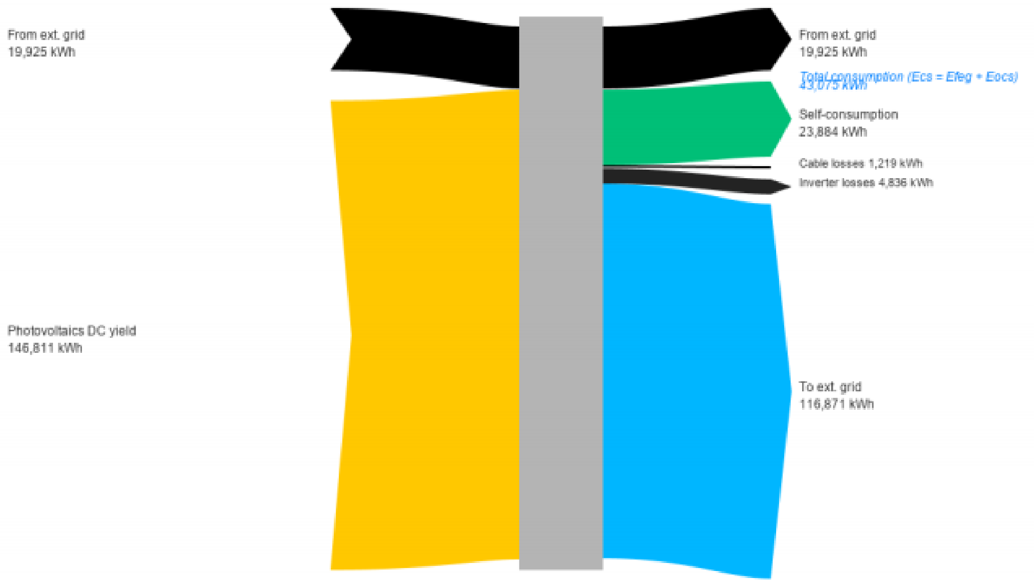

Fig. 9. PV System Annual Energy Balance

consumption requirement of the facility. The system transfers 116,871 kWh to the grid which is 79.6% of the total DC output of the system and retains 23,884 kWh of that transferred to self-consumption in the facility, creating a 16.3% self-consumption ratio.

The efficiency of the system is ensured by the low losses: the cable losses are 0.83% (1,219 kWh) and the inverter losses are 3.3% (4, 836 kWh) of DC yield. Verification of energy balance shows that grid imports (19,925 kWh) are used to supplement solar self-consumption in porting the constant demand of the load in the facility, with most of solar production being used to power the grid, which makes the main role of the system a decentralized power.

4.5 System Performance

4.5.1 Performance Ratio (PR) PV

The 97.2 kWp PV system will operate at a good level with 76.9% Annual Performance Ratio (PR). Seasonal analysis in Fig 10. demonstrates that PR values (78-80%) are greater when the seasons are colder and a moderate decrease (74-76%) is observed during summer, which can be attributed largely in part to efficiency losses to PV modules caused by temperature variations. There are also additional losses that happen during monsoon

system via the -0.4% to -0.5%/°C temperature characteristics of silicon cells which significantly degrade the power of the system in high summer even when maximum sun is available.

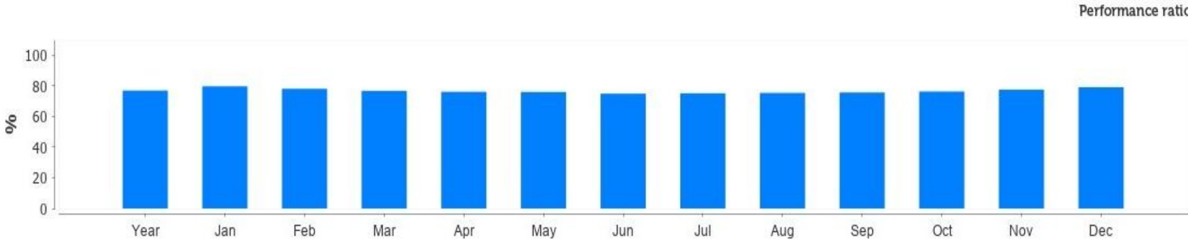

Fig. 10. Performance Ratio (PR) PV

months due to environmental conditions such as humidity and soiling.

The steadiness of the PR indicates that the operation of the system does not cause serious technical problems, and the dynamics of its performance are very similar to the data on the temperature of the modules and the anticipated seasonal effects.

4.5.2 PV Module Temperature

The seasons of photovoltaic module working temperatures indicated in Fig 11. have clear annual distribution with the highest during summer (April-

As a result, the best AC generation is in the spring and autumn months when the temperature-irradiance balance is optimal in promoting conversion efficiency. This thermal constraint explains the operational benefit of hybrid PV/T systems in which active heat removers ensure that cell temperatures stay low and stable, which essentially addresses the loss of efficiency when cells are challenged by high-stress conditions and helps ensure hotter-to-colder changes in electrical performance when cell temperatures change in response to changing climatic conditions.

4.6 Energy Production and Demand

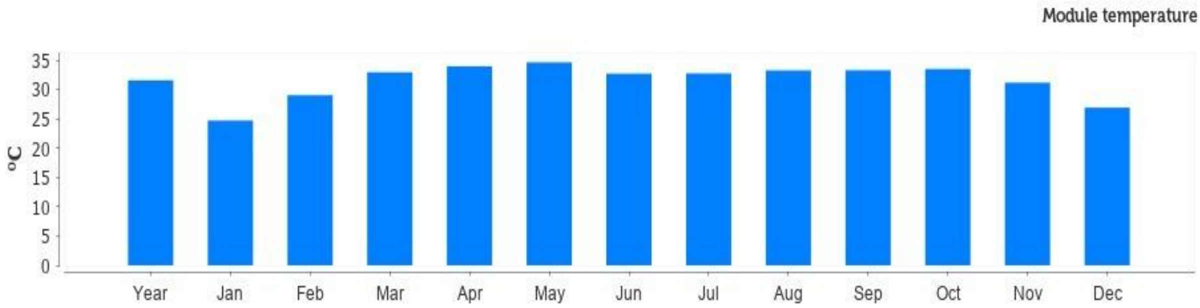

Fig. 11. PV Module Temperature

September) because of the combination of high solar irradiance levels with high ambient temperatures in the climate of Santhia. This thermal characteristic directly controls the efficiency of the

4.6.1 PVT Collector: Energy Production AC (from PV)

The yearly data from the Energy Production AC (from PV) Fig. 12 shows that there are some

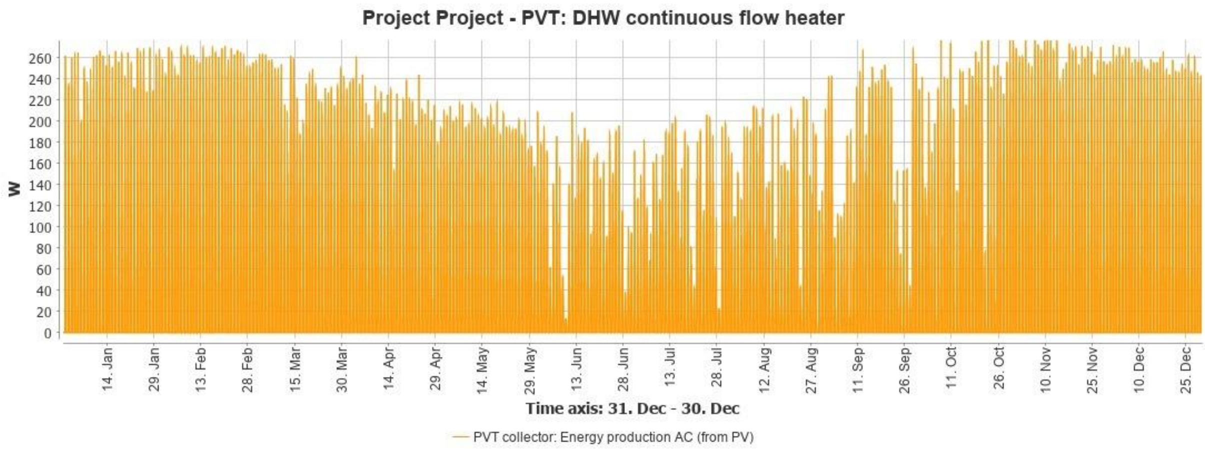

Fig. 12. PVT Collector: Energy Production AC (from PV)

significant trends and observ12 showshe overall energy generated by the year is 507 kWh which averaged 38.25 kWh every month. A more detailed analysis of the separate months reveals that the system is working especially well in November and December with 52 kWh output in each of the months. Such months are the most active months of power generation implying that the environmental conditions like availability of sunlight or weather conditions are favorable during such months.
The minimum energy production on the other hand is in June where the energy is only 29 kWh and in July when the energy is only 30 kWh. This significant decrease over the summer months is an indication of a seasonal drop in performance which is probably caused by a combination of factors like cloud cover, increased temperatures or alterations in the angle of incidence of the sun or a combination of both. The system demonstrates a decrease in the energy production rate gradually beginning with April (43 kWh) till June, the minimum point in the year. This mid-year dip is then succeeded by a gradual recovery in the second half of the year where production gradually boosts in July up to the high level of production in November and December.

4.6.2 PVT – Energy Demand

The PV/T system meets a steady annual thermal demand of 6,262 kWh of healthcare sterilization, where the monthly use is a steady 500-600 kWh. According to Fig 13. The fluctuations in the various seasons show the differences in the inlet water temperature and the slightly higher demand during the winter because the supply water is colder.
This continuous high-priority load leads to the 15.3% solar fraction with 1.3 m² collector area requiring extensive assistance by the 25-kW auxiliary heater to guarantee sterilization capacity is available always. The system design has been more inclined towards the reliability of its operation rather than energy autonomy, and the powerful auxiliary heater ensures the continuous service at times when the solar is inaccessible, which shows a balanced approach to both renewable integration and the necessity to meet healthcare services need.

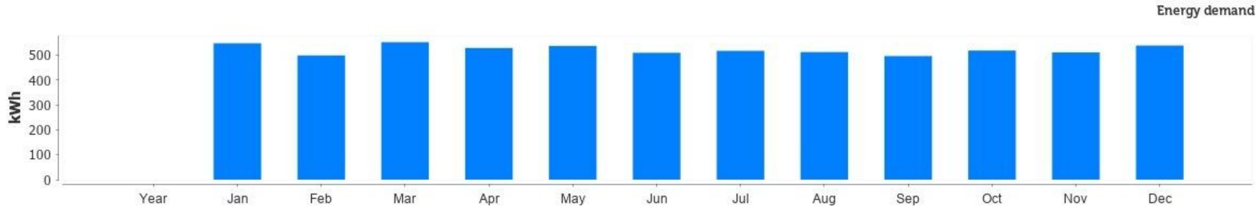

Fig. 13. PVT – Energy Demand

4.7 PV/T System Annual Energy Balance

The annual energy balance of the PV/T system given on Fig 14. demonstrates the grid-supported nature of the system where the electric auxiliary heater uses 5,932 kWh of electricity over 983 kWh solar thermal input - it creates a distinct 1:6 ratio between renew-able and grid energy inputs that matches the solar fraction of 15.3%. The system is effectively provides 5,852 kWh to fulfill the sterilization needs at the cost of considerable thermal dissipation: 1,040 kWh as the heating of the indoor space and 35 kWh as the external loss. This is indicated in the remarkably low pump consumption of 11.9 kWh which shows an optimized hydraulic design.

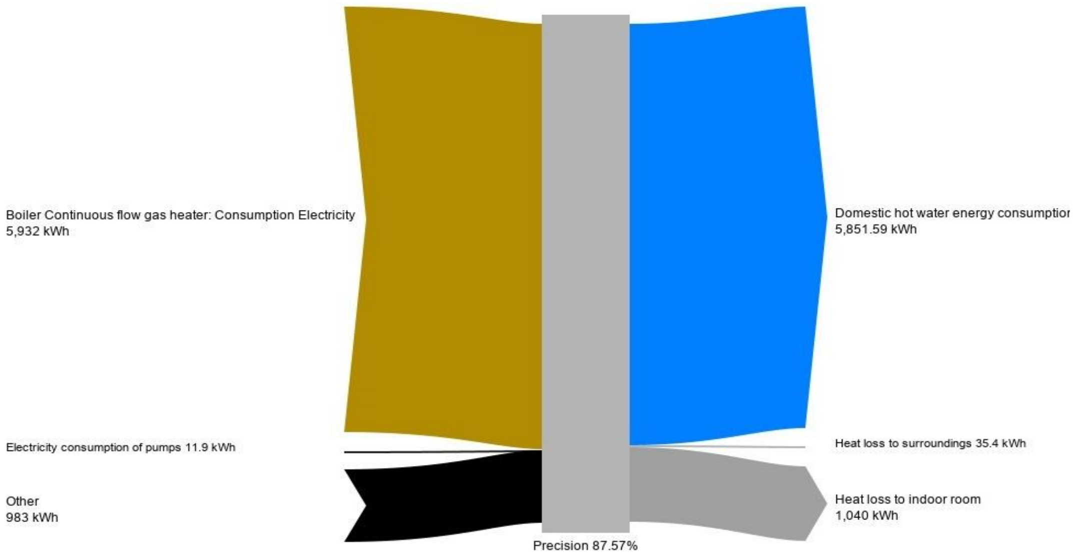

Fig. 14. PV/T System Annual Energy Balance

This energy profile explains why the auxiliary heater has been a crucial factor in ensuring continuous sterilization services with solar thermal energy offering good but auxiliary support to the main grid-based system.

4.8 Solar Thermal Performance and System Energy Balance

The seasonal variation of monthly useful solar thermal energy (Q_{sol}) to domestic hot water system by the PV/T collector as shown in Fig. 15 is very conspicuous and is directly related to climatic conditions at Santhia. The thermal yield of the system has a definite bimodal distribution, with the highest yield during the cooler months; the highest yield was recorded during the months of November (103 kWh) and December (95 kWh). This is high productivity period and is associated with good solar thermal collection conditions: high solar irradiance and low ambient temperatures, which promotes the efficiency of the heat transfer process because it maximizes the temperature difference between the collector and its surroundings. In contrast, there is a major slump in the summer with the low point of only 56 kWh in June and July, which is a direct result of such heavy cloud cover and diffuse irradiation by the monsoon season that reduces the amount of direct solar energy available drastically. This huge range of Q_{sol} (56 to 103 kWh or 84% over trough to peak) is the root cause of the solar fraction of the system fluctuating between a high of 19.4% in November and a low of about 10.6% in July. With a small variance of fluctuations in the month-to-month output (±5%), the PV/T system provides a stable yearly useful energy production of 5,852 kWh of electricity with consistent sterilization capability despite seasonal shifts in the sun. The highest efficiency of the system is observed in the transitional months of March (516 kWh) and December (504 kWh) when the optimum between the gain with solar thermal energy and the auxiliary heating is recorded (Fig. 16). This operational profile is an example of a successful system integration, in which strategic support by auxiliary systems is used to counteract variations in sun radiance so that thermal output remains constant, but uses favorable thermodynamic conditions of moderate seasons but not the optimum irradiance periods.

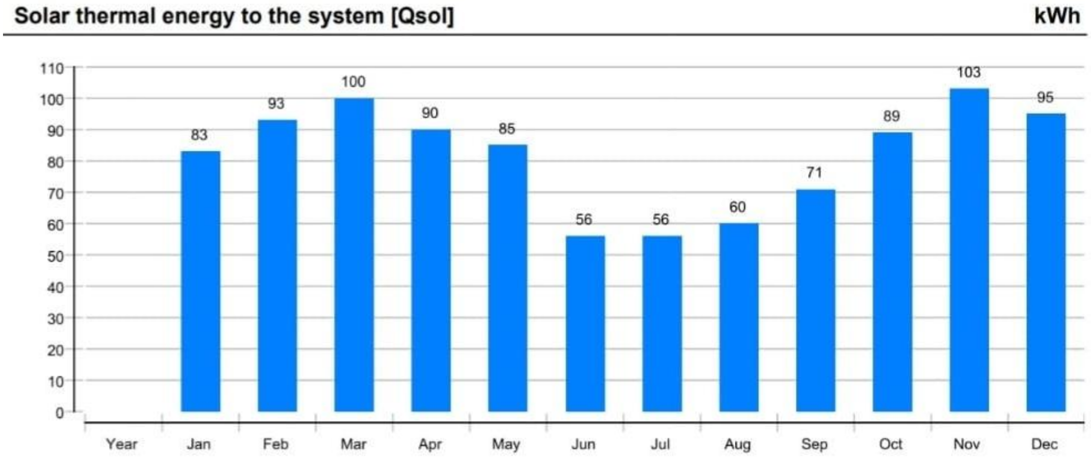

Fig. 15. Solar thermal energy (Q_{sol})

4.9 Solar Fraction (PVT)

The solar fraction of the PV/T system has a strong seasonal fluctuation with a high peak of 19.4% in November and high-performance levels (15-19%) during the period between October and April (Fig. 17). This high efficiency stage enjoys the optimum thermodynamic conditions that are characterized by great solar irradiance and lower ambient temperature that contributes to the high level of heat transfer.

Summer monsoon, in contrast, produces a specific operation trough, where the solar fraction decreases to 10.6% in July and 10.9% in June because of significantly decreased direct solar radiation under the constant cloud cover. These counteracting seasonal effects combine to constitute the annual solar fraction of the 15.3% system which is a weighted compromise between optimal collection conditions in

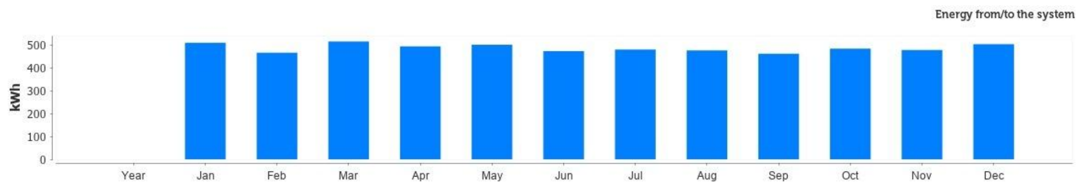

Fig. 16. Energy from /to the system

cooler periods and performance tied by weather limitations in monsoon periods, and which continually provides the necessary sterilization capacity through strategic auxiliary assistance.

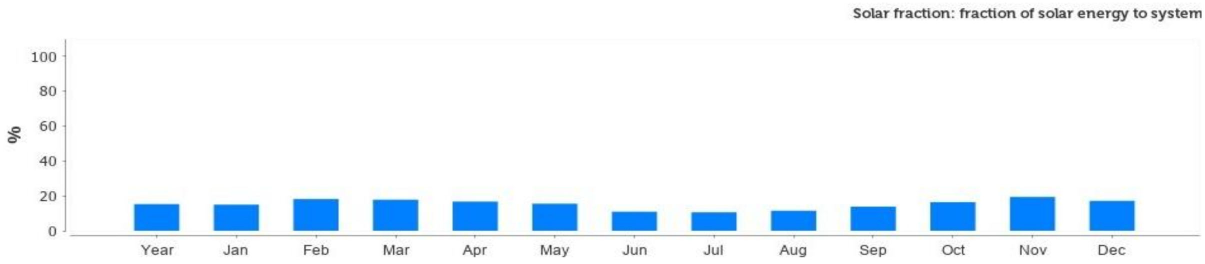

Fig. 17. Solar Fraction (PVT)

4.10 Temperature Performance of PVT Collector

Through the thermal behavior analysis of the PV/T collector, a highly efficient and stable system is found (Fig. 18). The maximum daily range is stable at 40.4°C to 46.2°C per annum. There is a recognizable seasonal trend, when the highest temperatures are seen in the autumn months (October: 46.2°C, November: 46.1°C) when the conditions of high irradiance and cooler ambient temperatures are the best to maintain the efficiency of heat transfer.

Fig. 18. PVT collector -Daily maximum temperature

The daily variations in the operational temperature profile shown in Fig. 19 indicates typical sawtooth shape of peaking in daytime and falling in the night indicating active heat extraction by the solar loop. This thermal control is highly beneficial, not only it guarantees consistent thermal output, but also improves electrical performance as PV cells are kept at moderate temperatures and as a result, prolongs the performance of a photovoltaic module that has a tendency of reducing under hot weather conditions, which is characteristic of traditional photovoltaic modules. There were no extreme stagnation temperatures which proves efficient design of the system and constant use of heat.

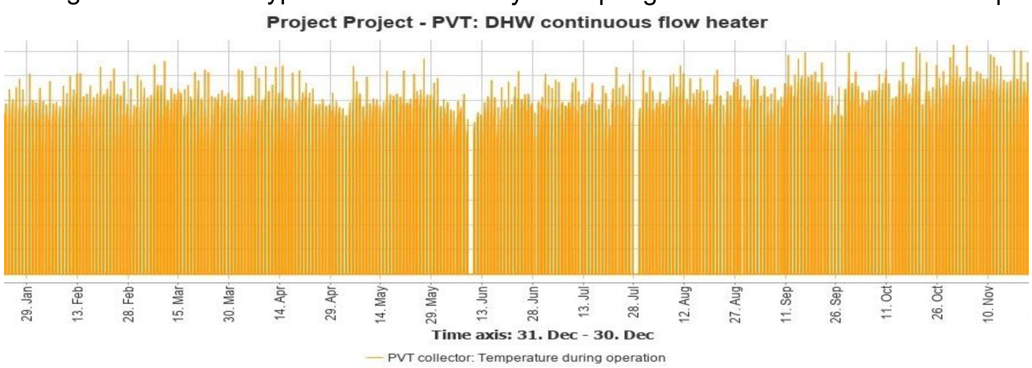

Fig. 19. PVT collector temperature during operation

5. Environmental Impact

5.1 Analysis of CO_2 Savings from PV and PV/T System

The 97.2 kWp PV system shown in Fig. 20 provides a significant reduction of CO_2 of 75,501 kg per annum. It has a strong energy production monthly savings pattern with major efficacy peaks in high yield spring and falls months accompanied by significant trough in summer months of monsoon season. This highlights its role as a large-scale decarbonization asset. On the other hand, according to Fig. 21 the PV/T system can give an annual reduction in CO_2 of 555 kg due to the dual generation of energy.

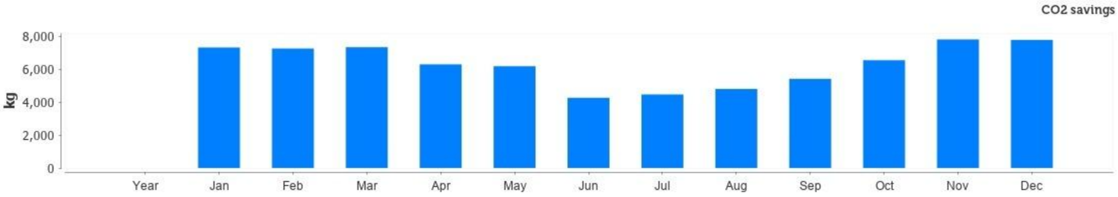

Fig. 20. CO2 savings of PV system

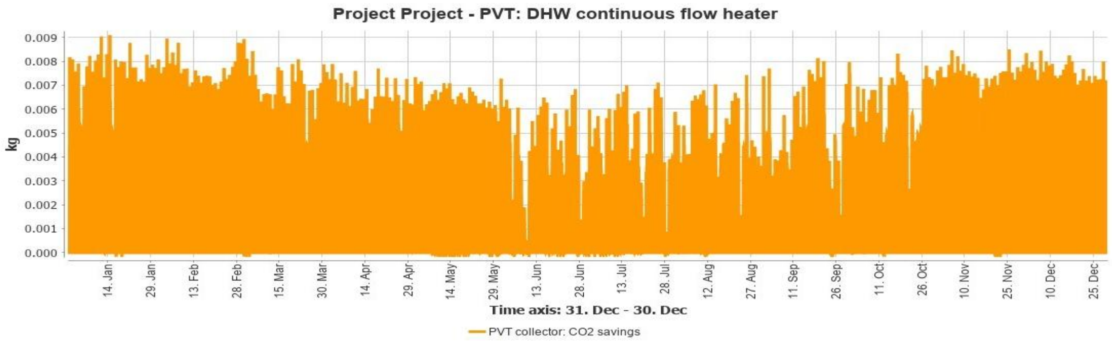

Fig. 21. PVT-DWH continuous flow heater

5.2 Energy Supplied to External Grid

The 97.2 kWp PV system is a major decentralized power generator with a notable seasonal profile of 116,871 kWh/year with peaks in the spring and fall months and lows in the summer monsoon. The export of power earns the company a significant amount of revenue of about $11,220 per year under net metering which is an important source of finance to the project. The fact that the 6.1 kWh battery has little influence on this pattern of export validates its use as a grid stabilizer and critical backup system.

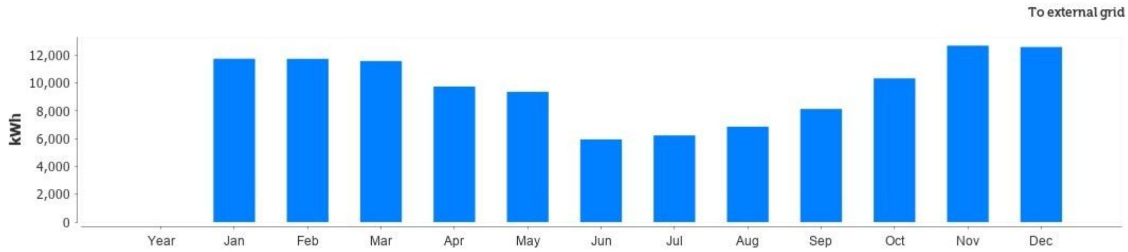

Fig. 22. Energy Supplied to External Grid

6. ECONOMIC ANALYSIS

To evaluate the economic feasibility of the two renewable energy systems that have been offered in the healthcare facility in Santhia, the life cycle economic analysis was carried out in detail. This comprises the disaggregation of the initial capital investment, operation and maintenance (O&M) costs, gross metering profits as well as a life cycle saving (LCS) analysis of the 25 years system life.

6.1 Initial Capital Investment

According to Table 3 the overall initial cost of the traditional photovoltaic (PV) system is estimated at $73, 251 which comprises of PV modules (97.2 kWp at $0.25/Wp, summing up to $24, 300), a 6.1 kWh battery storage system ($3660), inverter and protection units ($20776), balance of system (BoS) and installation costs ($21027) and contingency allowance of 5% ($3488). Conversely, the hybrid photovoltaic-thermal (PV/T) system has a very high capital cost of $105,003. Although the price of PV modules, battery storage, inverter, and BoS would be the same as that of PV system, the introduction of a thermal collector unit would incur an extra cost of $30240. There is also an additional amount of 5% contingency ($5,000). This causes the hybrid system to be 43.3% more costly in the initial cost with added thermal functionality being the main reason.

6.2 Net Metering Profit

PV/T is the most sustainable way to go in terms of the realization of energy-secure, low-carbon healthcare systems of developing countries. The traditional PV system has good potential for generating revenue via net metering. It sells a surplus of 116, 871 kWh in the grid each year. This yields a net profit in metering of $11,687 a year with a conservative feed-in tariff of $0.10/kWh. This is equivalent to $292,175 cumulative revenue on exports of electricity over a 25-year span.

6.3 Life Cycle Costing (LCC) and Operational Expenses

Both systems will face recurrent costs in the maintenance process over a lifespan of operations, which extends to 25 years. Given an O&M rate of 1.5% per annum of the capital cost: The total O&M of PV system in 25 years is $27,469. The 25-year O&M of the hybrid PV/T is $39,376. Combining these with the original investment the total life cycle cost will be:
PV system: $73,251 + $27,469 = $100,720
Hybrid PV/T system: $105,003 + $39,376 = $144,379

6.4 Life Cycle Savings (LCS)

The PV system has not only got the advantage of net metering but is also considerably saving grid electricity power. The PV system achieved 60% self-sufficiency, with approximately 23,884 kWh/year of PV-generated electricity consumed on-site, thereby reducing grid electricity purchases.
Annual electricity bill saving =$14,038/year
25-year electricity bill saving = $350,950
based on an average grid rate of electricity of $0.12/kWh, and 25-year saving. The net present value of the PV system life cycle is:
$350,950 (savings) + $292,175 (net metering) = $643,125

7. CONCLUSION

The study aimed to determine the possibilities of solar-based energy systems to increase sustainability and resiliency in healthcare facilities through a comparison of a 97.2 kWp photovoltaic (PV) system and a hybrid photovoltaic-thermal (PV/T) system using Polysun simulation software. The research was centered on how these systems could supply power and heat needs, especially for sterilization, in a healthcare facility in Santhia, Pabna, Bangladesh. The results show that the overall performance of the PV system was very good, with a system self-sufficiency of 53.6% and annual energy production of 146,811 kWh, along with a very high surplus capacity supplied to the grid. This not only helps to guarantee a stable energy supply but also reduces CO_2 emissions by about 75,501 kg annually, making it a very effective and economical option for large-scale carbon reduction and long-term cost savings. On the contrary, the hybrid PV/T system was able to generate both electricity and useful thermal energy, satisfying approximately 15.3% of the thermal requirement of the facility and supporting stable operation during sterilization periods. Even though its overall CO_2 reduction of 555 kg/year and economic returns were relatively lower, its capacity to produce both heat and power within a smaller area makes it a reliable and compact solution for healthcare operations, especially in areas with unreliable grid infrastructure. In short, the study finds that the PV system is the better option in terms of economic performance and emission reduction, while the hybrid PV/T system provides significant value in terms of energy security, thermal support, and operational reliability. Therefore, an integrated or site-specific solution that combines the high energy productivity of the PV system with the thermal stability of the PV/T system can offer a more resilient, sustainable, and practical energy strategy for healthcare facilities in Bangladesh.

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