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Optimized Solar-Assisted Clean Steam Generation: Advancing Sustainability in Healthcare Infrastructure

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Abstract - Buildings in the healthcare industry are significant contributors to global energy consumption and greenhouse gas emissions. Hospitals, in particular, require a large amount of steam for various purposes, which is currently generated by fossil fuel-based heaters and boilers. One of the essential streams in hospitals is hygienic steam, also known as clean steam. This study aims to contribute to the sustainability of healthcare buildings by proposing and developing an innovative solar-driven steam generator to supply clean steam to hospitals. The proposed system is designed, optimized, and economically assessed for two case study hospitals in Denmark and Sweden. During the optimization process, two decision variables were taken into consideration. These were the number of solar panels in parallel, and the number of solar panels in series. The goal of the optimization process is to maximize fuel savings. Based on the optimization results, the most optimal solar arrangement for the hospital in Denmark consisted of 30 parallel panels and 1 series panel. Similarly, the ideal solar arrangement for the hospital in Sweden was determined to be 10 parallel panels and 3 series panels. By implementing the optimized arrangements, the Denmark and Sweden hospitals saw annual fuel savings of 24.71 and 27.26 tons, respectively.

Keywords**:** Clean steam generator; Sustainability; Hospitals; Solar collectors; Techno-economic analysis; Multi-objective Optimization

1. Introduction

Buildings significantly contribute to climate change due to their high energy, water, and resource consumption, increasing greenhouse gas (GHG) emissions [1]. Hospitals require a lot of energy, especially for clean air and steam, making them one of the largest energy-consuming facilities. To meet the 2050 net-zero carbon policy, sustainable strategies must be adopted. Hospitals contribute significantly to greenhouse gas emissions due to their reliance on non-renewable energy sources, making them the second-largest energy-intensive commercial type [2].

Steam generation using fossil fuel boilers contributes significantly to greenhouse gas emissions. Transitioning to renewable energy sources for steam generation can help mitigate these emissions. Studies have explored using renewable energy for steam generation, with direct steam generation solar systems showing immense potential for reducing fossil fuel dependency. Dirker et al. [3] conducted a comprehensive review article exploring the current understanding and predictive capabilities of thermal-energy processes in direct steam generation solar systems, which include flow boiling, flow condensation, and thermal-energy storage. Their findings suggest that combining solar energy with direct steam generation is a promising technology that can help reduce dependence on fossil fuels. This technology has immense potential for power generation, particularly in industries that rely heavily on process steam. Saini et al. [4] conducted a comparative analysis of two decarbonization technologies for industrial process heat supply: electricity-driven steam-generating high-temperature heat pumps (HTHP) and solar parabolic trough collectors (PTCs). They found that a well-designed PTC system can achieve cost parity with HTHP in most analyzed locations by optimizing solar fraction, considering the levelized cost of heat (LCOH). In another study, Ghodbane et al. [5] performed a transient numerical simulation on a linear Fresnel solar reflector to produce superheated water steam for power plants. The primary focus of their study was to assess the optical and thermal efficiencies of the linear Fresnel solar reflector when the heat transfer fluid mass flow inside the copper absorber tube is

0.045 kg/s. The simulation results show the potential benefits of investing in this type of steam power plant, especially in desert areas with abundant solar energy.

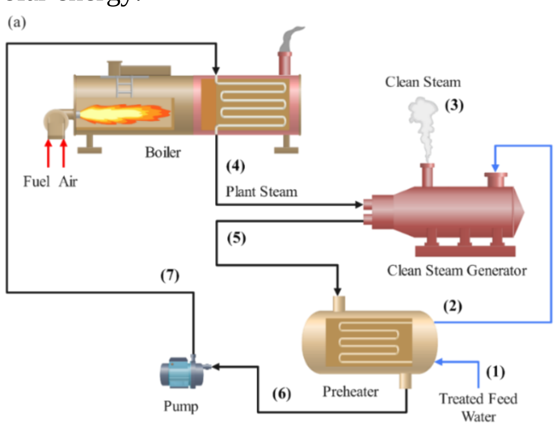
Hospitals generate significant greenhouse gas emissions through their steam generation process. Despite previous research, renewable technologies for sustainable steam generation in hospitals have not been implemented. This poses a risk to public health as conventional fossil fuel-based systems release substantial GHG annually.

This study proposes a new system for generating clean steam with solar energy. The system is evaluated by modelling and analyzing two hospitals, Frederiksberg Hospital in Copenhagen, Denmark, and Falun Hospital in Falun, Sweden. The proposed system is designed, optimized, and economically assessed for these two case study hospitals. During the optimization process, three decision variables are considered: the number of solar panels in parallel and, the number of solar panels in series. The optimization process aims to maximize the fuel savings. This optimization is performed under the constraint that no more than 2500 m^2 of land is used. Furthermore, the total number of panels connected in parallel or series configurations is restricted to 30. This research provides valuable insights into the potential benefits and practicality of implementing solar-assisted CSG systems in hospitals. This study paves the way for a transition to renewable CSG systems and a more sustainable future.

2. System Description

The CSG is a device that generates clean steam using treated water and plant steam (Figure 1a). It is used in hospitals and healthcare sectors for various applications, including humidification and sterilization. The CSG comes in varying capacities and is manufactured by different companies. The system works by heating the treated water using plant steam in a shell and tube heat exchanger, converting it into saturated steam. The condensed liquid water is pumped and sent to a boiler to regain its temperature and pressure before returning to the CSG. The boiler releases combustion gases, contributing to greenhouse gas emissions.

The solar-assisted CSGS (Figure 1b) operates by transferring energy from hot working fluid to water. The fluid (Therminol VP-1) is heated in the solar PTC field and directed to the heat exchanger. If the temperature is insufficient, it enters the boiler for more energy. This plan reduces greenhouse gas emissions from the boiler and powers hospitals' clean steam generation process using solar energy.



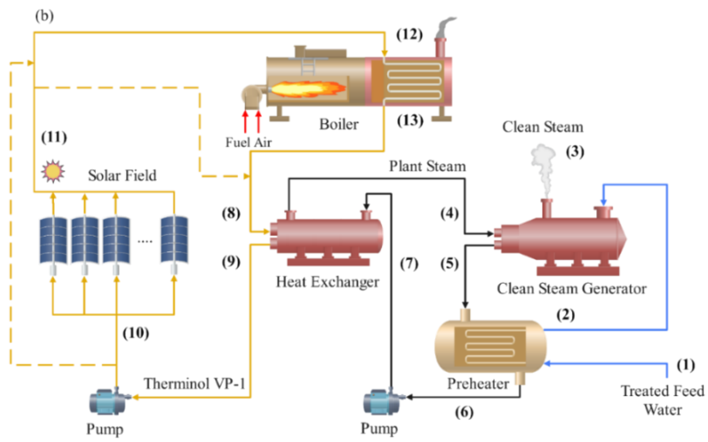


Figure1: Schematic diagram of (a) a conventional CSGS and (b) a solar-assisted CSGS.

The study suggests using meteorological data from Falun Hospital in Sweden and Frederiksberg Hospital in Denmark to implement solar-assisted CSGS. The solar irradiance in these countries is relatively low compared to other European countries, with an average horizontal irradiance of 101.4 W/m2 in Falun Hospital and 104.5 W/m2 in Frederiksberg Hospital. The maximum recorded horizontal irradiance at Falun Hospital was 754.5 W/m2, while at Frederiksberg Hospital, it was 750.6 W/m2. Frederiksberg Hospital tends to have slightly higher temperatures and wind speeds than Falun Hospital. For this study, the Mueller CSG with a clean steam capacity of 907 kg/h was used to create saturated clean steam at a pressure of 4 bar. A flow of 1194 kg/h of saturated plant steam at a pressure of 7 bar is required to generate this clean steam. Additionally, both hospitals are assumed to operate for 18 hours, from 4 A.M. to 10 P.M.

In the conventional steam generation system, a boiler that burns fossil fuels produces the required heat. On the other hand, in a solar-assisted steam generation system, a secondary heat exchanger generates steam. The secondary heat exchanger uses the boiler and solar fields as energy sources. The solar field consists of n_p parallel and n_s series LS-2 parabolic trough solar collectors that provide energy to the secondary heat exchanger. This system reduces the workload of the fossil fuel boiler when sufficient solar energy is available. Technical data for the conventional and solar-assisted systemsare listed in Table 1. Additionally, detailed information on the collector characteristics is listed in Table 2.

Table 1 Operating conditions of conventional and solar-assisted CSGSs.

State Point	Description	Value
1	The inlet temperature of the treated water into the preheater	300 K
2	Outlet temperature of the treated water from the preheater	373 K
3	Clean steam pressure at the exit of the CSG (saturated conditions)	0.45 MPa
3	The mass flow rate of clean steam at the CSG exit	0.252 kg/s
4	Plant steam pressure at the inlet of the CSG (saturated conditions)	0.7 MPa
4	The mass flow rate of plant steam at the CSG inlet	0.332 kg/s
7	Exit temperature of plant liquid from the pump	430 K
9	Exit temperature of Therminol VP-1 from the heat exchanger	444 K

Table 2 Characteristics of the PTC used in the present research.

Parameter	Quantity
Length (L)	7.8 m
Aperture Width (W)	5 m
Receiver inside diameter (D_i)	66 mm
Receiver outside diameter (D_o)	70 mm
Glass cover diameter (D_g)	115 mm
Aperture area (A_a)	38.45 m^2
Receiver area (A_r)	1.72 m^2
Glass cover area (A_g)	2.82 m^2
Rim angle (φ)	70°
Focal length (F)	1.84 m
Concentration ratio (C)	71
Receiver emittance (ε_r)	0.14
Glass cover emittance (ε_g)	0.95
Number of collectors per row	n_s
Number of rows of collectors	n_p
The mass flow rate of working fluid per collector (kg/s)	0.5
Total mass flow rate of working fluid (kg/s)	$0.5\times n_p$

3. Mathematical modeling

3.1. Conventional System

The following equations are used to determine the steam state of the plant at the outlet of the CSG.

$$h_5 = h_4 - \frac{\dot{m}_{CS}\left(h_3 - h_2\right)}{\dot{m}_{PS}\eta_{CSG}} \quad (1)$$

$$x_5 = \frac{h_5 - h_{f5}}{h_{g5} - h_{f5}} \quad (2)$$

Where, $\dot{m}_{CS}$, $\dot{m}_{PS}$, η_{CSG}, *h* and *x* represent the mass flow rate of clean steam (kg/s), the mass flow rate of plant steam (kg/s), CSG efficiency, specific enthalpy (kJ/kg), and plant steam quality. The subscripts *f* and *g* denote the states of saturated water and saturated steam.

The following equations determine the condition of the steam in the plant's preheater outlet:

$$h_6 = h_5 - \frac{\dot{m}_{CS}\left(h_2 - h_1\right)}{\dot{m}_{PS}\eta_{PH}} \quad (3)$$

$$x_6 = \frac{h_6 - h_{f6}}{h_{g6} - h_{f6}} \quad (4)$$

Where, η_{PH} represents preheater Efficiency.

The required power of the pump is calculated as:

$$\dot{W}_p = \dot{m}_{PS} v_6 \Delta P \quad (5)$$

Then, the state of plant steam at the outlet of the pump will be calculated by:

$$h_7 = h_6 + \frac{\dot{W}_P}{\dot{m}_{PS}\eta_P} \quad (6)$$

in which the ΔP is the overall system pressure drop (kPa). η_P and v_6 represent pump efficiency and the specific volume volume of the plant steam at point 6 (m^3/kg).

The calculation for the mass flow rate of the fuel is as follows:

$$\dot{m}_{fu} = \frac{\dot{m}_{PS}\left(h_4 - h_7\right)}{LHV_{fu} \times \eta_{BO}} \quad (7)$$

Where LHV_{fu} (kJ/kg) and η_{BO} represent fuel's lower heating value and boiler efficiency.

If we assume that the fuel is methane and that it undergoes complete combustion with air, the resulting amount of emitted CO_2 would be [6]:

$$\dot{m}_{CO_2} = \dot{m}_{fu} \times \frac{M_{CO_2}}{M_{fu}} \quad (8)$$

Where, M_{CO2} and M_{fu} are the molecular mass of CO_2 and fuel (kg/kmol), respectively.

3.2. Solar-Assisted system

In the solar-assisted system, equations 1 through 6 remain the same. Also, for calculating the fuel mass flow rate in boiler the following equation is used:

$$\dot{m}_{fu} = \frac{\dot{m}_{oil}\left(h_{13} - h_{12}\right)}{LHV_{fu} \times \eta_B} \quad (9)$$

Where $\dot{m}_{oil}$ is the mass flow rate of Therminol VP-1. The state of Therminol VP-1 at the outlet of the heat exchanger will be determined by:

$$h_9 = h_8 - \frac{\dot{m}_{PS}\left(h_4 - h_7\right)}{\dot{m}_{oil}\eta_{hex}} \quad (10)$$

In this equation, η_{hex}, is the efficiency of the heat exchanger.

$$\dot{Q}_{sun} = A_a \times G_b \quad (11)$$

where G_b is direct normal irradiance.

The net amount of heat which is received by the receiver of the collector is equal to [7]:

$$Q_r = F_R\left[G_b\, A_a \cos\theta\, \eta_0 - A_r U_L (T_i - T_a)\right] \quad (12)$$

This heat is delivered to the working fluid (Therminol VP-1 oil) flowing in the tube of the collector to increase the fluid temperature:

$$Q_r = \dot{m}_{oil}\, c_{p,oil}\, (T_o - T_i) \quad (13)$$

In equation 10, F_R is the removal factor, θ is the incident angle, η_0 is optical efficiency, and U_L is the overall collector heat loss coefficient. Also, T_i and T_a are, respectively, inlet temperature of working fluid and ambient temperature. In equation 11 $c_{p,\, oil}$ is the oil's specific heat capacity, and T_o is the outlet temperature of the working fluid.

The equation describing the removal factor is as below:

$$F_R = \frac{\dot{m}_{oil}\, c_{p,oil}}{A_r U_L}\left[1 - \exp\left(-\frac{U_L F' A_r}{\dot{m}_{oil}\, c_{p,oil}}\right)\right] \quad (14)$$

In which F' is the collector efficiency factor with the following relation:

$$F' = \frac{1/U_L}{\frac{1}{U_L} + \frac{D_o}{h_f D_i} + \left(\frac{D_o}{2k}\ln\frac{D_o}{D_i}\right)} \quad (15)$$

In equation 12, h_f is the convective heat transfer coefficient of the working fluid inside the receiver.

The overall collector heat loss coefficient, which is utilized in the above equations, is defined by the following relation [8]:

$$U_L = \left[\frac{A_r}{(h_a + h_{r,g-a})A_g} + \frac{1}{h_{r,r-g}}\right]^{-1} \quad (16)$$

In this equation h_a, $h_{r,g-a}$, and $h_{r,r-g}$ represent the convective heat transfer coefficient of the wind, the linearized radiation coefficient from the glass cover to the ambient, and the linearized radiation coefficient from the receiver to the glass cover, respectively. The relations describing these coefficients are provided in reference [8]. To maintain concision, these relations are not included in this article.

The temperature of glass and receiver of solar panel are calculated by the following equations. For further details on the modeling procedure, please refer to reference [8].

$$T_g = \frac{A_r\, h_{r,r-g}\, T_r + A_g\,(h_{r,g-a} + h_a)T_a}{A_r\, h_{r,r-g} + A_g\,(h_{r,g-a} + h_a)} \quad (17)$$

$$T_r = T_i + \left(\frac{Q_r}{A_r U_L}\right)\left(\frac{1}{F_R} - 1\right) \quad (18)$$

3.3. Economic Analysis

To evaluate the financial viability of a solar-assisted Combined Solar Gas System (CSGS), it is essential to consider the Initial Investment Cost (IIC), Maintenance and Operating Costs (MOC), Fuel Saving Revenue (FSR), and Carbon Emission Certificate Revenue (CECR). The annual revenues of FSR and CECR, and yearly expenses of MOC should be discounted for each year based on the Market Discount Rate (MDR) to the first year of operation. The Present Value (PV) of all revenue and expenses can be calculated as:

$$PV = C\left[\sum_{j=1}^{n} \frac{(1+i)^{j-1}}{(1+d)^{j}}\right] \rightarrow \left\{\begin{array}{l} i = d \rightarrow PV = C \times \dfrac{n}{1+i} \\ i \neq d \rightarrow PV = \dfrac{C}{d-i}\left[1 - \left(\dfrac{1+i}{1+d}\right)^{n}\right] \end{array}\right\} \quad (19)$$

This equation considers C as revenue or expense at the end of the first year, i as the annual increase rate of fuel or carbon emission certificate cost, d as the market discount rate, and n as the years for economic analysis. The study considers a fuel cost of 2.96 cents Euro/kWh with a 10% annual increase, CECR cost of 90 Euro/ton with an 8% increase, and MOC of 3% of IIC. The PTC revenue in the last year is 10% of the discounted IIC. The NPV is calculated using this formula.

$$NPV = FSR + CECR + DR - IIC - MOC \quad (20)$$

4. Optimization

Regarding the effect of number of solar panels in parallel (n_p) and the number of solar panels in series (n_s) on solar-assisted CSGS performance, we will have the following:

$$T_{os} = f(n_s) \tag{21}$$

$$Q_{solar} = g(n_p, n_s) \tag{22}$$

Increasing the number of solar panels in series (n_s) would result in a higher temperature output of the solar system (T_{os}), (T_{os}), which supplies more heat and saves fuel. Additionally, increasing parallel solar panels (n_p) would increase the mass mass flow rate of heating fluid, providing more heat and consequently more fuel savings. It should be considered that the the heating fluid temperature at the solar field and boiler outlets must not exceed 650 K that is the boiling point of the heating fluid (Therminol VP-1). It's important to note that the proposed solar-assisted system is designed to supply the energy required for generating plant steam only during maximum annual solar availability. This eliminates the need for an energy storage unit, simplifying the system and making it more cost-effective. The design process flow diagram is depicted in Figure 2.

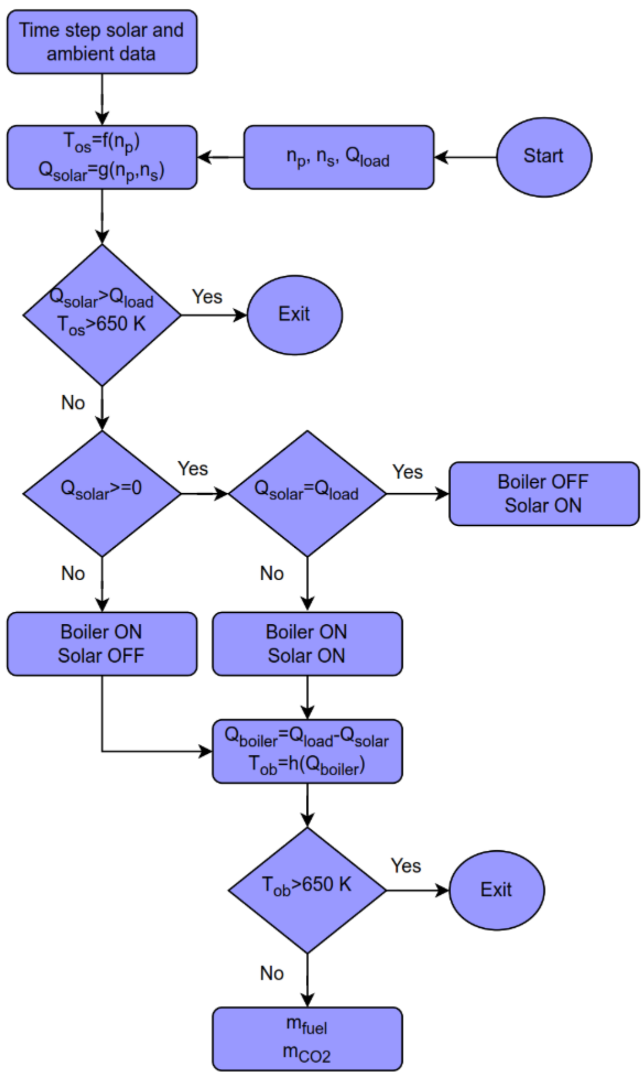


Figure 2: design process flow diagram.

As the number of solar panels increases, so does the cost of installation, operation, and maintenance of the solar system. On the other hand, increasing the number of solar panels would result in more fuel savings. To find the optimal arrangement of the solar field for both hospitals, we provide the following fitness function:

Figure. 3: Decision variables and Fitness functions.

The fitness function used in this study takes two inputs: np, and ns. It produces one output that is FS. The Genetic Algorithm in MATLAB is used to optimize the function. During the optimization process, we ensure that the area of land used is limited to no more than 2500 m^2, and the number of panels arranged in parallel and series are limited to 30.

5. Results and discussion

Firstly, a single-objective optimization is implemented to find the best arrangement of the solar field for both under-study hospitals that would result in finding the most annual fuel savings arrangement (Table 3).

Table 3 The results of optimization

Hospital name	n_p	n_s	Fuel Saving (ton/yr)
Frederiksberg (Denmark)	30	1	24.71
Falun (Sweden)	10	3	27.26

According to the optimization results shown in Table 1, the ideal arrangement for solar fields in hospitals situated in Denmark would be n_p=30 and n_s=1, while in Sweden, the optimal arrangement would be n_p=10 and n_s=3. If these arrangements are implemented, the annual amount of saved fuel would be 24.71 tons and 27.26 tons for Denmark and Sweden, respectively.

To analyze the economic impact of using a solar-assisted clean steam generator, we must assess the correlation between fuel saved (FS) and net present value (NPV). When we carry out an economic analysis for a particular year, we observe that the overall cost of the system increases as we add more solar panels. However, this also increases the fuel saved, consequently generating more revenue. We have included graphs that exhibit NPV for different solar field arrangements over six years. These graphs evaluate the effect of increased cost and revenue on NPV. For an assumed year of economic analysis, the higher the Net Present Value (NPV), the more financially feasible a project is.

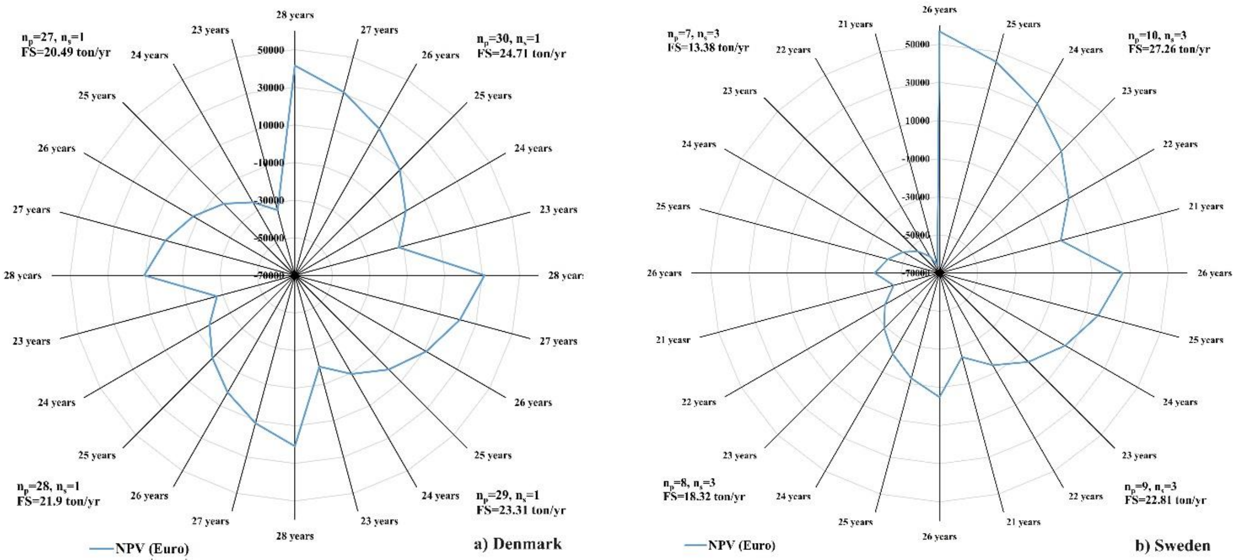


Figure 3: NPV for different solar field arrangements over six years, a) Denmark, b) Sweden.

These graphs illustrate that decreasing the number of panels results in a smaller reduction in installation and operating operating costs relative to the decline in fuel savings revenue, making the solar-assisted clean steam generator less cost-effective. For example, in Denmark, an np=30, ns=1 arrangement yields FS=24.71 ton/yr and NPV=9195 Euro after 25 years, while an np=29, ns=1 arrangement yields FS=23.31 ton/yr and NPV=779 Euro after 25 years. For a given time period of financial analysis, a project's financial feasibility increases with its NPV. Therefore, the arrangements obtained through single-objective optimization to find the most fuel-saving arrangement are also the most cost-effective.

Figure 4 illustrates the share of energy required by the solar field and boiler throughout the year and in different months for both Falun and Frederiksberg solar-assisted systems.

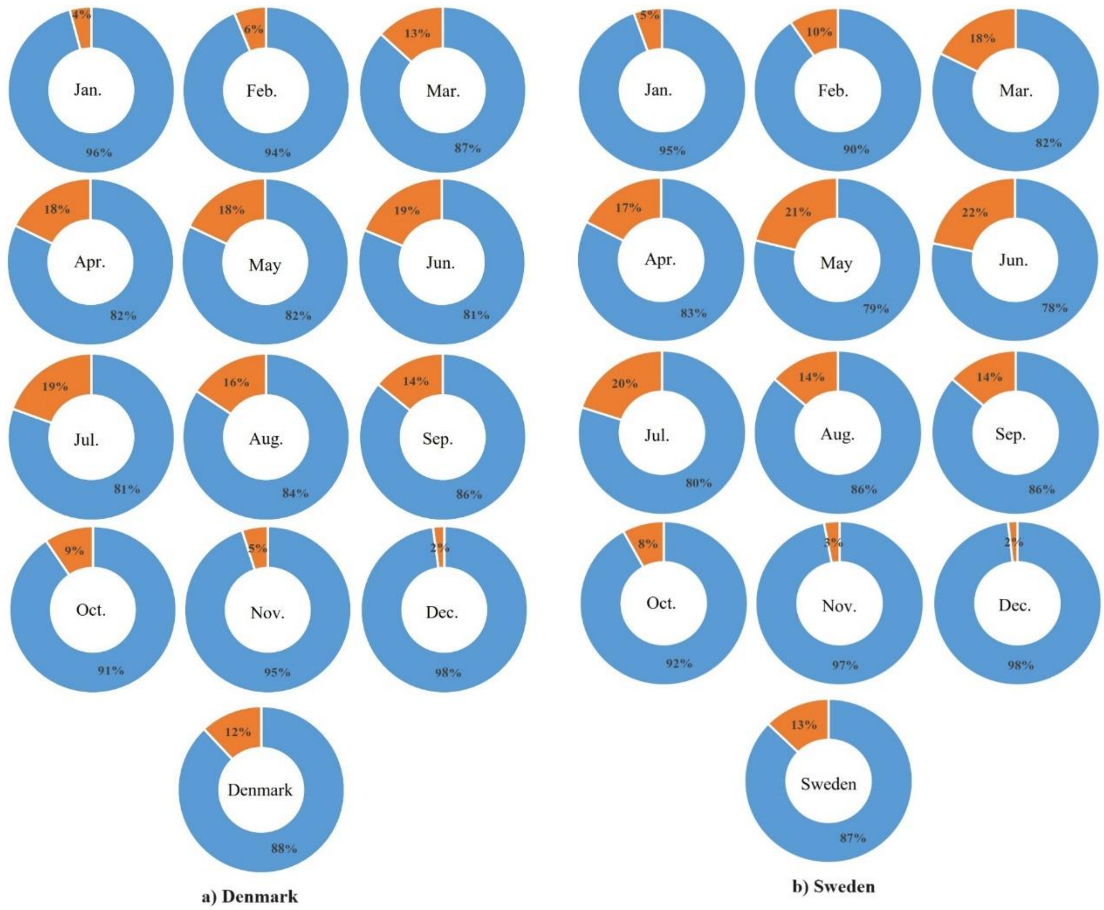


Figure 4: Annual and monthly contribution of the solar field and boiler to the total required energy for the a) Frederiksberg solar-assisted system (Denmark) and b) Falun solar-assisted system (Sweden).

According to the diagram, the solar field provided 13% of Sweden's total energy requirement and 12% of Denmark's over the year. This indicates that Sweden's Falun solar-assisted system relied slightly more on the solar field than Denmark's Frederiksberg solar-assisted field.

6. Conclusion

The purpose of this research is to make healthcare buildings more sustainable by proposing and developing an innovative solar-driven steam generator that can provide clean steam to hospitals. An optimization was done to identify the best solar field arrangements for two hospitals in Denmark and Sweden. The goal was to achieve maximum fuel savings while keeping the total land area to a maximum of 2500 square meters and limiting the number of panels connected in parallel or series configurations to 30. Economic analysis revealed that the most cost-effective solar field arrangements for both hospitals also maximized fuel savings. The optimal solar configuration for the hospital in Denmark is 30 parallel panels and 1 series panel, while for the hospital in Sweden, it is 10 parallel panels and 3 series panels. These configurations led to 24.71 and 27.26 tons of annual fuel savings for the Denmark and Sweden hospitals, respectively.

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