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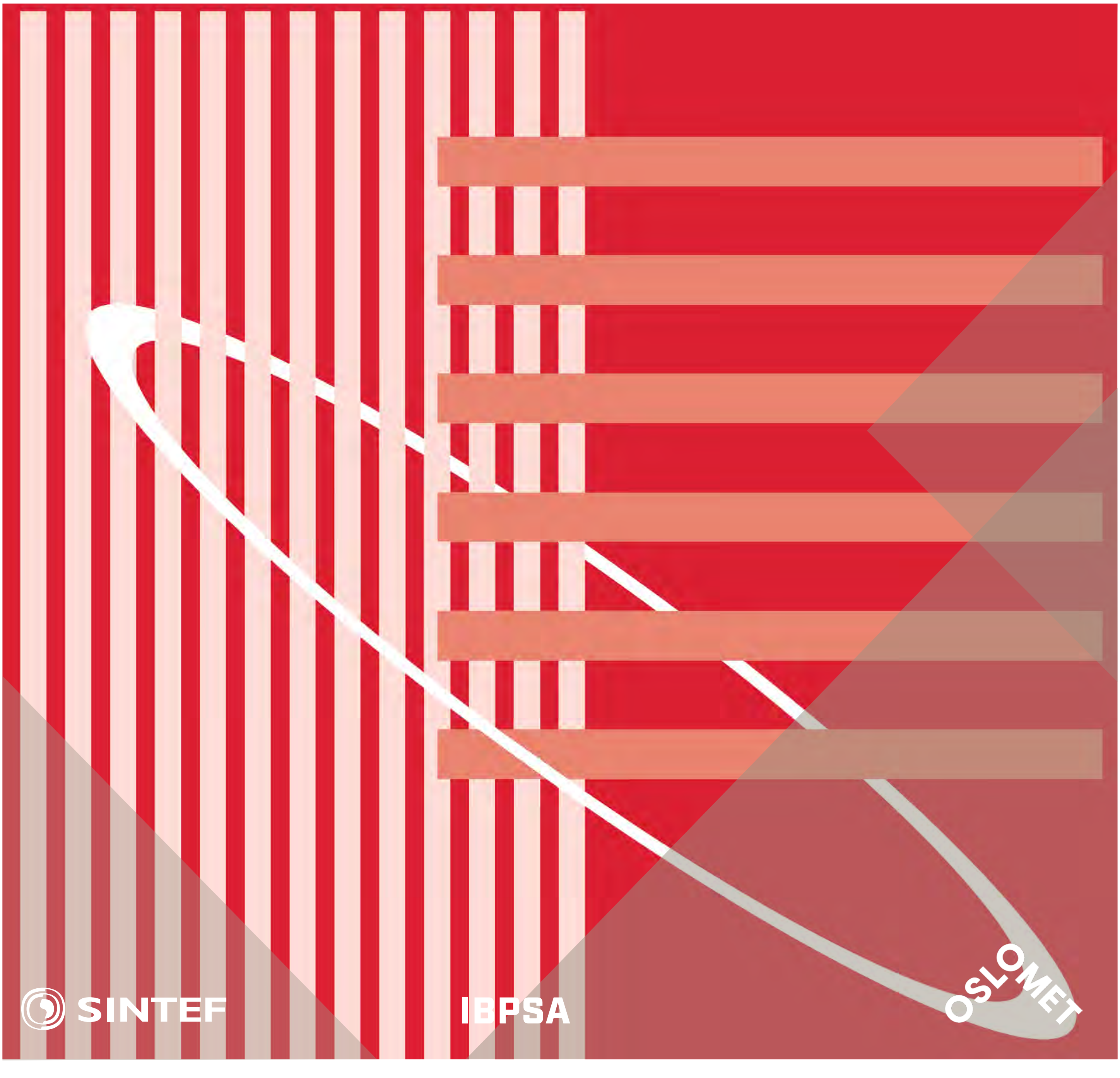

SINTEF Proceedings

Editors:
Laurent Georges, Matthias Haase, Vojislav Novakovic and Peter G. Schild

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Simulation and parametric study of a building integrated transpired solar collector heat pump system for a multifamily building cluster in Sweden

Puneet Saini[1,2], Frank Fiedler[1], Emmanouil Psimopoulos[1,2], Benedetta Copertaro[1], Joakim Widén[2], ,
Xingxing Zhang[1]

[1]Department of Energy and Built Environment, Dalarna University, Sweden
[2]Department of Engineering Sciences, Civil Engineering and Built environment, Uppsala University, Sweden

Abstract

Solar integrated building envelopes represent a significant energy harvesting potential in an era of decentralized building energy systems. This paper aims to simulate an energy system that consists of a transpired air solar collector component for a multifamily building cluster in Sweden. The energy system consists of an unglazed transpired solar collector in conjunction with air ventilation unit and exhaust air heat pump. The hot air from the solar collectors is used to increase the brine temperature at heat pump evaporator inlet to improve its coefficient of performance. The exhaust air heat pump is used to meet space heating and hot water demand for the buildings. The energy system is modelled using TRNSYS simulation program. The associated controls of the energy systems are optimized to increase the seasonal performance factor of the complete system, while maintaining the optimal performance of various subsystems. The quantification of the energetic benefits obtained from the proposed energy system is also presented using various key performance indicators. Furthermore, sensitivity analysis of different collector areas and operating variables such as airflow rate of the collector is conducted. The results show that the seasonal performance of the simulated energy system is 1.43 and the annual collector utilization factor is 0.18. Furthermore, the variation of the collector airflow rate has a positive impact on system performance, with an increase of 2 % in the annual heat pump coefficient of performance.

Introduction

The thermal demand for residential buildings in Nordic climates is characterized by large space heating (SH) loads in the winter and relatively constant domestic hot water (DHW) demand over the year (Chauvet. L,1994). Most of the thermal demand is often met by district heating (DH) networks. Even though DH has a low carbon footprint in Sweden, still the availability of the network is limited by the distance of the consumer from the central heat generation plant (Nilsson.S, 2007) In the non-availability of the DH, heat pumps (HP) are often used to meet the SH and DHW demand in the buildings (Davis.A, 2017). More specifically, air-source heat pump (ASHP) represents the state of the art in the Swedish climates to fulfil heating demand in the residential sector (Poppi.S, 2017). In a typical single-family house, ASHP is often connected to thermal store which is used to meet SH and DHW loads (Poppi.S, 2017). The performance of the ASHP is negatively affected by a decrease in ambient air temperature, assuming all other influencing parameters (e.g load temperature, operational capacity) remain unchanged. In the past few years, the exhaust air heat pump (EAHP), representing a special ASHP, has evolved as an efficient solution due to the capability a) of recovering the energy from the ventilation air of the building and b) of improving the ASHP performance due to the elevated temperature on the source side of HP (Fehrm.M,1990). However, a major share of the EAHP are installed in newly built single family houses in Sweden, as ventilation system and ducting can be designed to extract the air from the building to a centralised point.

Even though the seasonal performance factor (SPF) for EAHP is usually higher than the typical ASHP given the same boundary conditions, still there exist possibilities to alleviate the system performance by integrating various solar technologies such as PV, solar thermal, and hybrid technology (Wang.X, 2020). For instance, Liu et al. experimentally investigated a solar-driven exhaust air thermoelectric heat pump recovery system. The results showed that the proposed system can obtain higher fresh air supply temperature (12 °C higher than the indoor air temperature) in winter and lower fresh air (6 °C) supply temperature in Summer (Lui.Z, 2019). Psimopoulos et al. develop a techno-economic analysis of control algorithms for an EAHP system coupled to a photovoltaic system with the aim to minimize the building energy usage and maximize self-consumption. The developed method resulted to reduce energy usage by 5–31 % and the annual net cost by 3–26 % (Psimopoulos.E, 2019). Safijahanshahi and Salmanzadeh numerically simulated the performance of an air-to-air HP combined with an unglazed transpired solar collector (TSC). The results showed that the solar assisted heat pump could decrease the electricity consumption and the CO_2 generation up to 10 % with respect to a conventional air-to-air HP (Safijahanshahi.S, 2019). Similarly, Perisoglou et al . presented the performance of a TSC used as a preheater for an air to air HP installed in a demonstration house in Wales, UK. The results showed that the system contributed to 15 % of the heating and cooling demand in one year, which can be translated into £100 to £200 savings per year compared to a conventional heating source (Perisoglou.E, 2017). In their study Januševičius et al. validated a simulation model of a system that combines an unglazed TSC assisted with an ASHP. The results demonstrated good conformity between model and experimental performance (Januševičius.K, 2016). Saini et al. show that the variation in collector air flow rate can increase the savings up to 60 % in an TSC-ASHP system configuration analyzed for Swedish climates (Saini.P, 2019)

Amongst the various available solar technologies, TSCs are specially designed collectors that can easily be integrated with building facades and therefore can be installed potentially in a large area to heat the ambient air to meet the residential energy needs. Unlike state-of-the-art flat plate air collectors, TSC is made of the corrugated metallic sheet with perforation on the top surface to create a pressure difference across the plate while ensuring heat transfer form heated plate surface to the ambient air. The distribution of the holes on the plate surface results in asymptomatic boundary layer thickness leading to almost fixed convection losses, irrespective of the collector width (Kutscher.F, 1993). The distinct advantages of TSCs are related to their simple construction and installation on the building envelope, lack of hydraulic components, and well architectural integration with the building walls and roof.

As it can appreciated from the already mentioned state of the art, there is very limited literature which addresses the integration of TSC in conjunction with EAHP system, especially for Nordic climates, where the sensible parameters for system design and operation stay unclear. Therefore, this paper aims to fill the above-mentioned research gaps by analysing an EAHP system coupled with a TSC (in a series arrangement) for SH and DHW supply to a residential building cluster in Swedish climatic location. The specific objectives of the study are 1) the simulation and the energetic analysis of integrated TSC-EAHP system for multifamily building cluster in Sweden; 2) to perform a sensitivity analysis to identify the effect of the critical parameters, such as collector airflow control strategies and collector area on the proposed TSC-EAHP system performance. The overall structure of this paper is depicted as below: Next section illustrates the research methodology and defines the system input parameters as well as boundary conditions, followed by main results, insights and findings, the conclusion is finally summarized in last section

Research method and boundary Conditions

The study follows a systematic approach starting by the definition of various boundary conditions of the energy system, the selection of the most appropriate simulation tool and the relevant key performance indicators (KPIs) in the context of complete system performance. The data from a residential building cluster located in Sunannsjö, Sweden is used to define a reference energy system. As the focus of the study is on comparative analysis of the various energy systems which may require local programming of control strategies therefore TRNSYS (TRNSYS, 2020) simulation tool is used due to its open source code. TRNSYS also has a wide range of components library for solar heating systems and therefore provides higher flexibility compared to other tools such as Polysun (Polysun, 2020) or IDA-ICE (IDA, 2020). The annual dynamic simulation of the energy system is performed and the results are expressed using standard KPIs (such as seasonal performance factor, coefficient of performance etc.) used in most solar heat pump system analysis. The results are further analysed to identify the most critical system variables, and a sensitivity analysis is carried to study the effect of such variables on the system performance. The methodology used in the paper is summarized in Figure 1.

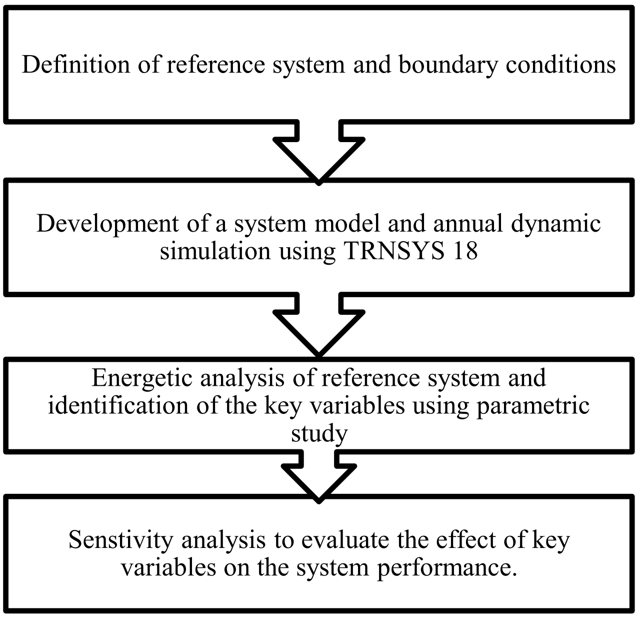

Figure 1 : Methodology used for the analysis

Reference system and system boundaries

To carry a transparent and reliable performance comparison among different systems, it is imperative to define a reference case and boundaries of the energy system. The following subsections address the building characteristics, energy system description, and meteorological conditions for system under study.

Building and loads characteristics

The system chosen for this paper consists of a multifamily dwelling unit made of three buildings built in 1973. The complex (three buildings) includes 53 apartments over 2 floors and a basement, having a lot size of 4488 m^2. The envelope is composed by 2146 m^2 of the total façade area and 1750 m^2 of the pitched roof. The building walls are insulated with an effective U-value of 0.33 $\mathrm{W/(m^2 \cdot K)}$. The aerial view of the buildings is as shown in Figure 2.

Figure 2: Ariel view of the buildings

The total thermal load of the building consists of SH and DHW load. The total heating load was simulated using a building simulation model in TRNSYS and later calibrated with real measurements within the framework of the project (EnergyMatching, 2020). The annual thermal energy demand for the cluster is 526.7 MWh. The specific SH and DHW demand 109.8 kWh/m^2 and 26.6 kWh/m^2 respectively. The monthly variation in the total demand is shown in Figure 3

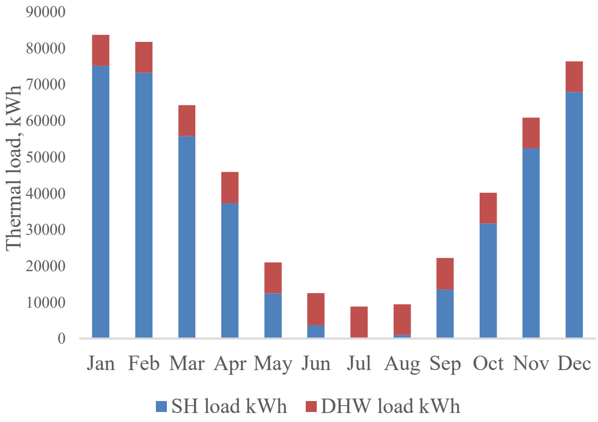

Figure 3 Annual thermal demand of the building cluster

Figure 3 illustrates that up to 80 % of the total demand is for SH and the rest 20 % is due to DHW. The seasonal variation in the SH demand is higher and most of the demand occurs in months with a low ambient temperature. On the contrary, the DHW demand has a small seasonal variation, as the requirement for hot water is consistent over the year.

Reference energy system description

The energy supply system for the buildings consists of a centralised EAHP and an auxiliary pellet boiler. The EAHP is a brine to water type and is designed based on the ventilation air rate of 0.35 l/m^2 · s available from the various building zones. The EAHP includes a variable speed compressor and has a designed capacity of 45 kW with COP of 4.11 defined at compressor frequency of 90 Hz, and brine (source) & water (load) temperature of 0 °C and 35 °C respectively. The ventilation air at room temperature from all 3 buildings is extracted and ducted to an air/brine heat exchange unit installed in the attic of each building, which recovers the heat from ventilation air and delivers this heat to HP via a brine circuit. The condenser side of the HP delivers heat either directly to SH circuit, or to a storage tank of 2.5 m^3 capacity to meet the DHW load. DHW circuit is designed to supply 55 °C hot water to the user, whereas the maximum allowable heating temperature of HP is 65 °C . The designed supply/return temperatures of SH circuit are 55/45 °C respectively and heat is dissipated using indoor radiator units. The operation mode of HP is determined based on the charging level of the DHW tank, with the priority being the full charging of the DHW tank at maximum HP capacity. A small storage vessel of 0.35 m^3 is installed in SH circuit and is used to cater the SH loads when the HP operates in DHW mode. The compressor speed of the HP is varied in SH mode, to achieve the designed radiator inlet temp. If the heat demand of the building exceeds the HP capacity, a pellet boiler is used as a supplementary heat source. TSCs are installed on the south facade with a total collector area of 207.5 m^2 and tilt of 90°. The hot air from the solar collectors is mixed with extracted building ventilation air and is fed to the air/brine heat exchanger to increase the brine temperature stream and thus the HP performance.

Meteorological parameters

The variation in monthly average global irradiation on the horizontal surface and the vertical South surface is shown in Figure 4. The annual global horizontal irradiation for the location is 971 kWh/m^2 and has a large seasonal variation. The annual average wind speed and ambient temperature for the location is 3.3 m/s and 4 °C respectively.

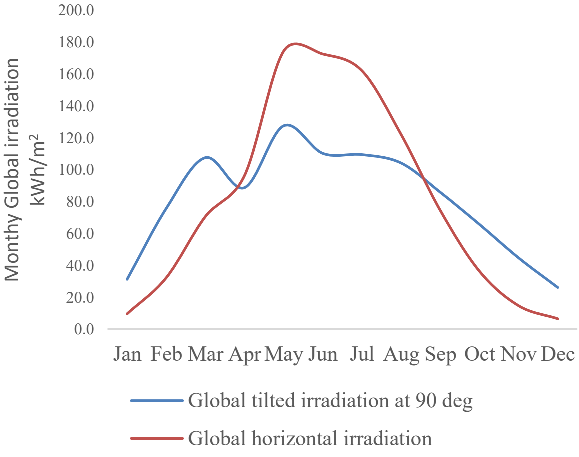

Figure 4 Monthly irradiation variation for project location

TRNSYS model description

The proposed energy system is modelled in TRNSYS 18 using appropriate types available in the components library. A quick overview of components used in the system is given in Table 1 with a brief description.

Table 1 Components overview for the developed model

Key elements	TRNYS type	Description
EAHP	Type 1927	The performance map model uses manufacturer's catalogue data and performance map under wide range of independent variable conditions. A scaling function is used to adapt the HP capacity based on the proposed heating system.
Air brine heat exchanger	Type 508b	This component model the heat transfer from ventilation air to the brine loop of HP.
Storage tanks	Type 158	This type model the DHW storage (2.5 m^3) and SH buffer (0.35 m^3) using a constant volume storage tank with a vertical configuration.
Auxiliary heater Type	Type 138	This component conditions the existing pellet boiler as a back-up source, with electricity to heat conversion factor of 0.9.
Hydronics	Valves (Type 11)	Control the flow direction in response to the receiving signals.
	Pumps (Type 114 & 742)	Variable speed pumps in SH and DHW circuit and to maintain outlet mass flow and temperature according to set points.
Transpired air solar collector	Type 201	An unglazed transpired plate model developed and validated as part of IEA SHC task 35 (Delisle, V, 2007).
Weather data	Type 15	Ground based weather data of year 2014 for Borlänge location, which is the closest weather station to the project location.
Heating loads	Type 9	One input file for all 3 buildings is used for SH and DHW loads.

System controls

The HP operates in either SH or DHW mode, and is governed by using a differential control (Type 165) to prioritize the DHW tank charging. The HP runs in DHW mode when the water temperature at bottom of DHW tank falls below a set point minus a hysteresis of 6 ℃ . The HP compressor works at full speed in DHW mode to charge the tank as quickly as possible. An external heat exchanger (Type 5) in counterflow mode and a variable speed water pump is used to prepare the hot water. The variation in the inlet DHW temperature is considered based on ambient temperature. When the DHW tank is fully charged, the HP switches to SH mode. The compressor speed is adapted in SH mode using a PID (proportion integration differentiation) controller (Type 22) to reach design supply temp at the radiator inlet. The supply temp to the radiator inlet is varied depending on the ambient temp according to the space heating curve. The mass flow variation in the radiator is obtained using PID controller to generate a control signal based on input parameters and setpoint temperature. The auxiliary electric heater is placed in both SH and DHW circuit and it adapts the capacity to provide heating rate required to reach set points in both circuits. The HP is turned off when the DHW tank is fully charged and SH demand is zero. The solar collector is simulated using Type 201, is mounted vertically on the South facade, and is integrated into a series arrangement with HP where the hot air is indirectly used as the heat source for heat pump evaporator in addition to exhaust ventilation air. The flow rate controls for the TSC are obtained using variable speed fan (Type 147), PID controller and equation blocks to control the fan speed. The fan starts only if the irradiation on the collector plane is more than 100 W/m^2 and varies the airflow rate to reach an outlet air temperature of more than 21 ℃ , while keeping the minimum collector efficiency limit, and maximum brine temperature limit.

Key performance indicators

The following energetic KPIs are used in this paper for results discussion and system modus operandi.

Component performance figures

Coefficient of performance: The COP of the heat pump is the ratio between heating capacity ($Q_{hp,h}$), and electricity consumption ($P_{el,hp}$), and is given in the Equation 1.

$$COP = \frac{Q_{hp,h}}{P_{el,hp}} \qquad (1)$$

Collector energy utilization ratio: It depicts the performance of solar collector (or field) over a specific period as given in Equation 2, where Q_{coll} is the annual thermal output of solar collector in kWh, G_{coll} is global irradiation on the collector plane in kWh, and A_{coll} is the gross area of the collector in m^2.

$$\omega_{th} = \frac{Q_{coll}}{\int G_{coll} dt\, A_{coll}} \qquad (2)$$

System performance figures

Total electricity use (P_{el}): It is used to define the electricity used by system components such as HP, auxiliary heater, pumps, and fans, etc. For the given system integrated with the solar collector, total electricity use is described as per Equation 3, where the $P_{el,hp}$, $P_{el,wp}$, $P_{el,aux}$, $P_{el,fan}$ are electricity consumption of HP, water pumps, auxiliary, and fan respectively.

$$P_{el} = P_{el,hp} + P_{el,wp} + P_{el,aux} + P_{el,fan} \qquad (3)$$

In case when the solar collector is not integrated, the power consumption of fans and relevant pumps is not considered.

Seasonal performance factor: SPF is used to express the final energy efficiency of the whole system and is defined as the ratio of total useful thermal energy supplied to the user ($Q_{SH} + Q_{DHW}$) to the total electricity use (P_{el}) of the system. The SPF can be defined as per Equation 4

$$SPF = \frac{Q_{SH} + Q_{DHW}}{P_{el,hp}} \qquad (4)$$

Results

The energy system is simulated with a time step of one minute for a period of one year. The results show that HP supports 51.1 % of total heating load, whereas the rest of the demand is met using the auxiliary heating system. The HP covers all the DHW load and 37 % of the SH load, and the rest of the SH load is covered by Auxiliary (Q_aux_sh) as shown in Figure 5. The annual heat losses from SH (Q_loss_sh) and DHW tank (Q_loss_dhw) are 600 kWh and 4200 kWh respectively.

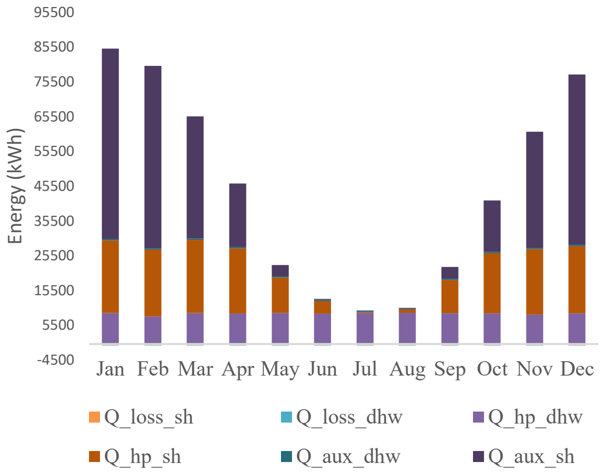

Figure 5 : Energy balance for the proposed system

The total electricity use P_{el} for the system is 368 MWh, and is shown in Figure 6. Over 80 % of electricity is used by the auxiliary heating system, anda 16.8 % is used by HP compressor. Other system components such as fans, and pumps consume 2.1 % of the total electricity. The SPF of the complete system is 1.43. The annual average COP of the heat pump is 4.55 and the monthly variation in HP COP is shown in Figure 7. The HP performs more efficiently in the winter (November-February) period as it operates majorly in SH mode and thus with a lower water outlet temp. However, in a period from July to August, the SH load is negligible and thus HP operates majorly in DHW mode with a higher designed water temp compared to SH system, which results in a lower COP. The period from April to June and September to October shows a large variation in HP COP, as it operates in almost equally in both DHW and SH mode.

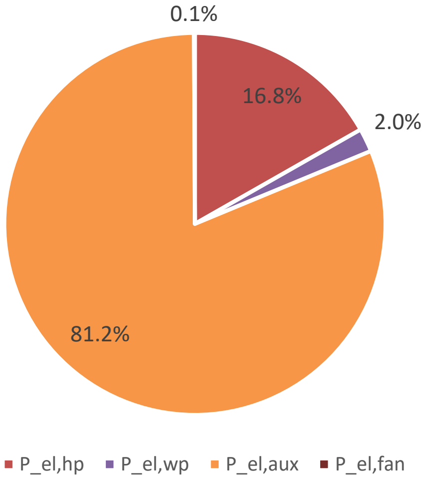

Figure 6 : Electrical consumption % of system components

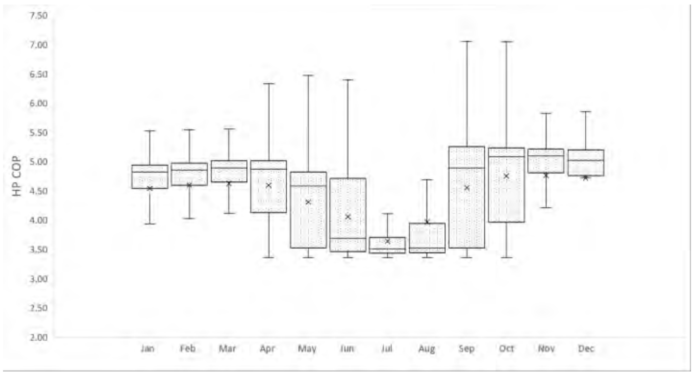

Figure 7 : Monthly variation in HP COP.

The annual thermal output of the solar collector field is 36 MWh, and the annual utilization factor ω_{th} is 0.18. The variation in monthly specific thermal output of the collector is shown in Figure 8.

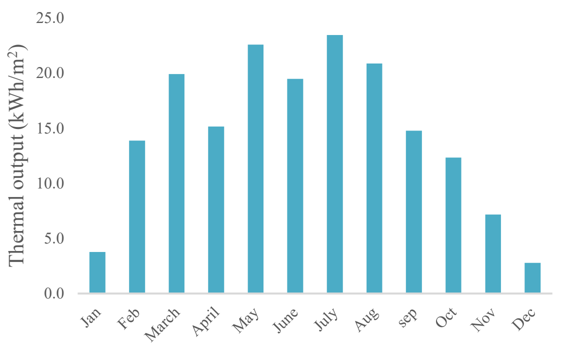

Figure 8 : Thermal output variation for solar collector

Effect of fixed collector flow rate on system performance

In the reference system, the airflow rate behind the collector surface is controlled using a variable speed fan and a PID controller. The fan adjusts the flow rate based on the global irradiation, ambient temperature, and brine temperature to reach a design collector outlet temperature. The minimum and maximum limit of design outlet air temperature is governed by exhaust ventilation air temp and brine temperature into HP respectively. However, in most of the installations, TSCs are installed with fixed design flow, without any fan speed control provision. Therefore, a comparative analysis is carried by simulation of an energy system with a fixed collector flow rate of 60 $\mathrm{kg/(h \cdot m^2)}$ as used in most of the real installations. Figure 9 compares the monthly HP COP for reference case (variable flow), and a fixed flow case.

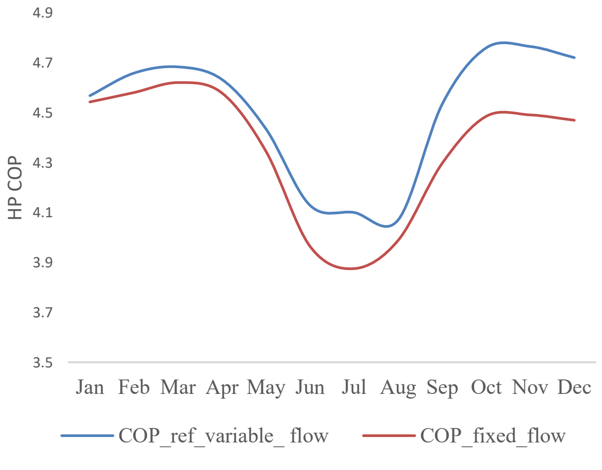

Figure 9 : HP COP variation for various flow conditions

The results show that HP COP is higher with variable airflow, as the variation in airflow allows to leverage the lower irradiation in the winter months to heat the ambient air above the ventilation air temperature, and thus increasing the HP COP. However, in a fixed flow case, the collector outlet air temperature seldom exceeds the ventilation air temperature during winters and thus the HP COP is lower. During summer with high irradiation, the fixed flow control strategy exceeds the maximum limit of design outlet air temperature, and thus the partial volume of the heated air needs to bypass to keep the HP brine temperature below the maximum limit, and thus the HP COP is lower than variable flow rate case which can provide a higher volume of the air at maximum design temperature. The SPF for the fixed flow case is 0.5 % lower than the reference case.

Effect of collector area on the total electricity use

The effect of TSCs area on the HP performance and total electricity use is investigated. The collector area and fan capacity are varied using a scale factor of 0, 0.5, 0.75, 1.5 in comparison to the reference system. The change in total electricity use (ΔP_{el}) is used as an indicator which is the difference in the total electricity use of the system under study and the of the reference system (P_{el}). The variation in (ΔP_{el}) and SPF for various collector area is shown in Figure 10. The results show that higher collector area results in lower total electricity use, and thus lower ΔP_{el}. A system without any solar collector (scale factor = 0) installation consume nearly 1700 kWh of additional electricity compared to the reference system. Similarly, a small increase in SPF can be seen at higher collector areas.

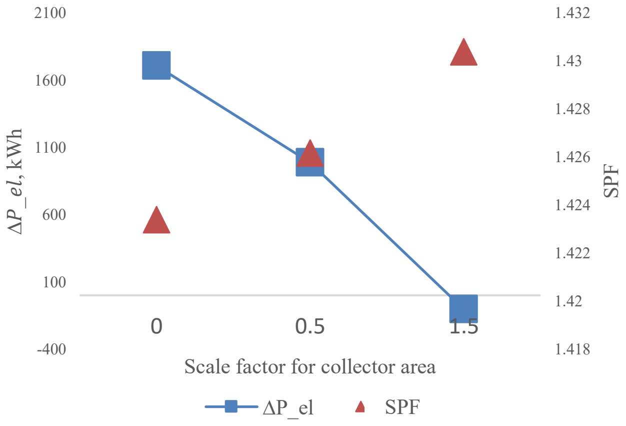

Figure 10 : SPF and electricity variation at various collector area

Conclusions

From the analysis of the results applied to a residential building cluster in Sweden, it can be seen that the integration of TSCs has a small but positive impact on the overall system performance. A system without any solar collector installation consume nearly 1700 kWh of additional electricity compared to the reference system. Furthermore, it can be concluded that the variation of the collector air flow rate can be used as an effective control strategy to increase the annual HP COP and thus the SPF of the overall system to maximize the savings. The result shows that the simulated reference system has SPF of 1.43, and annual collector energy utilization factor of 0.18. The optimization and variation in collector flow rate resulted in a 2 % increase in HP COP and a 0.5 % increase in system SPF in comparison to a fixed flow rate case. Furthermore, the sensitivity analysis shows that an increase in the collector area can result in lower total electricity use, and thus higher SPF. Compared to the conventional roof-mounted liquid-based solar collector, a transpired solar collector component can be easily mounted on building facades, and does not require any hydronic system. This results in reduction of major space/cost in installation and systems. However, lower irradiation in Nordic climates can be a limiting factor for the annual performance of these collectors, and thus can be a barrier for wide adaption of the technology for the proposed system configuration. The future work includes testing of improved airflow control strategies and system analysis for southern European climates.

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