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A PRELIMINARY OPTIMISATION AND TECHNO-ECONOMIC ANALYSIS OF SOLAR ASSISTED BUILDING HEATING SYSTEM USING TRANSPIRED AIR SOLAR COLLECTOR AND HEAT PUMP IN SWEDEN

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ABSTRACT

Transpired solar air collector can be used in combination with heat Pump to meet space heating and hot water demand in domestic dwellings. Moreover, the solar pre-heated fresh air can be used as a heat source for the heat pump evaporator, improving its coefficient of performance. Many research articles have been published on this subject, however the optimal analyses about techno-economic feasibility of a heat pump with the transpired solar collector are still lacking. Therefore, an optimisation tool is developed, based on non-linear programming using coherent operation strategy and variation in collector flow rate for a solar heat pump system. The effect of optimisation along with techno-economic feasibility for a demo case in Sweden is then preliminary studied based on the defined boundary conditions. The results are used to select the most cost-effective collector area installation, along with an efficient operation strategy for a given system configuration. Results indicate that the hourly flow rate optimisation can determine 35 % increased savings, compared to a non-optimised fixed flow rate case. Moreover, the simulated system has a net present value of € 5000 when calculated at 2 % discount rate for 30 years. The tool has potential use for pre-feasibility check at an earlier stage of the dedicated design and operation, without the need for extensive system simulations.

Keywords: Transpired air solar collectors, heat pump, solar energy, techno-economic feasibility.

NOMENCLATURE

COP	Coefficient of performance
DSHP	Dual source heat pump
HP	Heat pump
NLP	Non linear programming
NPV	Net present value
SHP	Solar heat pump
TSAC	Transpired air solar collector

1. INTRODUCTION

Residential and commercial buildings represent up to 40% of the global energy consumption in developed countries [1]. Moreover, in the residential sector, 60 % of the supplied energy is used for heating, ventilation, and cooling purpose [2]. A significant fraction of the energy demand is still fulfilled by non-renewable energy sources resulting in large greenhouse gas emissions and other air pollutants [3]. Therefore, the increased use of renewable energy sources appears as one of several promising strategies for reducing emissions of pollutants. In this regard, a heat pump that uses renewable energy from their surroundings (e.g., air or water) is considered as candidate environment friendly technology for residential dwellings in Europe, showing an annual growth rate of 10 % in 2018 [4]. In recent years, the hybrid solar heat pump (SHP) systems are proposed to improve the system coefficient of performance (COP), in which heat pumps are combined with solar thermal, photovoltaic or hybrid (PVT) collectors in order to preheat the fresh air delivered to the evaporator [5,6]. The hybrid SHP system features better collector efficiency due to low operating temperatures, and improved heat pump performance owing to higher temperature than ambient air [7]. SHP systems with liquid heating solar collectors are extensively studied in the literature, however there is a lack of investigations for air pre-heated SHP systems [8, 9-11]. Loveday [12] assessed a system consist of a heat pump and solar heated profiled sheet cladding, using mathematical correlations. The study concluded that heated air

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augments the system energetic performance compared to a no-solar case, along with a strong impact of fan power consumption on the cost economics. Haller *et al.* [7] performed a mathematical analysis to define an irradiation limit to switch between series and parallel arrangement of solar collector and heat pump system. The results show that the irradiation limit is dependent on the collector characteristics curve, heat pump performance curve, and ambient temperature. Badescu [13] developed a model for SHP system to propose an operation strategy based on the solar irradiance, to switch among two operation modes (with and without solar heat) for maximum savings. The results indicate 8 % less power consumption of compressor using solar heated air compared to the case when collector heat is not utilized. However, there are still lacking of the optimal analyses about system operation parameters and the corresponding techno-economic feasibility of heat pump system with solar thermal collectors [6].

In this paper, the investigated system consisting of a façade mounted transpired solar air collector (TSAC) connected in series with a dual source heat pump (DSHP) by using air and ground sources, is utilized for space heating and hot water demand in Swedish domestic dwellings. Moreover, the fresh air preheated by the TSAC is used as one type of source for heat pump evaporator to augment its performance. TSAC consists of a perforated metal sheet with a high solar absorptive coating applied on it. The thermal collector is designed to be mounted on the building structural walls, with an optimal gap to allow the airflow behind. A fan-assisted unit directs the pre-heated air to the heat pump evaporator through a conventional duct system. The conceptual scheme of the system under study is shown in Figure 1.1. The objective of the research presented in this paper adhere to:

-develop an optimisation approach applied to series integrated TSAC-DSHP system to maximize the savings for the customer. The approach makes use of coherent operation strategy and variation in collector flow rate to improve the system performance.

-develop a simple tool for engineers and researchers to study the techno-economic feasibility of a TSAC-DSHP system, for a given location, load profile, and collector mounting arrangement.

The tool is used for feasibility study of TSAC-DSHP system for a residential building located at Ludvika, Sweden. The techno-economic performance of the system is examined and the main factors influencing the results are discussed such as collector flow rate, building wall thermal resistance, and efficiency. The impact of optimisation process on system performance is evaluated and compared with respect to a non-optimized case having a fixed flow rate. The tool has potential use for the feasibility check at earlier stage of the project without the need for extensive system simulations.

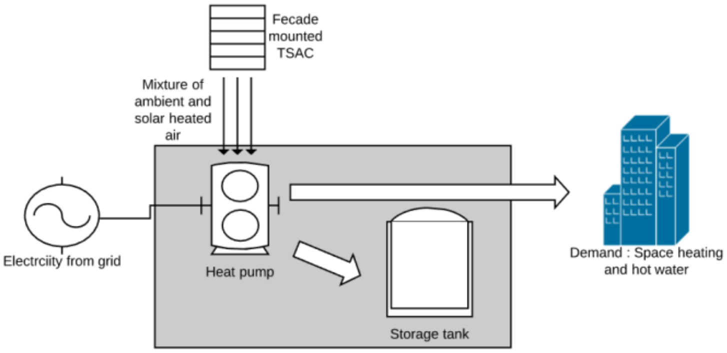

Figure 1.1 Conceptual scheme of the analysed system

2. METHODOLOGY

2.1 Optimisation approach and basic assumptions

The optimisation tool is developed using non-linear programming (NLP) on Microsoft Excel platform. The total electricity expenses with the reference system are evaluated using the approach shown in Figure 2.1.1.

The annual operational expenses of the heat pump $E_{total,ref}$(€) can be calculated by the sum of hourly electricity expenses for the year during heat pump working hours as shown in Equation 2.1.1

$$E_{total,ref} = \sum_{n=1}^{8760} \frac{Q_{total,n}}{CoP_{hp,n}} \cdot E_p \qquad \text{Eq. 2.1.1}$$

Where, n is the hour number, $Q_{total,n}$ (kWh) is the hourly heat demand of the building, $CoP_{hp,n}$ is coefficient of performance of heat pump based on ambient temperature, and E_p (€/kWh) is the household electricity price.

The system working hours are limited by heat demand and heat pump capacity, and provided as an input by the user. The hourly irradiation on the collector plane is determined by using Liu and Jordan method as defined in [15]. The collector efficiency, collector thermal output, outlet air temperature, and recaptured building losses by

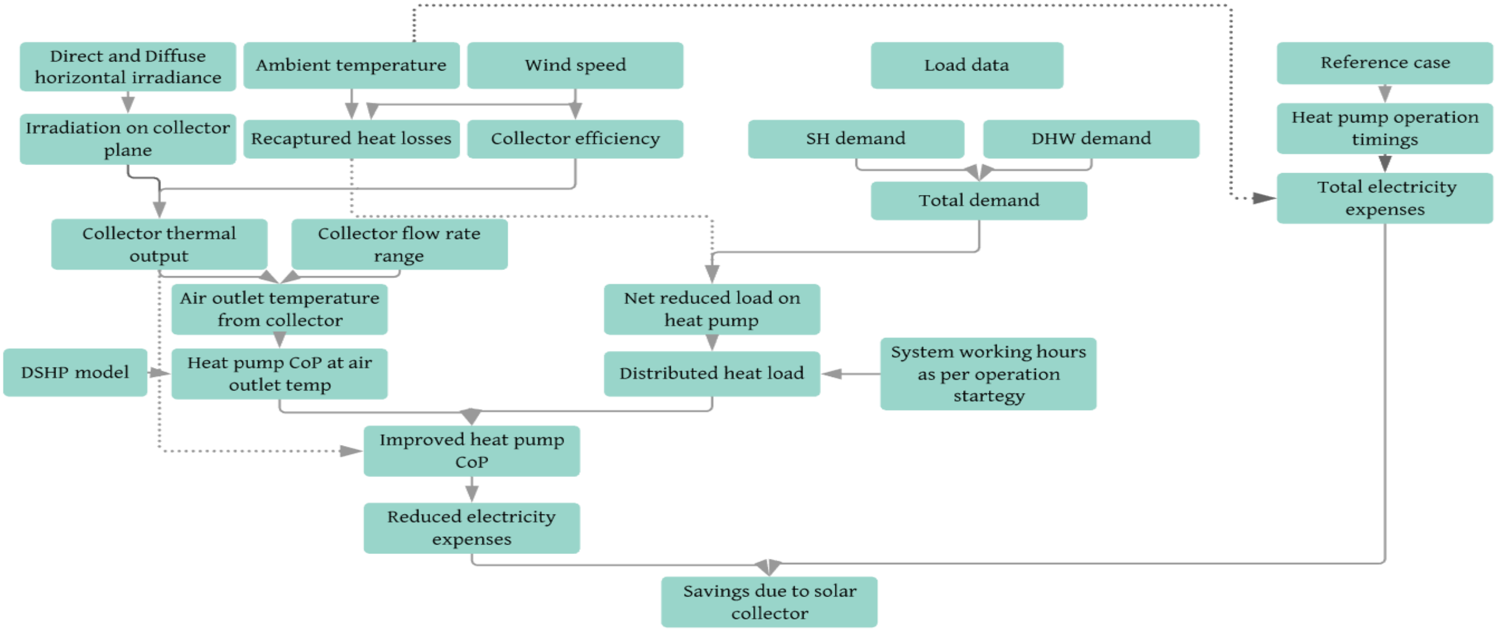

Figure 2.1.1 Framework for the current study

TSAC are calculated using methodology defined in [16] on an hourly basis. The analysis is carried for an air volume flow rate ($\dot{v}$) ranging between 20 m^3/(h·m^2) to 150 m^3/(h·m^2), with an increment step of 10 m^3/(h·m^2) considering the operation range of fan from real case data. The collector acts as insulation for the wall and the recaptured losses reduce the space heating load and thus total load on the heat pump. The reduced daily heat load is distributed equally among system working hours to maximise the savings. The working hours are determined as part of an operation strategy, and governed by the heat pump capacity, irradiation, ambient temperature and wind speed. The collector thermal output and outlet air temperature are used to determine the improved COP of the heat pump due to heated air.

The effect of the TSAC is to reduce the heat load and improve the COP of the heat pump which results in less electricity consumption compared to the reference case. In addition, the air is assumed as a heat source in order to maximize the benefits of TSAC, while the ground is considered as a backup source in this tool. These savings are evaluated on an hourly basis for volume flow rate range $\dot{v}$ using Equation 2.1.2

$$S = E_{total,ref} - \left[\sum_{n=1}^{8760} \left(\frac{Q_{net,n}}{CoP_{i,n}} + E_f\right) \cdot E_p\right]_{\dot{v}} \qquad \text{Eq. 2.1.2}$$

Where S (€) is the annual savings due to TSAC, $Q_{net,n}$ (kWh) is the reduced load on the heat pump, $CoP_{i,n}$ is improved coefficient of performance of heat pump, E_f is electricity consumption of fan including the pressure drop due to TSAC, and $\dot{v}$ [m^3/(h · m^2)] represents the flow rate range for which calculations are made. Flow rate corresponding to maximum saving for each hour is determined to provide an annual flow rate map for effective system operation. Moreover, The net present value (NPV) of the system is determined using equation 2.1.3

$$NPV = \sum_{t=0}^{30} \frac{S}{(1+r)^t} - C \qquad \text{Eq. 2.1.3}$$

Where S is annual the saving from solar collector, t is the year number, r is the discount rate and C is initial the capital investment for system.

2.2 Optimisation framework

The overall optimisation is based on NLP, where the boundary conditions and constraints are non-linear, with the objective function as total savings. The user is able to modify hourly data for meteorological parameters (irradiation, wind speed, and ambient temperature), thermal demand (space heating and hot water) and other inputs such as electricity price and building wall thermal resistance. Once the simulation is initiated, the results are presented in terms of NPV, system operation strategy and annual flow rate map.

3 CASE STUDY

The system under analysis consists of three major components, including: 1) TSAC 2) Ground source heat pump with air ventilation unit as a heat source and 3) Variable speed fan. The components are arranged so that the heated air from the TSAC is ducted to evaporator coil of DSHP by using a fan assisted unit. A mixture of ambient air and solar heated air may be used, when the collector flow rate is not sufficient, to match the heat pump flow rate requirement. Based on the application there is no provision to deliver the hot air from collector directly to the building. The DSHP is used to meet both the space heating (SH) and domestic hot water (DHW) demand for the building and, if integrated with a storage tank of suitable capacity, the stored heat can be used for night time usage. It is assumed for the reference case analysis that heat pump operates from 9:00 to 16:00 to meet the load demand and no TSAC is installed. The residential building under study is located in Ludvika $(60^o 21' N, 14^o 95' E)$ with façade area of 2146 m^2 and total heated area of 1548 m^2. The building walls are insulated with effective U value of 0.33 $W/(m^2 \cdot K)$. The external shading and wind sheltering on the building wall is neglected for the current analysis. The simulation is performed using the weather data of Borlänge, located 50 km from Ludvika and it is the closest available weather data to the location of the project in TRNSYS [17]. Total monthly thermal demand is estimated using building energy model in TRNSYS, and shown in Figure 3.1. The SH load constitutes a major part of the total load in the winter period and is variable throughout the year, in comparison to fairly fixed DHW load. The monthly average ambient air temperature and wind characterizing the Swedish location is 4.1 ℃ and speed 3.3 m/s respectively.

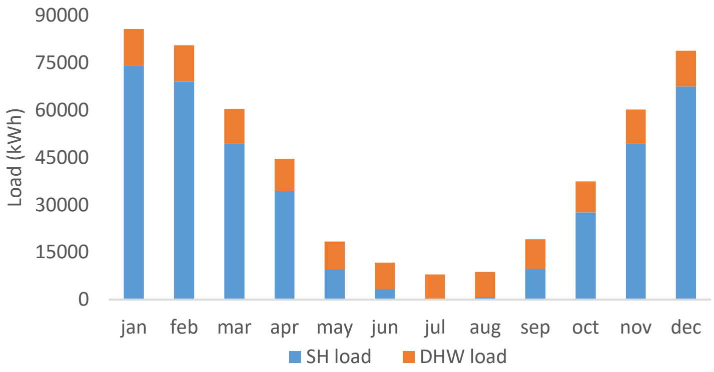

Figure 3.1 Monthly load demand of the building

The TSAC is mounted on south façade with a tilt of 90^o. The monthly global irradiation on the collector plane is shown in Figure 3.2. As can be appreciated that the irradiation on the collector plane is 28 % lower than the global horizontal irradiation

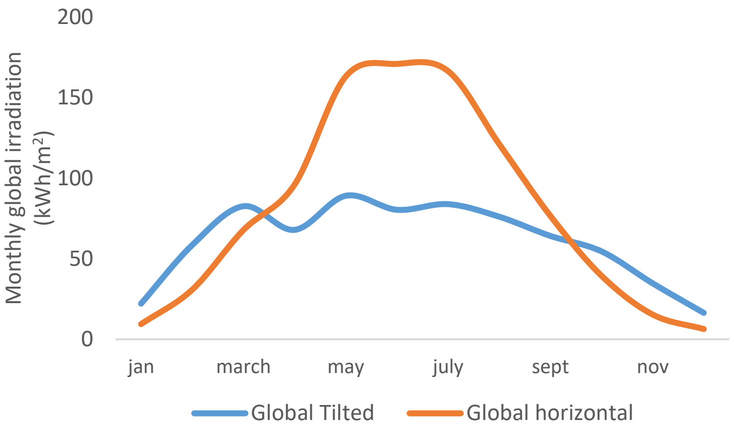

Figure 3.2 Monthly global horizontal and tilted irradiation.

The boundary conditions used for the analysis are shown in Table 3.1.

Table 3.1 Boundary conditions used for simulations.

Sr No.	Parameter	Value
1	Location	Ludvika, Sweden
2	Electricity price	0.14 $€/kWh$
3	Heat pump operation timings	09:00 to 16:00
4	Solar collector area under analysis	50 m^2
5	Collector tilt	90^o
6	Collector azimuth	0^o
7	Collector flow rate range	20-150 $m^3/(h \cdot m^2)$
8	U collector [16]	3 $W/(m^2 \cdot K)$
9	U building wall	0.33 $W/(m^2 \cdot K)$
10	Maximum hot air temperature limit	40 ℃
11	Fan power consumption [18]	0.06 $W/(m^3 \cdot h)$
12	Wall loss component in SH load	30 %
13	Building indoor air temp	21 ℃
14	Assumed collector cost	400 $€/m^2$

4 RESULTS AND DISCUSSION

The analysis reflects that installation of 50 m^2 TSAC results in 3 % savings compared to the reference case. The system shows a positive NPV of € 5000 during 30 years project life time at 2 % discount rate. However, the NPV become negative at higher discount rates as shown in Figure 4.1. The monthly collector thermal output at various flow rates is shown in Figure 4.2. The collector output is higher in summer due to high irradiation and lower losses. Moreover, the increase in flow rate leads to better performance due to lower outlet air temperature and thus reduced convection losses from the collector.

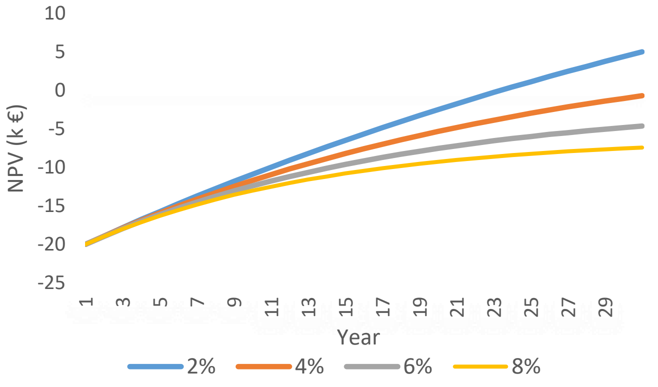

Figure 4.1 Variation of system NPV at various discount rates

In Figure 4.3, which shows the annual optimized flow rate map, it is possible to appreciate that the suggested flow rate due to optimization, is lower in winters and vice versa. Specifically, the flow rate at a specific hour is determined by multiple factors such as ambient temperature, heat load, irradiation, exiting air temperature, COP and recaptured losses. As the irradiation and ambient air temperature is lower in winter, therefore optimisation suggest low flow rate to obtain high outlet air temperature, minimize fan energy consumption and maximise the COP. During summer, the irradiation and ambient temperature is high, thus suggested flow rate is higher as it can improve heat pump COP by leverage of better collector output. The results show that flow rate optimisation increase the savings up to 35 % compare to a case if collector is operated at a fixed flow rate throughout the year. The annual operation strategy for maximum savings is shown in Figure 4.4. The operational hours are constrained by the hourly ambient temp, heat pump capacity and irradiation. The optimisation limits the operation hours to daytime to make use of the higher ambient temperatures and thus higher COP.

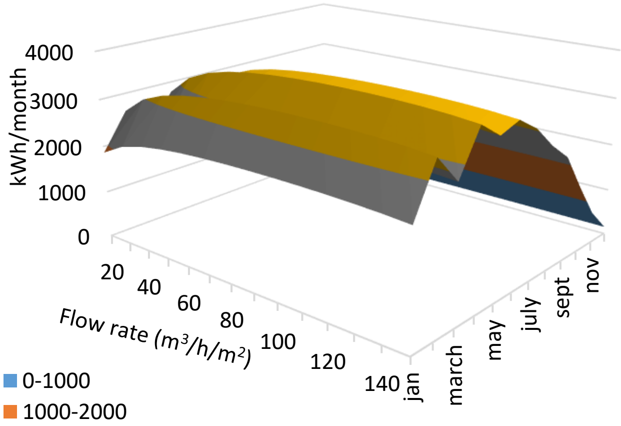

Figure 4.2 Collector output variation with flow rate

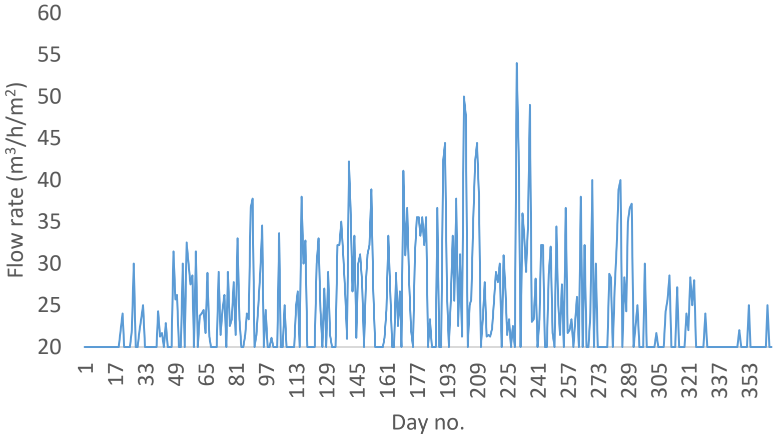

Figure 4.3 Annual optimised flow rate map

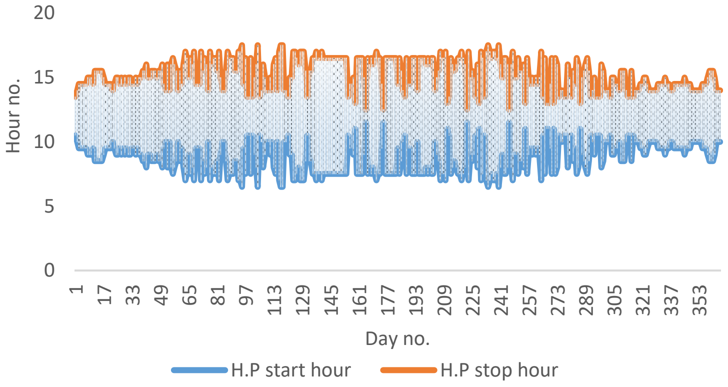

Figure 4.4 Operation strategy suggested by optimisation tool

5 CONCLUSIONS

From the analyses of the results applied to a residential building in Sweden, it can be concluded that optimisation has a strong potential to improve the overall system performance and an increase in savings. The optimisation basis is due to non-linearities of collector performance, recaptured losses with increased flow rates and due to variation in heat pump COP with ambient air temperature. Feasibility study results in a positive NPV of € 5000 at 2 % discount rate for the defined case. The savings due to solar collector in the analysed case has a strong dependence on the defined boundary conditions such as user load profile, building wall U value, irradiation, fan power consumption electricity price and discount rate. An operation strategy is defined to take advantage of higher ambient temperatures in the day time and is limited by the heat pump capacity and irradiation. The tool can be useful to study economic feasibility for various locations, collector orientations, and user load profiles. However, the results have uncertainties subjected to the shading on the collectors, wind sheltering and electricity price variation which are not considered in the analysis. The future work will include (1) optimisation of the coupled operation modes by considering both ground and air sources, (2) calibration of results using more sophisticated, dynamic modeling and simulation tool such as TRNSYS.

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