Analysis of operation performance of three indirect expansion solar assisted air source heat pumps for domestic heating

Li Wei Yang[a], Nan Hua[a], Jin Huan Pu[a], Yu Xia[a], Wen Bin Zhou[b], Rong Ji Xu[c], Tong Yang[d], Yerzhan Belyayev[e], Hua Sheng Wang[a*]

[a]School of Engineering and Materials Science, Queen Mary University of London, Mile End Road, London E1 4NS, UK
[b]Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, UK
[c]Beijing University of Civil Engineering and Architecture, Beijing 100044, China
[d]Faculty of Science and Technology, Middlesex University, London NW4 4BT, UK
[e]Department of Mechanics, Al-Farabi Kazakh National University, Almaty, Al-Farabi ave.71, 050040, Kazakhstan

Abstract

To achieve the goal set for net-zero emissions of greenhouse gases in the UK by 2050, the domestic heating must be decarbonised. Solar assisted air source heat pumps, integrating solar collector, thermal energy storage tank and heat pump, offers a promising alternative application under the UK weather conditions. Literature review shows that investigations of solar assisted air source heat pumps in the regions like the UK are still insufficient. The serial, parallel and dual-source indirect expansion solar assisted air source heat pumps are modelled and simulated under the weather conditions in London using TRNSYS to investigate the operation performance over a typical year. These three heat pumps are applied to provide space heating and hot water of 300 L per day for a typical single-family house. The simulation results show comparisons of the three systems. The serial type heat pump shows the highest seasonal performance factor of 5.5, but requiring the largest sizes of the solar collector and thermal energy storage tank. The dual-source and parallel type heat pumps show slightly lower seasonal performance factors of 4.4 and 4.5, respectively, requiring smaller sizes of solar collector and thermal energy storage tank. Furthermore, the results show that the air source part contributes to an important proportion of the heat provision and stable operation of the systems. The yearly seasonal performance factor higher than 4.4 achievable by the three heat pumps suggests that they are potentially applied in the regions with relatively lower solar irradiance. The economic analyses indicate that the parallel and dual-source type heat pumps provide good alternatives to replacing the gas-boiler heating system.

* Corresponding to: H.S. Wang, School of Engineering and Materials Science, Queen Mary University of London, Mile End Road, London E1 4NS, UK
TEL: +44 (0)20 7882 7921
E-mail: h.s.wang@qmul.ac.uk

Highlights

- Three indirect expansion solar assisted air source heat pumps are numerically studied.
- Space heating and hot water performances of three heat pumps are examined in detail.
- Their yearly seasonal performance factors are higher than 4.4 in high latitude regions.
- The heat pumps are economically applicable in high latitude regions.

Keywords: Solar assisted air source heat pump, Seasonal performance factor, Domestic heating, Solar thermal energy, Numerical simulation

1. Introduction

In the UK, in 2017, space heating (SH) and hot water (HW) took up 80% of the total energy consumption in the domestic sector [1]. To meet the goal of the net-zero emissions of greenhouse gases by 2050, the domestic heating must be decarbonised [2]. To compensate the intermittency of solar energy availability, solar thermal energy [3] can be integrated with heating technologies [4]. Solar-assisted air source heat pump (SAASHP), combining solar thermal energy storage and heat pump (HP) [5], is promising to achieve the decarbonised domestic heating [6].

SAASHPs include direct expansion SAASHPs (DX-SAASHPs) and indirect expansion SAASHPs (IX-SAASHPs). In the DX-SAASHPs, the solar collector serves as the evaporator. In the IX-SAASHPs, the solar collector transfers heat to the water which is circulated either through the evaporator of the heat pump or through the heat exchanger in the thermal energy storage (TES) tank. IX-SAASHPs have shown high potential for domestic SH and HW [7]. The serial, parallel and dual-source IX-SAASHPs have been developed.

In the past two decades, many investigations of IX-SAASHPs for SH and/or HW in the domestic heating sector have been conducted. Table 1 summarises some earlier studies on SAASHPs operation in relatively higher latitude regions. Summaries of more studies on SAASHPs are given in [7]. Freeman et al. [8] numerically simulated three types of IX-SAASHPs for SH of a room with the floor area 120 m^2 and HW of 279.5 L per day. The averaged *COP*s of these heating systems are 2.0 for parallel IX-SAASHP, 2.5 for dual-source IX-SAASHP and 2.8 for serial IX-SAASHP. Fraga et al. [9] monitored the performance of a serial IX-SAASHP providing SH and HW for an apartment block with a floor area of 927 m^2 (80 flats). The seasonal performance factor (*SPF*) of this IX-SAASHP is 2.9. Ji et al. [10] reported measurements of a triple-functional dual-source IX-SAASHP for SH, space cooling (SC) and HW using an enthalpy-difference test facility. The *COP*s of the system range from 1.75 to 3.0 in the HW operation mode and from 2.35 to 2.75 in the SH operation mode. Further experimental studies of this system using a lager water TES tank show the averaged COP_s of 2 - 3.25

and 2.25 - 2.5, respectively [11]. Poppi et al. [12] numerically simulated two parallel IX-SAHPs providing SH and HW for single family houses (SFH) named as 45 and 100. The *SPF*s of the two IX-SAHPs vary from 2.43 to 3.85 when the ambient temperature are -10 ^{o}C and -5 ^{o}C in Zurich and Carcassonne, respectively. Liu et. al. [13] presented measurements of a dual-source IX-SAASHP for SH and HW using a novel composite heat exchanger as the evaporator. The *COP* of the system ranges from 2.0 to 3.1. Ran et al. [14] numerically simulated the performance of a dual-source IX-SAASHP for SH and HW operation in cities of Lhasa, Chengdu, Beijing and Shenyang in China having significantly different weather conditions. The *SPF*s of the system operation in these locations are 6.92, 3.61, 3.27 and 2.45, respectively. The latitudes of these locations are below 50^{o}. The high *SPF* of the system operation in Lhasa plateau is attributed to the high solar irradiance due to the extremely high elevation.

Some studies have been reported for applications of SAASHPs in relatively high latitude regions. Kutlu et al. [15] numerically simulated a serial IX-SAASHP using phase change material (PCM) for TES and the evacuated-tube solar collector for HW. The evacuated tube reduces the heat loss and hence increases the collector efficiency. The *COP* of the system achieves from 3.4 to 4.6 under the UK summer weather conditions. Yerdesh et al. [16] numerically simulated a solar assisted two-stage cascade HP for SH and HW under the weather conditions in Kazakhstan. The maximum *COP* of the system is 2.4 for each stage of the HP using R32 and R290, respectively. Treichel and Cruickshank [17-19] studied experimentally and numerically a serial IX-SAASHP using a novel air-type solar collector for HW under the Canadian weather conditions. The *COP* of the system ranges from 1.9 to 2.4. Ma et al. [20] numerically studied the applicability of a two-stage serial IX-SAASHP, using R410A and CO_2 as the working fluids, for SH under the weather conditions in Canada.

This work aims to investigate the feasibility for applications of SAASHPs in relatively high latitude regions such as London in the UK (51.5^{o} N). A typical single-family house is taken from a reference building given in the International Energy Agency (IEA) Standard [21] with geometrical dimensions and relevant properties. The serial, parallel and dual-source type IX-SAASHPs are used to provide SH and HW of 300 L per day. The three types of IX-SAASHPs are modelled and simulated using TRNSYS 17 based on a typical meteorological year. The *SPF* and economic performance of the SAASHPs are compared in view of the electricity generation scenarios and the guidelines to adopt heat pumps under the net zero carbon emission in the UK by 2050. For the purpose of comparing the true characteristics of the heating systems, auxiliary heater is not considered in this work.

Table 1: Summary of some earlier studies on SAASHPs operation in relatively higher latitude regions

Authors	Location	Function	Refrigerant	Collector		Storage volume (m^3)	T_{amb} (°C)	*HC* (kW)	*COP*	*SPF*	System category
				Type	Area (m^2)						
Freeman et al., 1979 [8]	Madison, USA 43°N Albuquerque, USA 35°N Charleston, USA 38°N	SH for a room of 120 m^2, HW of 279.5 L daily	-	FPC	10, 20 30, 40 50, 60	0.075 per m^2 solar collector	-	1.95 (SH), 0.68 (SH) 0.94 (SH), 0.68 (SH) 0.485 (SH), 0.68 (SH)	2 (parallel) 2.5 (dual-source) 2.8 (serial)		Parallel IX-SAASHP, Dual-source IX-SAASHP, Serial IX-SAASHP
Fraga et al., 2015 [9]	Geneva, Switzerland 46 °N	SH for a block of 927 m^2, HW	-	bare FPC	116	6 + 0.3×8	-2.4-20.5	2.13 (SH), 5.28 (SH)	-	2.9	Serial IX-SAASHP
Ji et al., 2015 [10]	Hefei, China 32 °N	SH, SC, HW	-	FPC	3.2	0.2	7	1.2-2.4 (HW) 1.4-2.2 (SH)	1.75-3 (HW) 2.35-2.75 (SH)		Dual-source IX-SAASHP
Cai et al., 2016 [11]	Hefei, China 32 °N	SH, SC, HW	-	FPC	3.2	0.3	7	1.9-2.4 (HW) 1.3-1.5 (SH)	2-3.25 (HW) 2.25-2.5 (SH)		
Poppi et al., 2016 [12]	Zurich, Switzerland, 47°N	SH for a room of 140 m^2, HW	R410A	FPC	9.28	0.763	-10	0.347 (HW), 0.944 (SH)		3.16	Parallel IX-SAASHP
								0.347 (HW),		2.43	

								1.966 (SH)			
	Carcassonne, France 43°N						-5	0.307 (HW), 0.419 (SH)		3.85	
								0.307 (HW), 1.047 (SH)		2.93	
Liu et al., 2016 [13]	Zhengzhou, China 34°N	SH, HW	-	FPC	-	-	-15, -10, -7, -5, 2, 7	1.2-2.9	2-3.1		Dual-source IX-SAASHP
Ran et al., 2020 [14]	Lhasa, China 29.5ºN	SH, HW	-	FPC	300	10	-	120	-	6.92	Dual-source IX-SAASHP
	Chengdu, China 30.7ºN							90	-	3.61	
	Beijing, China 40.1 ºN							180	-	3.27	
	Shenyang China 41.8ºN							270	-	2.45	
Kutlu et al., 2020 [15]	UK	HW	R134a	evacuated tube	4	0.15 (PCM)	9–25	–	3.4–4.6	-	Serial IX-SAASHP
Yerdesh et al., 2020 [16]	Kazakhstan	HW, SH	R134a/R410A, R32/R290, R32/R1234yf, R32/R134a, R410A/R290, R410A/R1234yf, R744/R290, R744/R1234yf, R744/R134a	FPC	6	0.3	-30-10	-	1.8-3	-	A solar assisted cascade HP
Treichel and Cruickshank,	Canada and US	HW	R134a	air-type solar collector	1.26	0.189	-	-	1.9-2.4	-	Serial IX-SAASHP

2021 [17], [18], [19]											
Ma et al., 2020 [20]	Canada	SH	CO_2, R410A	-	70	3	-6.6-12.7	-	-	-	A two-stage serial IX-SAASHP

2. Reference building and heat demand

The building of SFH 45 given in the IEA standard [21] is selected as the reference building for domestic heating. The geometrical dimensions and relevant properties are given in [21]. The indoor floor area of the building is 140 m^2. The radiant floor is used as the heating method. Table 2 gives the parameters and their values of TRNSYS module for modelling the temperature of house ground. Figure 1 shows hourly cooling (positive) and heating (negative) loads of the house SFH 45 at room air temperature T_{room} of 18 °C over a typical year of weather conditions in London. The peak and the averaged heating loads are seen to be 3.15 kW and 1.24 kW, respectively.

Table 2: TRNSYS module for modelling the temperature of house ground

Component	Module	Parameter	Value
Ground temperature	Type 501	Mean surface Temperature	10.78 °C
		Amplitude of surface temperature	18.04 °C
		Time shift	12^{th} day
		Depth at point	0.445 m

For the reference building of SFH 45, IEA recommends the SH period to be days when the 24-hour averaged ambient air temperature is below 14 °C. Under the weather conditions in London, the results show that the SH period is from 0 to 2736 hour and from 7224 hour to 8760 hour of the year, corresponding to the heating season from 1st October to 30th April. The rest period of the days is the non-heating season.

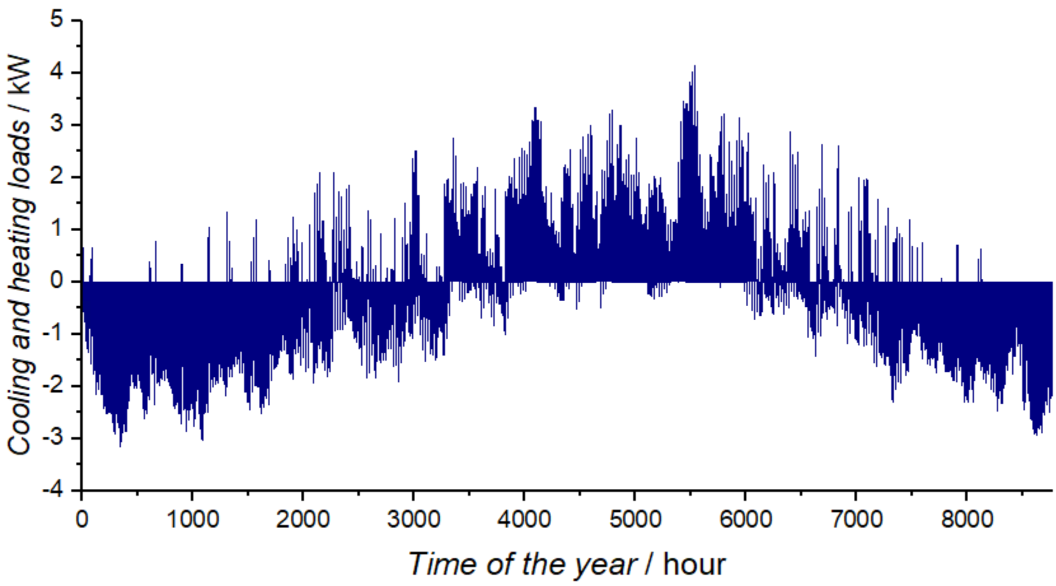


Figure 1: Hourly cooling (positive) and heating (negative) loads of the house SFH 45 at room air temperature T_{room} of 18 °C over a typical year of weather conditions in London.

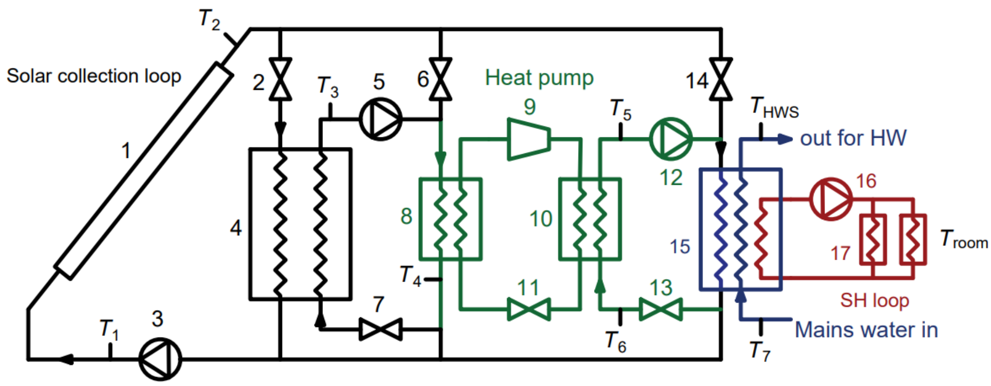
3. Description of the heating systems

In this work, serial, parallel and dual-source IX-SAASHPs are modelled and simulated using TRNSYS 17. Water is used as the medium to transport heat and to store thermal energy. Refrigerants R134a and R410A are used as the working fluids of SWHP and ASHP, respectively. In each HP system, two water tanks are employed for TES. One tank stores thermal energy collected by the solar collector and the other serves as TES for the end use i.e. providing HW and/or SH. Details about the systems are described below.

3.1 Serial system

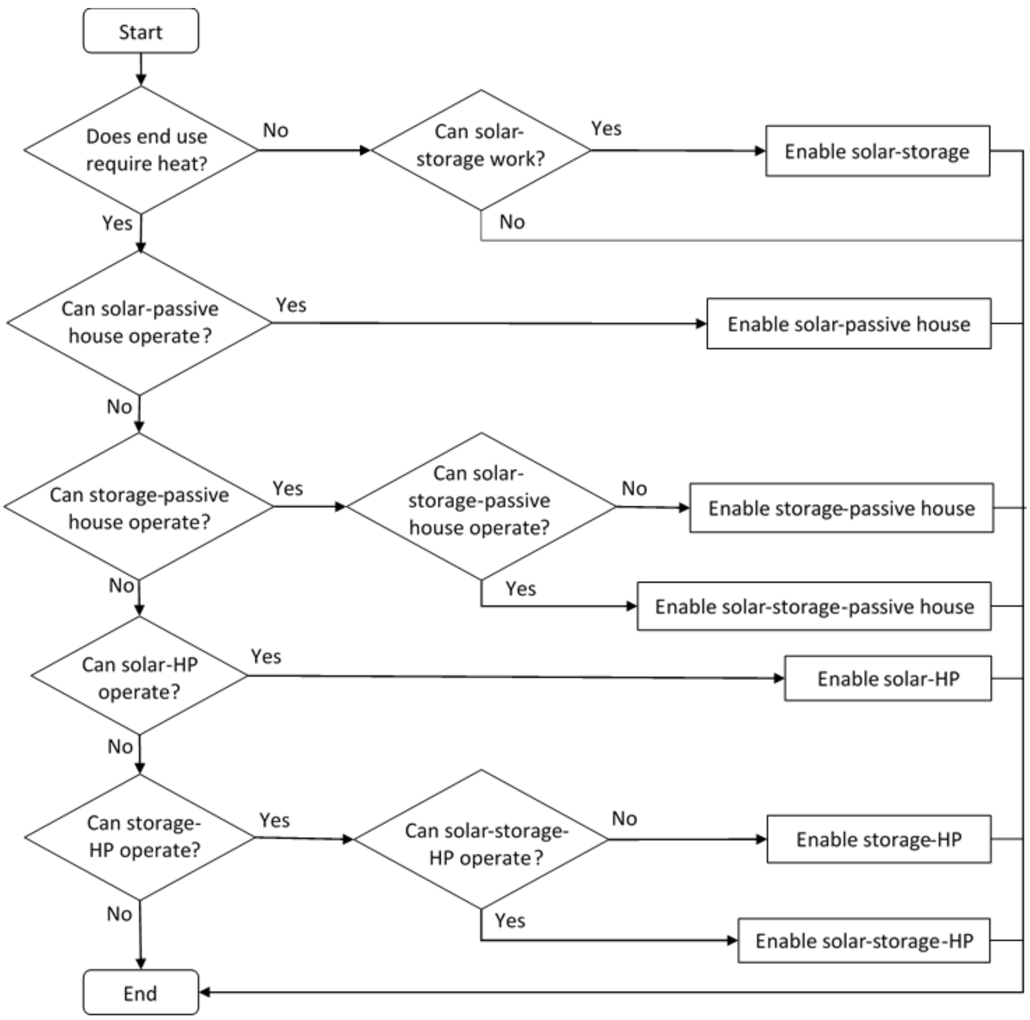
Figure 2(a) shows a serial IX-SAASHP system, which consists of a solar collection loop (in black), a SWHP unit (in green), a HW loop (in blue) and a SH loop (in red). The solar collector converts solar energy into thermal energy and the heat is transferred to water being circulated by pump 1 (3). The thermal energy is normally stored in the TES tank 1 (valve 2 open) but the hot water can also be circulated to either SWHP (valves 2 and 14 closed, valve 6 open) or to the TES tank 2 (valves 2 and 6 closed, valve 14 open). The SWHP consists of a water-to-refrigerant evaporator (8), a compressor (9), a condenser (10), and an expansion valve (11). When the SWHP is in operation, the TES tank 1 (4) serves as the low-temperature heat source and the TES tank 2 (15) serves as the high-temperature heat source. When the system provides hot water, the mains cold water flows into the TES tank 2. When the system is in operation for heating, the pump 4 (16) circulates the hot water in the TES tank 2 through the radiant floor (17).

Figure 2(b) shows the flow chart for control of the serial system operation. The room air temperature (T_{room}), ambient air temperature (T_{amb}), local solar irradiance (I) as well as water temperatures at several locations such as the temperatures at the inlet and outlet of the solar collector (T_1, T_2), the temperature at the outlet of TES tank 1 to load (T_3), hot water storage (HWS) temperature (T_{HWS}) are measured/monitored for control of the serial system operation. The water temperature at the outlet of the evaporator (T_4), the water temperatures at the inlet and outlet of the condenser (T_5 and T_6) and the temperature of the mains cold water supply (T_7) are measured/monitored for analysis of energy conservation of the heating system. Table 3 gives the rule-based look-up table for control of the serial system operation.



1: Solar collector 2, 6, 7, 13, 14: Valves 3: Pump 1 4: TES tank 1 5: Pump 2
8: Water-to-refrigerant evaporator 9: Compressor 10: Condenser
11: Expansion valve 12: Pump 3 15: TES tank 2 16: Pump 4 17: Radiant floor

a) Schematic of the serial system



b) Flow chart for system operation control

Figure 2: System and operation control of the serial IX-SAASHP

Table 3: The rule-based look-up table for control of the serial system operation

Operation mode	**Temperature range (°C)**	**Pumps**				**Valves**					**SWHP**
		3	5	12	16	2	6	7	13	14	
Collector–TES 1	$T_2 > T_3$, $T_{HWS} > 50$	O	X	X	X	O	X	X	X	X	X
Collector–TES 1–TES 2	$T_2 > T_3 > 50 > T_{HWS}$	O	O	X	X	O	O	O	X	O	X
Collector-TES 1–SWHP-TES 2	$T_2 > T_3$, $-5 < T_3 < 50$, $T_{HWS} < 50$	O	O	O	X	O	X	O	O	X	O
Collector–SWHP-TES 2	$T_2 < T_3$, $50 > T_2 > -5$, $T_{HWS} < 50$	O	X	O	X	X	O	X	O	X	O
Collector-TES 2	$T_{HWS} < 50 < T_2 < T_3$	O	X	X	X	X	X	X	X	O	X
TES 1–TES 2	$T_3 > 50 > T_{HWS}$	X	O	X	X	X	O	O	X	O	X
TES 1–SWHP-TES 2	$-5 < T_3 < 50$, $T_{HWS} < 50$	X	O	O	X	X	X	O	O	X	O
SH: TES 2	$T_{room} < 18$	X	X	X	O	X	X	X	X	X	X
SH: Collector–TES 1	$T_2 > T_3$, $T_{HWS} > 50$, $T_{room} < 18$	O	X	X	O	O	X	X	X	X	X
SH: Collector–TES 1–TES 2	$T_2 > T_3$, $T_{HWS} < 50$, $T_{room} < 18$	O	O	X	O	O	O	O	X	O	X
SH: Collector–TES 1–SWHP–TES 2	$T_2 > T_3$, $-5 < T_3 < 50$, $T_{HWS} < 50$, $T_{room} < 18$	O	O	O	O	O	X	O	O	X	O
SH: Collector–SWHP–TES 2	$T_2 < T_3$, $50 > T_2 > -5$, $T_{HWS} < 50$, $T_{room} < 18$	O	X	O	O	X	O	X	O	X	O
SH: Collector-TES 2	$T_{HWS} < 50 < T_2 < T_3$, $T_{room} < 18$	O	X	X	O	X	X	X	X	O	X
SH: TES 1-TES 2	$T_3 > 50 > T_{HWS}$, $T_{room} < 18$	X	O	X	O	X	O	O	X	O	X
SH: TES 1–SWHP -TES 2	$-5 < T_3 < 50$, $T_{HWS} < 50$, $T_{room} < 18$	X	O	O	O	X	X	O	O	X	O

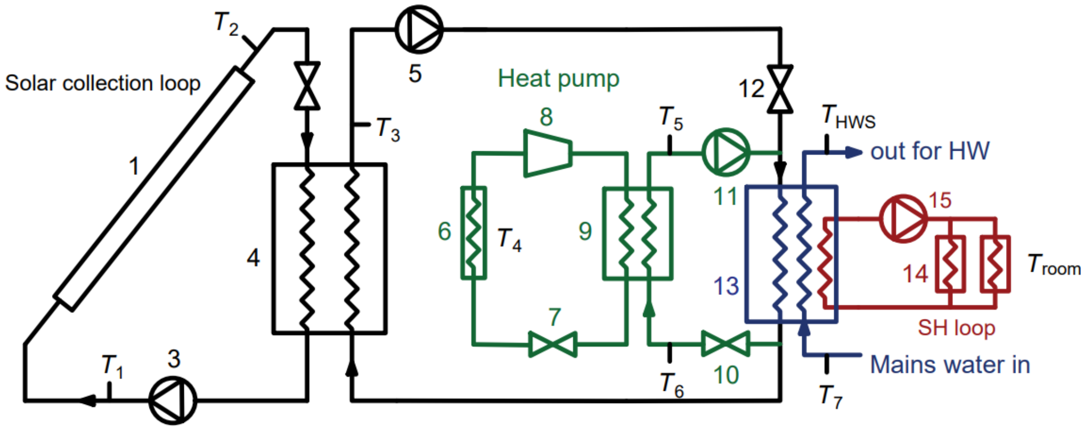
Note: Collector: Solar collector. TES 1: Water TES tank1. TES 2: Water TES tank 2.

O: Pumps and SWHP are in operation; Valves is open. X: Pumps and SWHP are not in operation; Valves are closed.

3.2 Parallel system

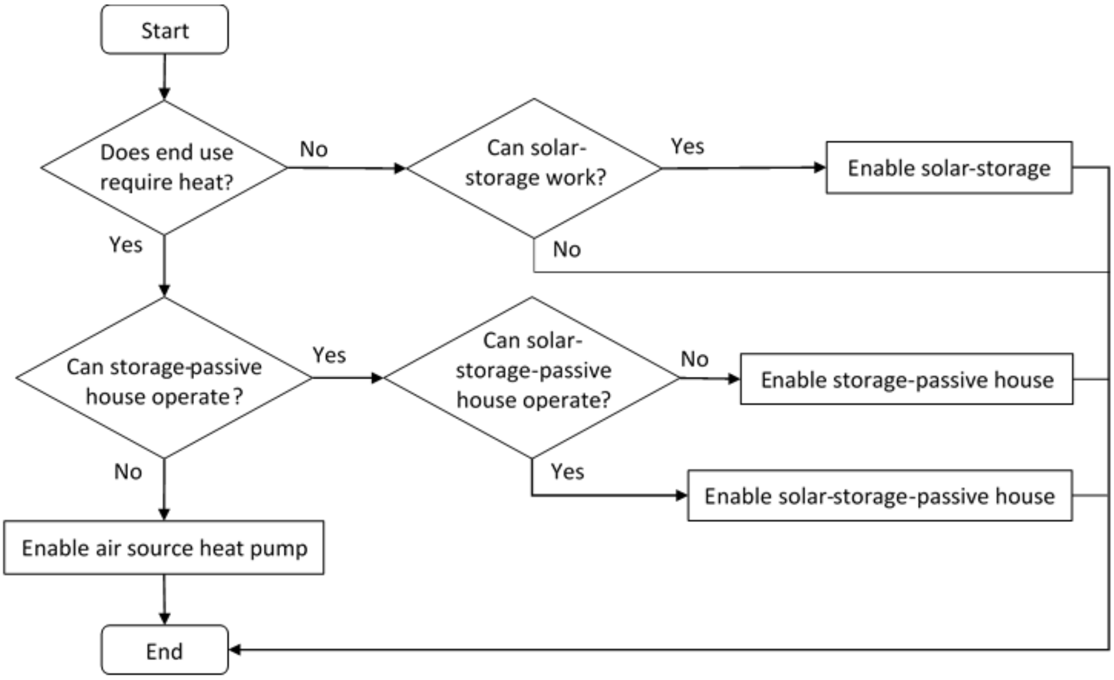
Figure 3 shows a parallel IX-SAASHP, which consists of a solar collection loop (in black), an ASHP unit (in green), a HW loop (in blue) and an SH loop (in red). The thermal energy is stored in the TES tank 1 (valve 2 open) and circulated to TES tank 2 by pump 2 (valve 12 open). The ASHP consists of an air-to-refrigerant evaporator (6), an expansion valve(7), a compressor (8) and a condenser (9). When the ASHP is in operation, the ambient air serves as the low-temperature heat source.

Figure 3(b) shows the flow chart for control of the parallel system operation. Compared with the serial system, the same temperatures are measured/monitored for control of the parallel system operation. The air temperature at the outlet of the evaporator (T_4), the water temperatures at the inlet and outlet of the condenser (T_5 and T_6) and the temperature of the mains cold water supply (T_7) are measured/monitored for analysis of energy conservation of the heating system. Table 4 gives the rule-based look-up table for control of the parallel system operation.



1: Solar collector 2, 10, 12: Valves 3: Pump 1 4: TES tank 1 5: Pump 2
6: Air-to-refrigerant evaporator 7: Expansion valve 8: Compressor
9: Condenser 11: Pump 3 13: TES tank 2 14: Radiant floor 15: Pump 4

a) Schematic of parallel system



b) Flow chart for system operation control

Figure 3: System and operation control of the parallel IX-SAASHP

Table 4: The rule-based look-up table for control of the parallel system operation

Operation mode	**Temperature range (ºC)**	**Pumps**				**Valves**			**ASHP**
		3	5	11	15	2	10	12	
Collector-TES 1	$T_2 > T_3$, $T_{HWS} > 50$	O	X	X	X	O	X	X	X
Collector–TES 1-TES 2	$T_2 > T_3 > 50 > T_{HWS}$	O	O	X	X	X	X	O	X
ASHP-TES 2	$T_3 < 50$, $T_{HWS} < 50$	X	X	O	X	X	O	X	O
TES 1–TES 2	$T_3 > 50 > T_{HWS}$	X	O	X	X	X	X	O	X
SH: TES 2	$T_{room} < 18$	X	X	X	O	X	X	X	X
SH: Collector-TES 1	$T_2 > T_3$, $T_{HWS} > 50$, $T_{room} < 18$	O	X	X	O	O	X	X	X
SH: Collector–TES 1–TES 2	$T_2 > T_3 > 50 > T_{HWS}$, $T_{room} < 18$	O	O	X	O	X	X	O	X
SH: ASHP–TES 2	$T_3 < 50$, $T_{HWS} < 50$, $T_{room} < 18$	X	X	O	O	X	O	X	O
SH: TES1–TES 2	$T_3 > 50 > T_{HWS}$, $T_{room} < 18$	X	O	X	O	X	X	O	X

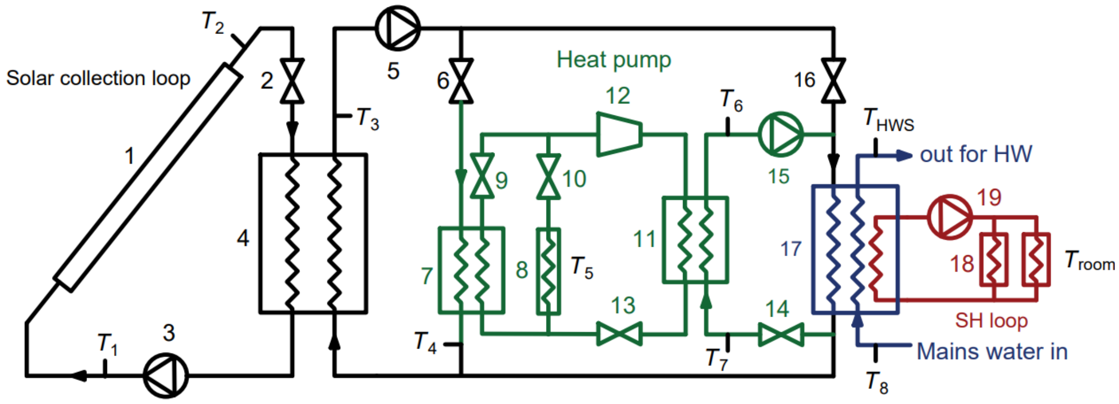
Note: Collector: Solar collector. TES 1: Water TES tank1. TES 2: Water TES tank 2.

O: Pumps and ASHP are in operation; Valves is open. X: Pumps and ASHP are not in operation; Valves are closed.

3.3 Dual-source system

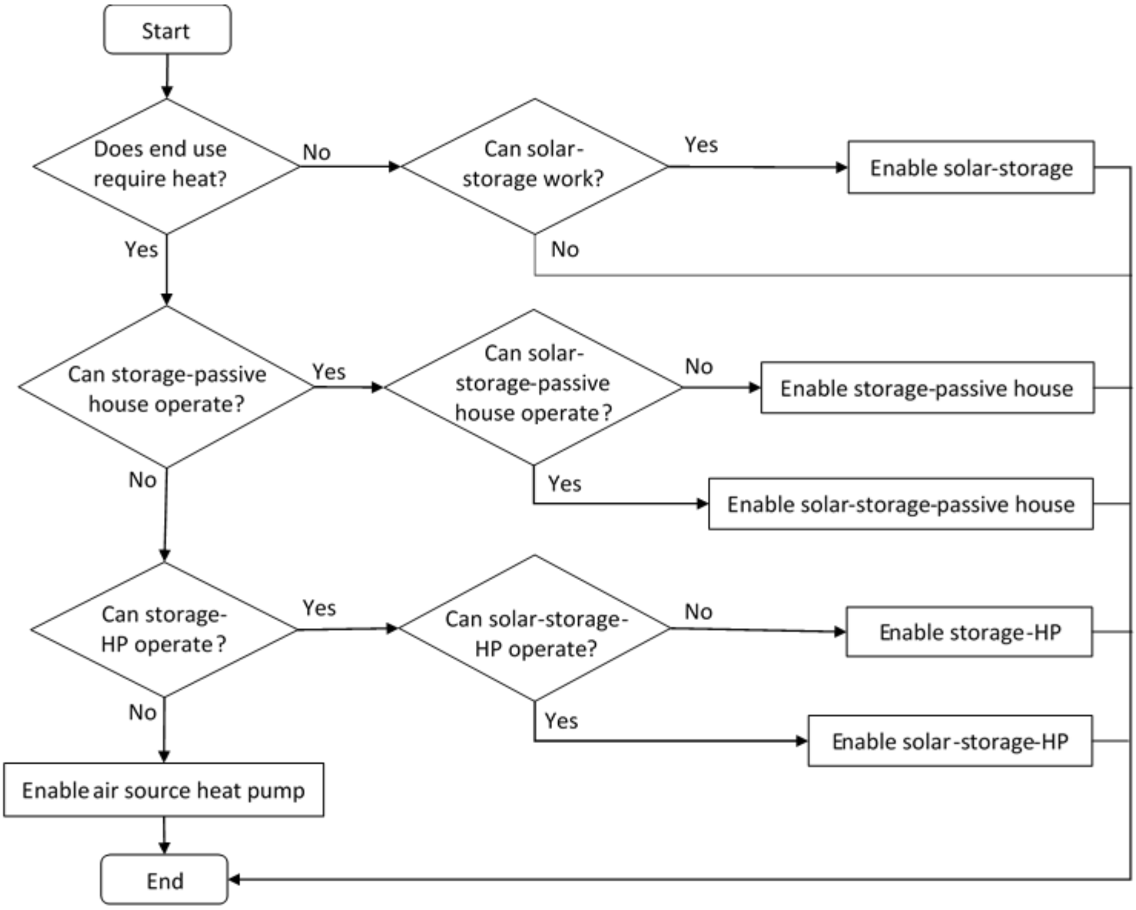
Figure 4 shows a dual-source IX-SAASHP, which consists of a solar collection loop (in black), a SW-ASHP unit (in green), a HW loop (in blue) and an SH loop (in red). The SW-ASHP consists of a water-to-refrigerant evaporator (7), an air-to-refrigerant evaporator (8), a condenser (11), a compressor (12), and an expansion valve (13). When the SWHP is in operation, the TES tank 1 (4) serves as the low-temperature heat source. When the ASHP is in operation, the ambient air serves as the low-temperature heat source.

Figure 4(b) shows the flow chart for control of the dual-source system operation. Compared with the serial and parallel systems, the same temperatures are measured/monitored for control of the dual-source system operation. The water and air temperatures at the outlet of the evaporator (T_4 and T_5), the water temperatures at the inlet and outlet of the condenser (T_6 and T_7) and the temperature of the mains cold water supply (T_8) are measured/monitored for analysis of energy conservation of the heating system. Table 5 gives the rule-based look-up table for control of the dual-source system operation.



1: Solar collector 2, 6, 9, 10, 14, 16: Valves 3: Pump 1 4: TES tank 1 5: Pump 2
7: Water-to-refrigerant evaporator 8: Air-to-refrigerant evaporator
11: Condenser 12: Compressor 13: Expansion valve 15: Pump 3
17: TES tank 2 18: Radiant floor 19: Pump 4

a) Schematic of dual-source system



b) Flow chart for system operation control

Figure 4: System and operation control of the dual-source IX-SAASHP

Table 5: The rule-based look-up table for control of the dual-source system operation

Operation mode	**Temperature range (ºC)**	**Pumps**				**Valves**						**ASHP**	**SWHP**
		3	5	15	19	2	6	9	10	14	16		
Collector-TES 1	$T_2 > T_3$, $T_{HWS} > 50$	O	X	X	X	O	X	X	X	X	X	X	X
Collector-TES 1-TES 2	$T_2 > T_3 > 50 > T_{HWS}$	O	O	X	X	O	X	X	X	X	O	X	X
Collector-TES 1–SWHP-TES 2	$T_2 > T_3$, $T_{amb} < T_3 < 50$, $T_{HWS} < 50$	O	O	O	X	O	O	O	X	O	X	X	O
ASHP-TES 2	$T_{amb} > T_3$, $T_{HWS} < 50$	X	X	O	X	X	X	X	O	O	X	O	X
TES 1-TES 2	$T_3 > 50 > T_{HWS}$	X	O	X	X	X	X	X	X	X	O	X	X
TES 1–SWHP-TES 2	$T_{amb} < T_3 < 50$, $T_{HWS} < 50$	X	O	O	X	X	O	O	X	O	X	X	O
SH: TES 2	$T_{room} < 18$	X	X	X	O	X	X	X	X	X	X	X	X
SH: Collector-TES 1	$T_2 > T_3$, $T_{HWS} > 50$, $T_{room} < 18$	O	X	X	O	O	X	X	X	X	X	X	X
SH: Collector-TES 1–TES 2	$T_2 > T_3 > 50 > T_{HWS}$, $T_{room} < 18$	O	O	X	O	O	X	X	X	X	O	X	X
SH: Collector-TES 1-SWHP–TES 2	$T_2 > T_3$, $T_{amb} < T_3 < 50$, $T_{HWS} < 50$, $T_{room} < 18$	O	O	O	O	O	O	O	X	O	X	X	O
SH: ASHP–TES 2	$T_{amb} > T_3$, $T_{HWS} < 50$, $T_{room} < 18$	X	X	O	O	X	X	X	O	O	X	O	X
SH: TES 1-TES 2	$T_3 > 50 > T_{HWS}$, $T_{room} < 18$	X	O	X	O	X	X	X	X	X	O	X	X
SH: TES 1–SWHP–TES 2	$T_{amb} < T_3 < 50$, $T_{HWS} < 50$, $T_{room} < 18$	X	O	O	O	X	O	O	X	O	X	X	O

Note: Collector: Solar collector. TES 1: Water TES tank1. TES 2: Water TES tank 2.

O: Pumps, SWHP and ASHP are in operation; Valves is open. X: Pumps, SWHP and ASHP are not in operation; Valves are closed.

4. Modelling and simulation methods

TRNSYS 17 is used for the simulations. The working conditions of the systems, selection of TRNSYS modules and simulation schemes are described below.

4.1 Working conditions

The systems are designed to provide SH and HW for the building over a year. The T_{room} for thermal comfort is set to be 18 °C – 22 °C in the heating season. In the HP heating mode, the water temperature in the TES tank 2 is controlled to be not lower than 50 °C [22]. Four fifteen-minute water draws per day at a rate of 300 kg/h are used to represent typical low flow showers at 6 a.m., 8 a.m., 8 p.m., and 10 p.m. every day. To avoid scalding, the hot water supply temperature is set at 40 °C [23], which is supplied by mixing the stored hot water and mains water at the outlet of the hot water tank. For safe operation of the system, in the SHW operation mode, the maximum HWS temperature is controlled to be 80 °C.

4.2 Selection of TRNSYS modules

Since flat plate solar collectors occupy about half of the current market share [7], the flat plate solar collector is selected as the solar collector. Solar collector module of Type 1b in TRNSYS is chosen to model this type of solar collector. To investigate the performances of the configurations of the three systems, auxiliary heater is not used and the demanded thermal energy is fully provided by the HPs and SHW. If the heat provided by the heating system is insufficient, the HWS temperature will be lower than the temperature set and the room air temperature will fall to below the temperature set for thermal comfort.

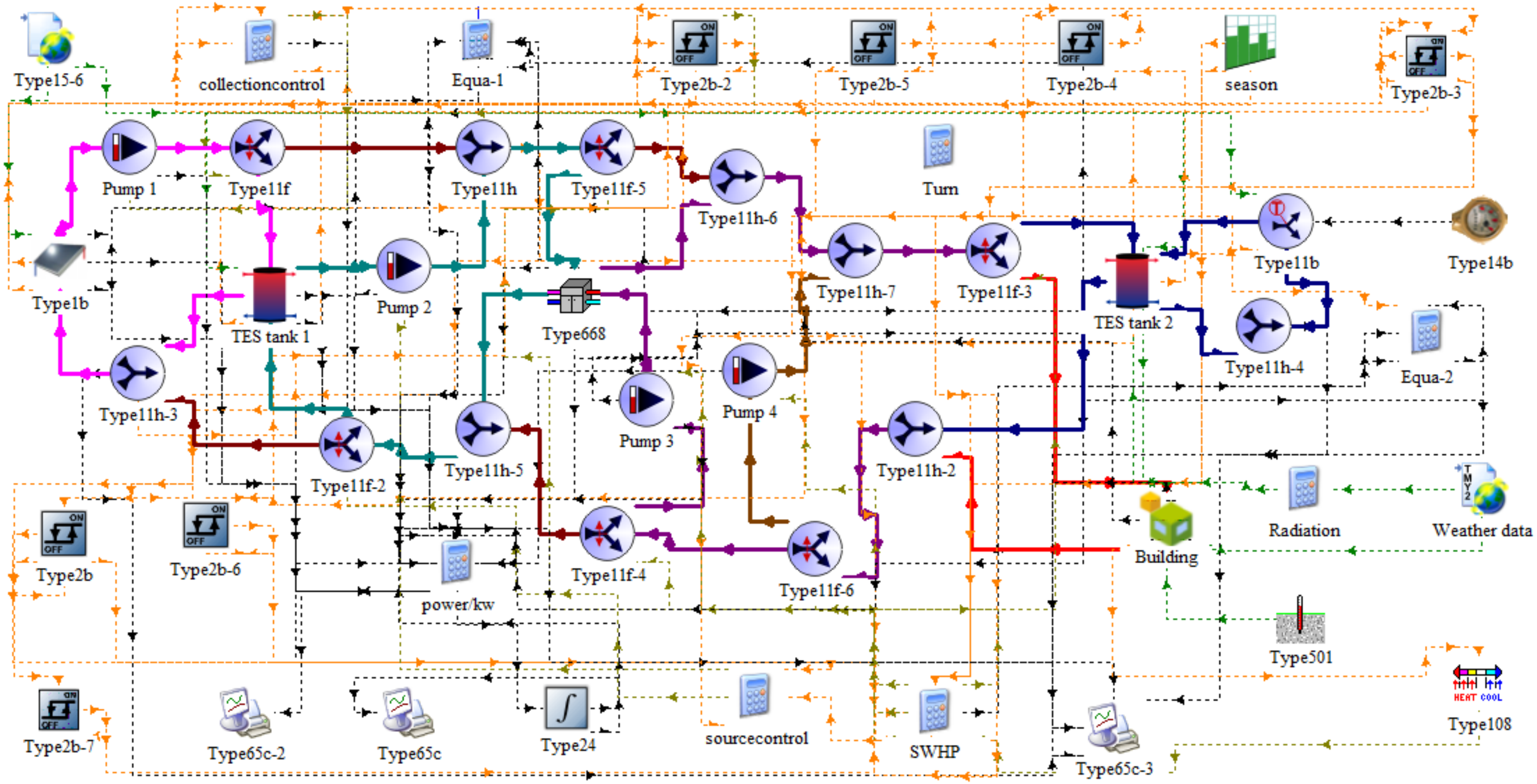
The sizing of the system is based on the demands of SH and HW. To meet the demands, different systems have different sizes of components. Since the serial system uses thermal energy collected by solar collector as the sole heat source, the required solar collector area is large to be 45 m^2 and the required size of water TES tank is large to be 3 m^3. Since the parallel and dual-source systems have ASHP for compensation at low solar energy availability, the required sizes of solar collector and water TES tank are much smaller, 18 m^2 and 500 L, respectively, to ensure SHW temperature to be higher than 40 °C in non-heating seasons. When the SHW temperature is below 50 °C in non-heating seasons, the HP operates to ensure the HWS temperature in the safe range to inhibit bacteria.

All the HPs are set at a heating capacity of 8 kW. In the models of serial and dual-source IX-SAASHPs, the SWHP module (Type 668) is modified based on sample file of 30HXC-HP2 from Carrier United Technologies. In the models of the parallel and dual-source IX-SAASHPs, the ASHP module (Type 941) is modified based on the sample file of YVAS012, York, Jonson

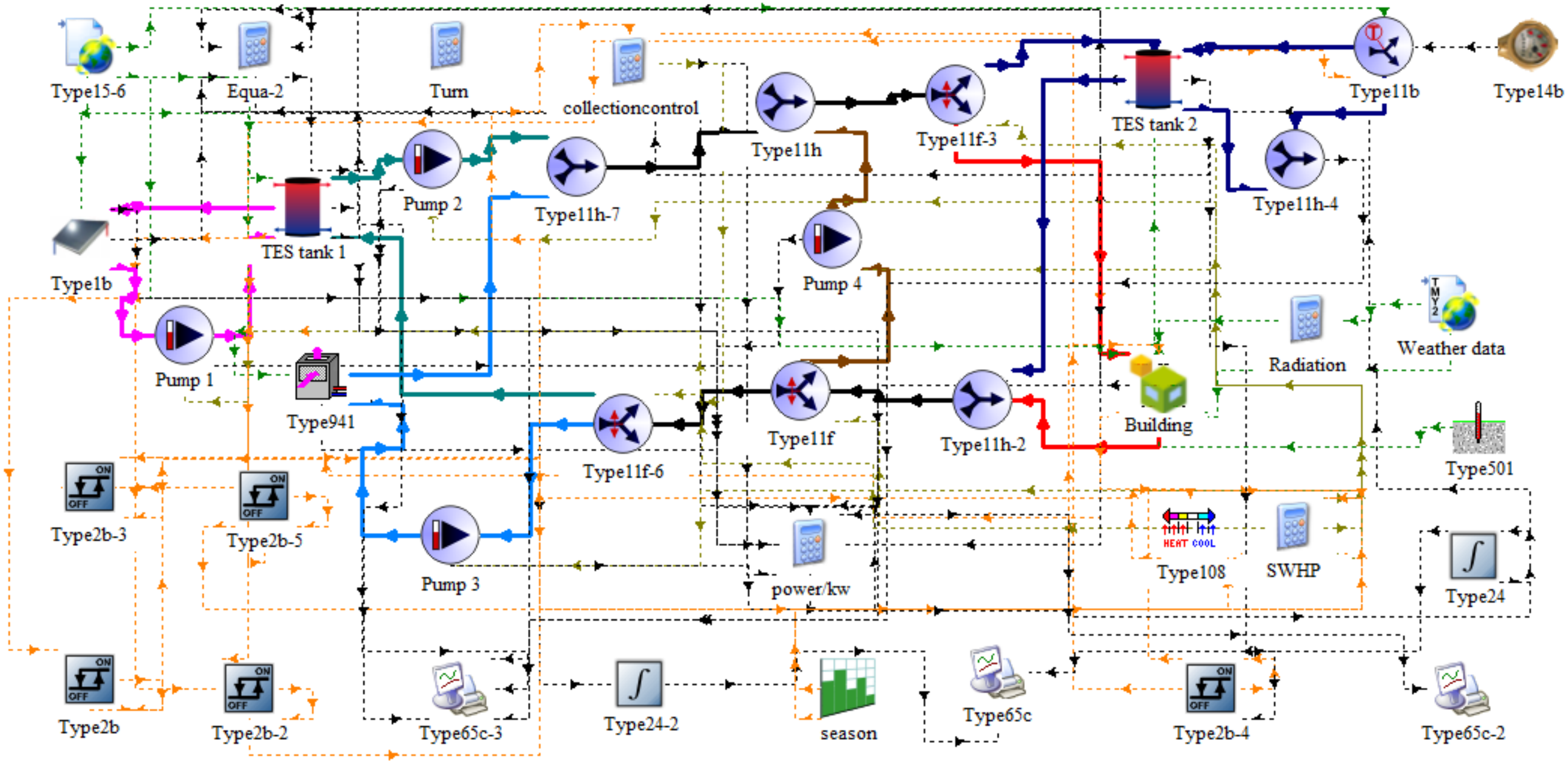
Control. Note that the ASHP module (Type 941) available in TRNSYS does not consider the frosting and defrosting and their effects on the ASHP performance. It is anticipated that the results provide deep understanding for application potential of SAASHPs in high latitude regions. In the model of dual-source IX-SAASHP, the dual-source HP is simulated by combining a SWHP (Type 668) and an ASHP (Type 941). TRNSYS modules selected for modelling the components of the three systems and relevant parameters are listed in table 6. Figure 5 shows the TRNSYS models and control functions for serial, parallel and dual-source IX-SAASHPs. The solid lines stand for the pipe connections, and the dot lines stand for the control connections.

Table 6: TRNSYS modules selected for modelling the components of the three systems and relevant parameters

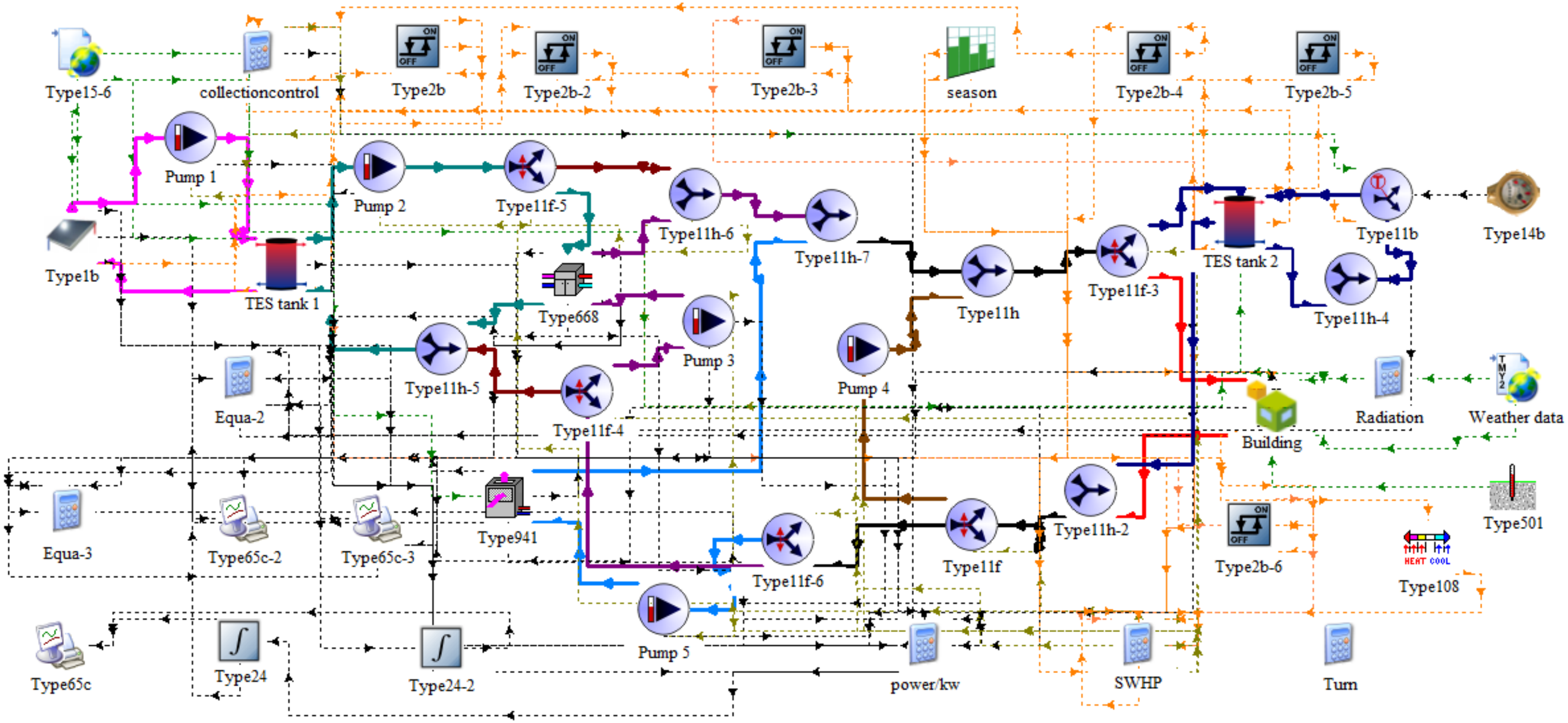
Component	Module	System	Parameter	Value
Solar collector	Type 1b	Serial system	Area	45 m^2
		Parallel and dual-source systems	Area	18 m^2
		All systems	Inclination angle	51.5°
			Tested flow rate	30 kg/hm^2
			Intercept efficiency	0.8
			Efficiency slope	13 kJ/hm^2k
			Efficiency curvature	0 kJ/hm^2k^2
			1^{st} order IAM	0.2
			2^{nd} order IAM	0
TES tank 1	Type 4a	All systems	Heat loss coefficient	0.2 $W/(m^2 K)$
		Serial system	Volume	3000 L
			Height	2.15 m
		Parallel and dual-source systems	Volume	500 L
			Height	1.175 m
TES tank 2	Type 4a	All systems	Heat loss coefficient	0.2 $W/(m^2 K)$
			Volume	300 L
			height	1 m
ASHP	Type 941	Parallel and dual-source systems	Blower power	0.15 kW
			Total air flow rate	1500 l/s
			User defined file	YVAS012, York, Jonson Control
SWHP	Type 668	Serial and dual-source systems	User defined file	30HXC-HP2, Carrier United Technologies
Pump 1	Type 110	All systems	Rated flow rate	500 kg/h
			Rated power	30 W
Pump 2	Type 110	All systems	Rated flow rate	800 kg/h
			Rated power	50 W
Pump 4	Type 110	All systems	Rated flow rate	800 kg/h
			Rated power	50 W
Pump in SWHP loop	Type 110	Serial and dual-source systems	Rated flow rate	870 kg/h
			Rated power	50 W
Pump in ASHP loop	Type 110	Parallel and dual-source systems	Rated flow rate	870 kg/h
			Rated power	50 W



a) Serial IX-SAASHP



b) Parallel IX-SAASHP



c) Dual-source IX-SAASHP

Figure 5: TRNSYS models and control functions for serial, parallel and dual-source IX-SAASHPs. (Solid lines: pink - solar collector-TES tank 1 loop; dark red - bypass; green - TES tank 1-SWHP loop; purple - SWHP loop; light blue - ASHP loop; black - user side loop; brown - TES tank 2-radiant floor loop; red - SH loop; dark blue - HW loop). (Dot lines: orange - monitored parameters; sage green - control signals; dark green - weather parameters; black - data outputs).

4.3 Simulation scheme

The operation period is set at one year with a time step of 0.0167 h. The systems start to operate from the middle of the year (4380 h) with an initial water temperature of 13.4 ^{o}C in the TES tanks, which is the water temperature of mains water supply.

5. Evaluation of performance

The three IX-SAASHPs have different system configurations. They all include a vapour-compression cycle HP. Their performance can be evaluated by the performance indicators.

5.1 Thermodynamics cycle of the heat pumps

Figure 6 shows the ideal vapour-compression cycles of the ASHP (1-2-3-4-1) and SWHP (5-6-7-4-5) on *P-h* diagram. The degree of superheat of the refrigerant vapour entering the compressor is taken to be the same for both HPs. The flow resistance on the refrigerant side in both evaporator and condenser is neglected.

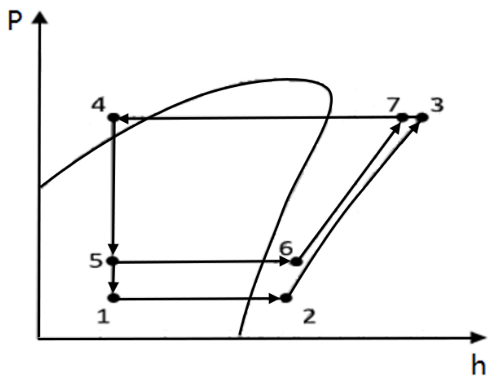


Figure 6: *P-h* diagram of ideal vapour-compression cycle HPs

5.2 System performance indicators

The performance of the heating systems is evaluated by a variety of indicators including the room air temperature, HWS temperature, *SPF* of the system (SPF_{sys}), *SPF* of the HP (SPF_{HP}), *COP* of the HP module, and the solar fraction (*SF*). The room air temperature is an indication whether the heat provision by the heating system meets the heat demand of the building. The measured room air temperature is also the quantity that determines the on/off operation of the heating system. The HWS temperature indicates the amount of thermal energy stored in the TES tanks and also determines the on/off operation of the SWHP. The SPF_{sys} describes the overall performance of the whole heating system over the heating season of the year and is defined by Eq. (1):

$$SPF_{sys}=\frac{\int(Q_{SH}+Q_{HW})\times dt}{\int W_{tot}\times dt} \quad (1)$$

where Q_{SH} and Q_{HW} are the thermal energies supplied by the system for SH and HW, respectively, and W_{tot} is the total electricity consumed by the HP and all water pumps given by Eq. (2):

$$W_{tot}=W_{HP}+W_{pumps} \quad (2)$$

where W_{HP} is the electricity consumed by the HP calculated by Eq. (3):

$$W_{HP}=j_{ASHP}W_{ASHP}+j_{SWHP}W_{SWHP} \quad (3)$$

where W_{ASHP} and W_{SWHP} are the electricity consumed by the ASHP and SWHP, respectively, j_{ASHP} and j_{SWHP} have values either 1 or 0 representing on or off operation status of ASHP and SWHP. For serial system, $j_{ASHP} = 0$ and $j_{SWHP} = 1$. For parallel system, $j_{ASHP} = 1$ and $j_{SWHP} = 0$. For dual-source system, j_{ASHP} and j_{SWHP} can be 1 or 0, depending on their on/off operation status.

The SPF_{HP} describes the overall performance of a HP over the heating season and is defined by Eq. (4):

$$SPF_{HP}=\frac{\int Q_{HP,con}\times dt}{\int W_{HP}\times dt} \quad (4)$$

where $Q_{HP,con}$ is the heat transferred from the condenser of the HP to water circulating to TES tank 2, given by Eq. (5):

$$Q_{HP,\,con}=j_{ASHP}Q_{ASHP,\,con}+j_{SWHP}Q_{SWHP,\,con} \quad (5)$$

where $Q_{ASHP,\,con}$ and $Q_{SWHP,\,con}$ are the heat transferred from the condenser of ASHP and SWHP to water circulating to TES tank 2, respectively.

The *COP* of the HP is defined by Eq. (6):

$$COP=Q_{HP,\,con}/W_{HP} \quad (6)$$

The *SF* of the heating system, the contribution ratio of the solar thermal energy collected to the system heat provision over the heating season, is defined by Eq. (7):

$$SF= 1-\frac{\int(Q_{ASHP,con}+W_{SWHP})\times dt}{\int(Q_{HW}+Q_{SH})\times dt} \quad (7)$$

6. Results and discussions

Based on the three IX-SAASHPs, the models in TRNSYS are established. Simulations are performed and the system performances are then obtained.

6.1 Seasonally heating performance

Figure 7 shows the variations of the room air temperature (T_{room}, the black line) and the HWS temperature (T_{HWS}, the red line) over the heating season for serial, parallel and dual-source IX-SAASHPs. It is seen that the HWS temperature may suddenly drop to below 50 ^{o}C because after water draws, feedwater enters the hot water tank. However, the IX-SAASHPs respond quickly to lift the HWS temperature to above 50 ^oC. From Fig.7(a), it is seen that, the serial IX-SAASHP cannot meet the heat demand in winter; in some cases the room air temperature is below 18 ^oC. The lowest room air temperature is 13.4 ^oC and the lowest HWS temperature of 11.3 ^oC. The lowest water temperature at the outlet of the evaporator is -7.1 ^oC. This is still within the safe operation range of the system according to the operation introduction of the 30HXC-HP2 of Carrier United Technologies.

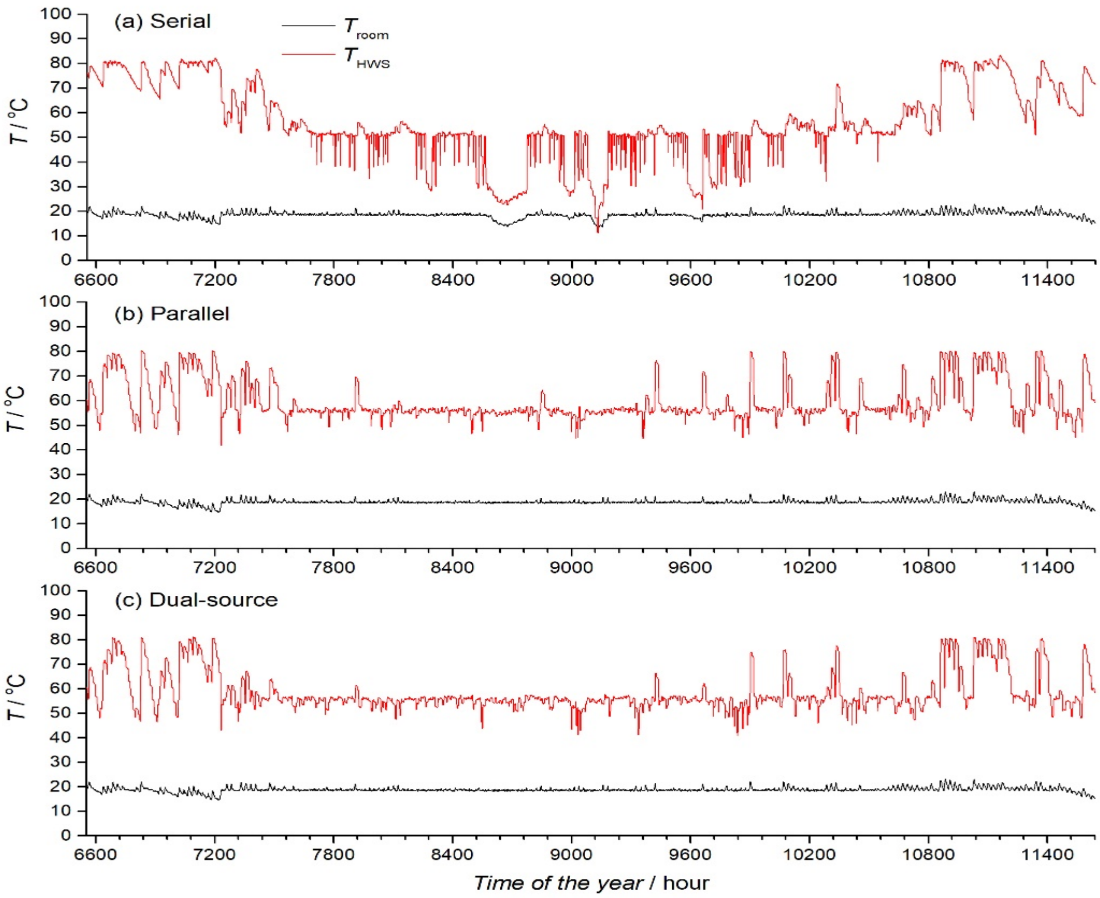


Figure 7: Variations of room air temperature and HW temperature at the outlet of TES tank 2 for three systems over a heating season

During the simulation of serial IX-SAASHP, to improve the heating capacity in winter, larger collector areas, collectors with better efficiencies and larger storage tanks have been tried. It was found that heating capacity is mainly limited by solar irradiation intensity, rather than component parameters. Improving collector area and efficiency can hardly enhance system performance. For example, when a solar collector of 48 m^2 is used, the lowest room temperature and HWS temperature are almost the same, 13.5 ^oC and 11.5 ^oC, respectively. When a solar collector with an intercept efficiency of 0.85 is used, the lowest room temperature and HWS temperature are almost the same, 13.7 ^{o}C and 11.5 ^{o}C, respectively. The use of a larger TES tank 1 increases the capacity of TES, but may reduce its water temperature i.e. the heat source temperature for SWHP, resulting in lower heat provision of the system. When a TES tank 1 of 3.5 m^3 is used, the lowest HWS temperature is almost the same at 11.4 ^{o}C, but the lowest HWS temperature occurs 4 times in winter. In addition, the lowest room air temperature drops even to 11.8 ^{o}C.

As shown in Figure 7 (b) and (c), the use of ASHP make the system meet the heat demands well. The lowest water temperature at the outlet of the SWHP evaporator is about -5 ^{o}C and the air temperatures at the outlet of the ASHP evaporator are also about -5 ^{o}C. This ensures the safe operation of SWHP and ASHP over the heating season.

6.2 Daily heat provision

Figure 8 shows the variations of daily heat provision (kWh) for SH and HW for three systems over a heating season. The blue column represents the daily heat provision for SH and the pink column represents that for HW. The columns are stacked to represent the total heat provision. It can be seen that the heat provision for space heating is mainly required in December to February. The parallel and the dual-source IX-SAASHPs have almost the same daily heat provision, higher than that of the serial IX-SAASHP. The largest daily heat provision from parallel and dual-source systems are around 100 kWh. At the same day, the serial system only provides thermal energy of 3.2 kWh. Especially, in December, the daily heat provision of the serial system is obviously lower than those of the other systems.

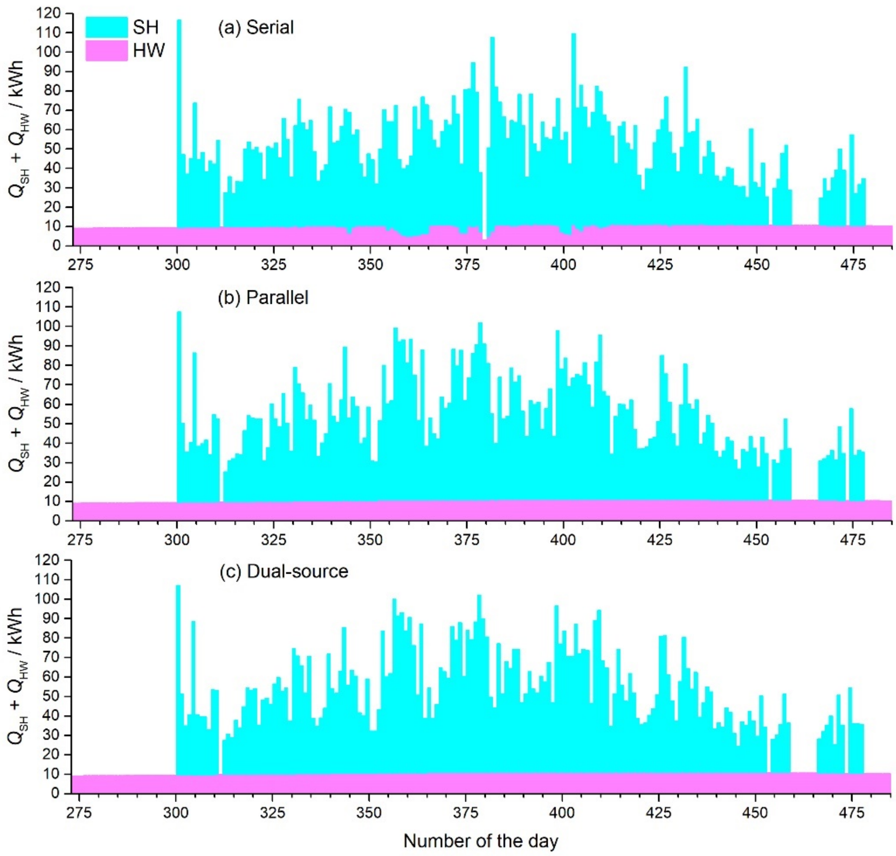


Figure 8: Variations of daily heat provision for SH and HW for three systems over a heating season

Figure 9 shows the variations of daily heat provision (kWh) supplied by direct SHW (green), ASHP (red) and SWHP (orange) for three systems over a heating season. The columns are stacked to represent the total daily heat provision. The black line refers to the daily HW provision as a reference. The thermal energy loss and storage from the hot water tank is included as a part of the daily heat provision. For the serial system, the use of solar energy as the sole heat source providing heat either directly or by the SWHP may result in zero heat provision e.g. on the 14th (379th) day. For the dual-source system, the large proportion of heat is provided by the ASHP. This suggests the importance of employing ASHP in a heating system for stable operation while the SWHP benefits to improve system performance.

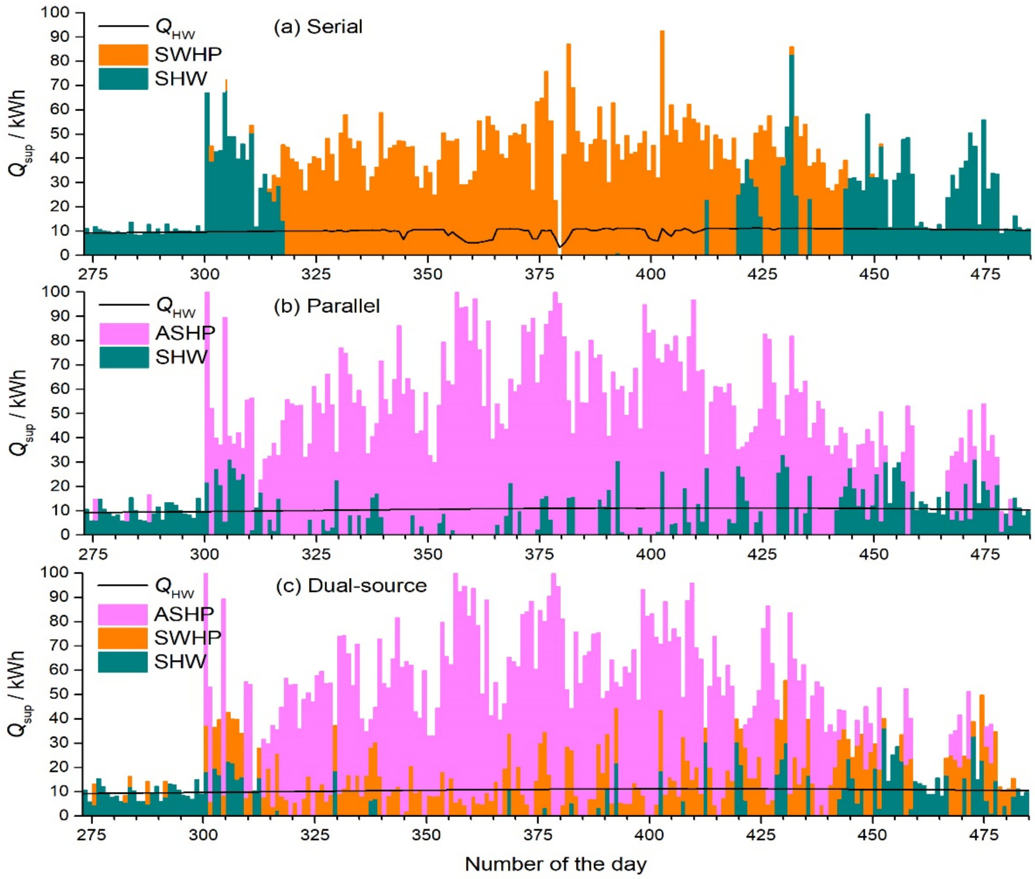


Figure 9: Variations of daily heat provision supplied by direct SHW, ASHP and SWHP for three systems over a heating season

Figure 10 displays the variations of daily electricity consumed (kWh) by the systems over a heating season. The red column is the electricity consumed by the ASHP, the orange column is that by the SWHP and the purple column is that by the pumps. The columns are stacked to represent the total electricity consumed by the system. In all systems, pumps are mainly used to support HPs. The electricity consumed by the pumps in SHW periods is low, only around 0.1 - 0.4 kWh per day. Since parallel and dual-source systems have smaller solar collector and storage tank, their solar utilisation is lower than that of serial system. Their electricity consumption is thereby higher. The largest electricity consumption is around 32 kWh on the 14th day. However, considering the large scale of the serial system, its electricity consumption is still relatively high. The largest electricity consumption is around 25 kWh a day because serial IX-SAASHP requires more pumps during operation. This indicates that it is not feasible to use solar thermal energy as the dominant heat source in London.

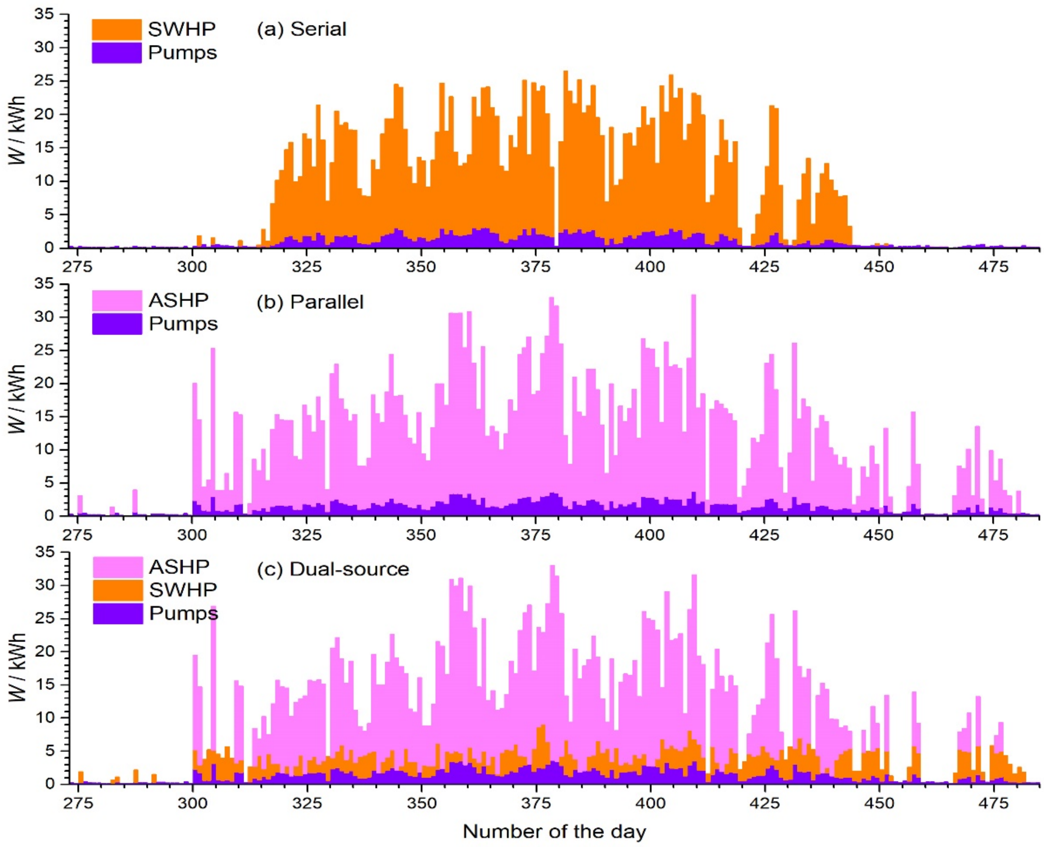


Figure 10: Variations of daily electricity consumed by the systems over a heating season

Figure 11 shows variations of daily solar thermal energy (kWh) used for SH and HW over a heating season. The green column is the solar thermal energy to SHW, and the orange column is that to SWHP. The columns are stacked to represent the total solar thermal energy collected in the system. The black line refers to the average daily HW provision for reference. In most days using SWHP, solar thermal energy mainly works as the heat source to the SWHP and that left for direct SHW is limited. Especially, for the serial system, the solar thermal energy is purely used for SWHP in winter.

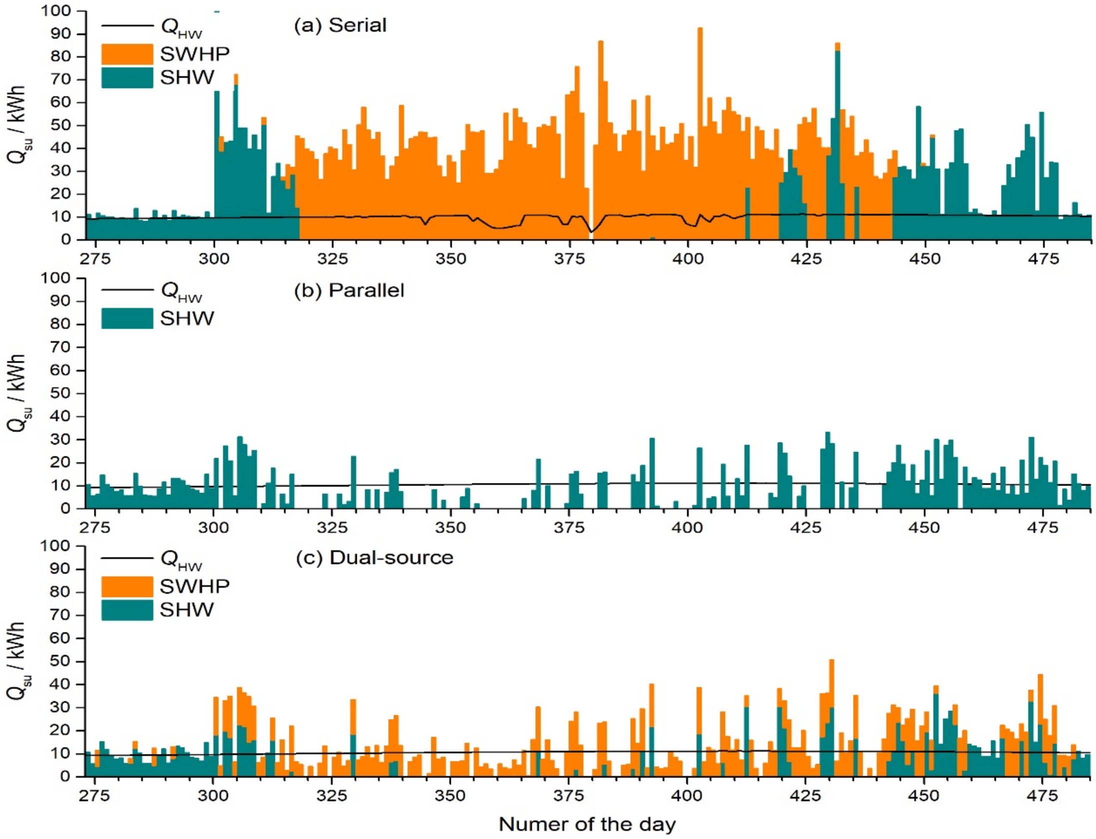


Figure 11: Variations of daily solar thermal energy used for SH and HW over a heating season

Figure 12 shows the variations of daily thermal energy storage (Q_{TES}) in serial (blue), parallel (black) and dual-source (red) IX-SAASHPs over a heating season. Positive value refers to the thermal energy charged and negative value refers to the thermal energy discharged. Comparison between Figures 11 and 12 indicates that using SWHP increases the utilisations of solar thermal energy and the seasonal storage. For example, at the beginning of the heating period, in the serial system, the storage tank discharges around 100 kWh thermal energy stored in non-heating seasons. On the one hand, employing seasonal thermal storage can balance the seasonal difference between solar irradiance and heat demand, improving the system performance. On the other hand, large requirements on seasonal thermal storage imply insufficient solar availability in winter, impacting the stability of system operation.

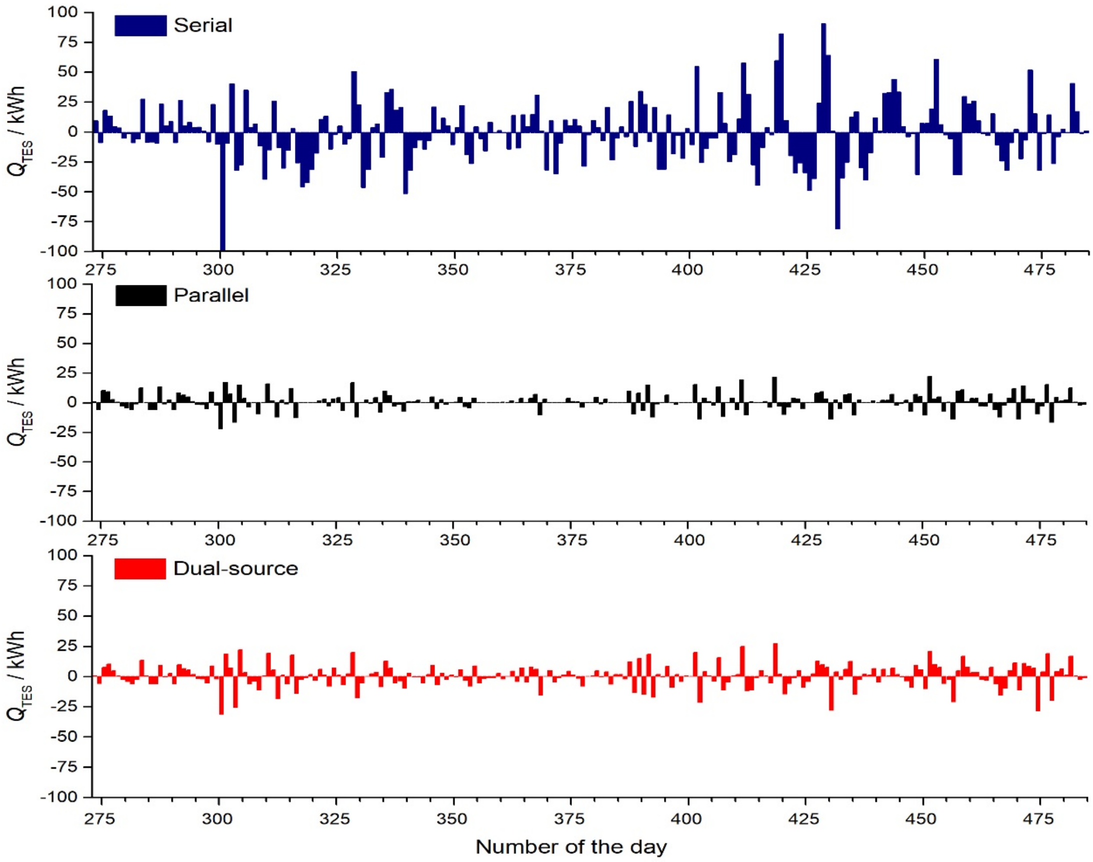


Figure 12: Variations of daily thermal energy storage (Q_{TES}) over a heating season. Positive value refers to the thermal energy charged and negative value refers to the thermal energy discharged.

6.3 Efficiencies of the heat pump module(s)

Figure 13 shows the variations of daily averaged *COP* of the HPs in three systems over a heating season. The daily average *COP*s of the SWHP in serial system and the ASHP in parallel system are in black and red, and those of the ASHP and SWHP of the dual-source IX-SAASHP are in blue and green. It can be seen that, in the serial IX-SAASHP, the *COP* of the SWHP module ranges from 3 to 7. Wherein, the *COP* ranges from 3 to 5 in most occasions. In the parallel system, the *COP* of the ASHP module ranges from 2.5 to 4.5. Even though the serial IX-SAASHP has higher *COP* of the HP module, according to previous analysis, it has low heat provision due to the limits of weather conditions. In the dual-source IX-SAASHP, the *COP* of the SWHP and ASHP modules are the same to those in serial and parallel system, ranging from 2.5 to 4.5 and from 3 to 7, respectively.

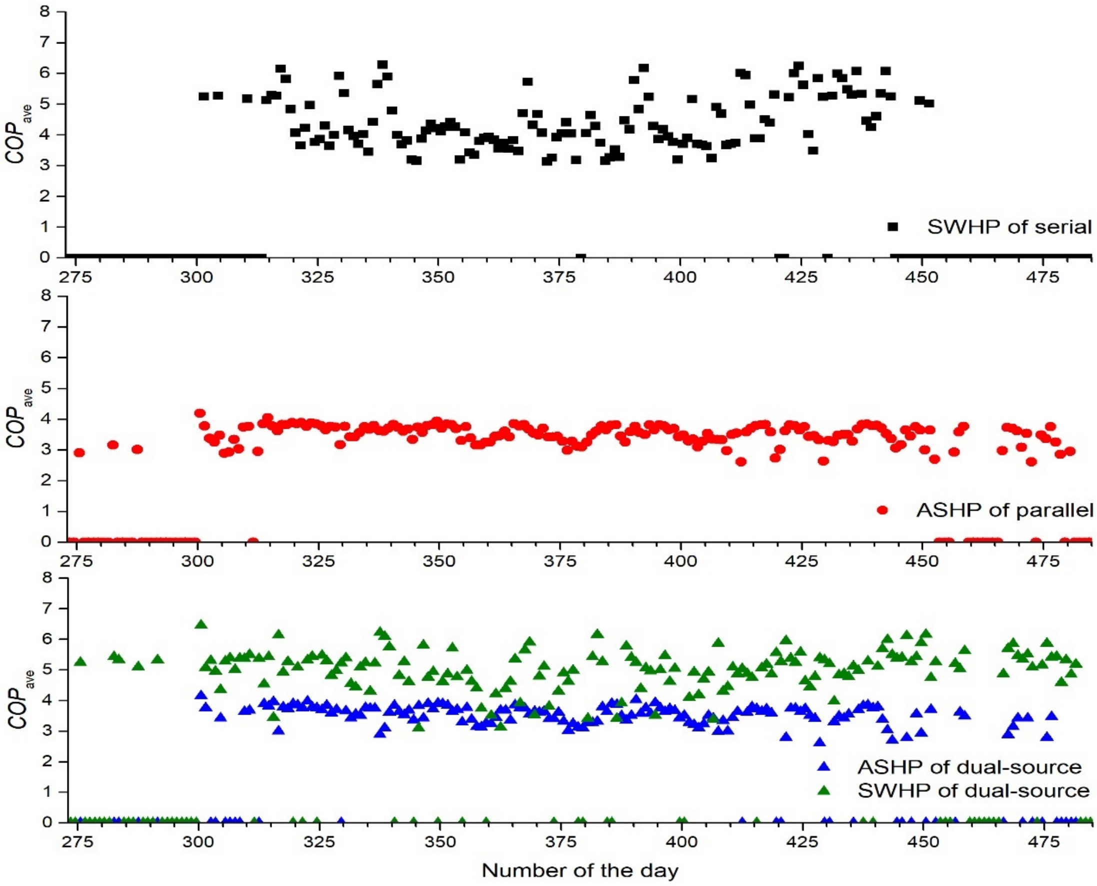


Figure 13: Variations of daily averaged *COP* of the HPs in three systems over a heating season.

Figure 14 shows the SPF_{sys} of the system (blue symbols) and SPF_{HP} of the HPs (black symbol for SWHP and red symbols for ASHP) for three systems. In all three systems, the lowest daily SPF_{HP} is 2.9-3.1. Considering the electricity consumed by pumps, SPF_{sys} is lower than SPF_{HP} in HP dominant periods. The lowest daily SPF_{sys} of the serial and parallel systems is 2.4 and that of the dual-source system is 2.9. All the lowest daily SPF_{sys}s occur in December.

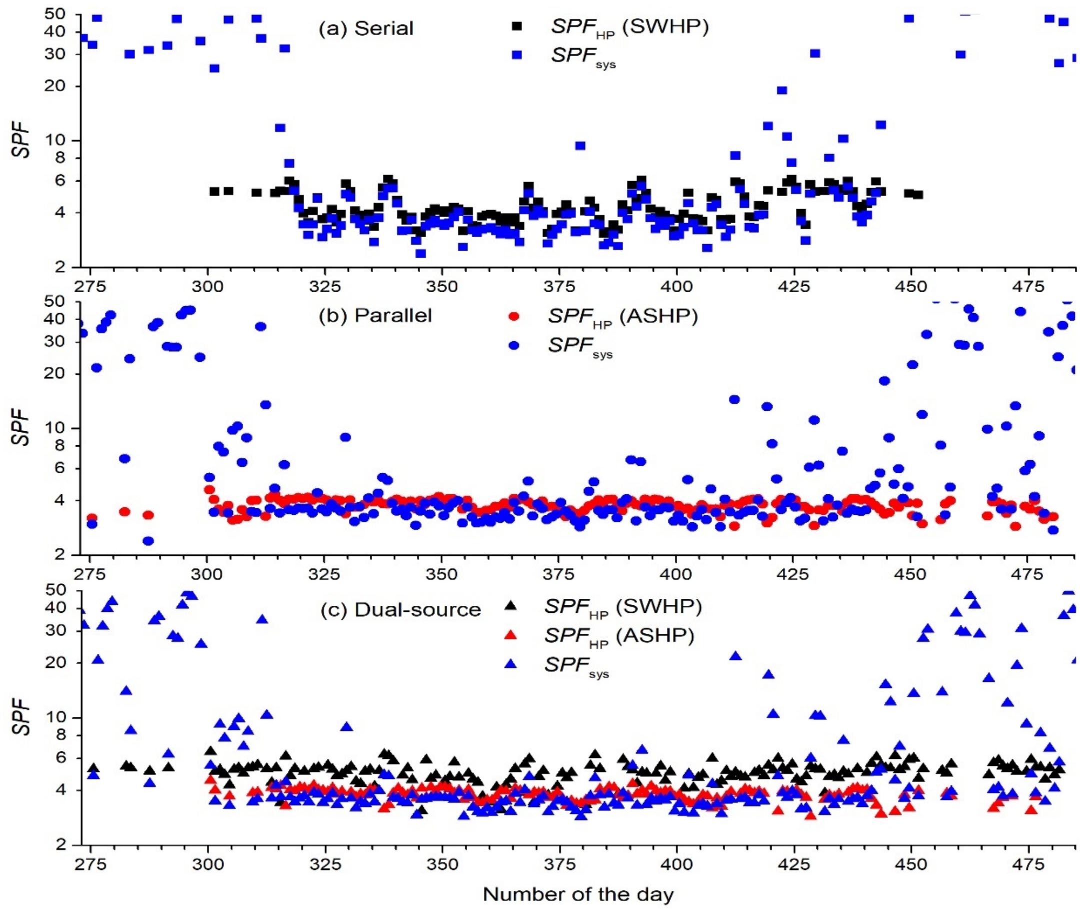


Figure 14: Variations of daily SPF_{sys} and SPF_{HP} over a heating season

6.4 Yearly operation performance

The overall operation performances of the IX-SAASHPs are listed in table 7. The system simulation considers heat exchange with the ambient environment and the thermal energy stored in the tanks at the beginning and the ending.

Table 7: Overall operation performance of the IX-SAASHPs

System		Period	Serial	Parallel	Dual-source
Heat provision (kWh)	HW	Heating season	2124.8	2235.2	2237.7
		Non-heating season	1427.3	1426.9	1427.5
	SH		7270.5	7523.7	7527.9
	Total		10822.6	11185.8	11193.1
Heat provision (kWh)	SWHP		7008.6	0	2289.1
	ASHP		0	8218.0	6586.6
	Solar	Heating season	2567.1	1802.6	1187.6
		Non-heating season	1528.7	1444.1	1409.4
	SWHP		1705.7	0	449.2
	ASHP		0	2136.9	1737.7

Electricity consumption (kWh)	Water pumps	Heating season	233.2	304.7	295.0
		Non-heating season	27.8	42.7	40.7
	Total		1966.763	2511.3	2522.6
SPF$_{HP}$	SWHP		4.1	0	5.1
	ASHP		0	3.8	3.8
COP_{ave}	SWHP		4.5	0	5.0
	ASHP		0	3.5	3.5
Solar thermal energy (kWh)	To SWHP		5302.9	0	1839.9
	To end use	Heating season	2567.1	1802.6	1187.6
		Non-heating season	1528.7	1444.2	1409.4
	Total		9980.0	3593.2	4706.7
Thermal energy from ambient air (kWh)			0	6054.1	4848.9
SF	Heating season		83.8%	18.5%	31.0%
	Yearly		86.7%	29.0%	39.6%
SPF_{sys}	Heating season		4.9	4.0	3.9
	Yearly		5.5	4.5	4.4

All the IX-SAASHPs can obtain yearly SPF_{sys} above 4.4. Compared with the systems listed in table 1 [8-20], the simulated results show relatively good system performances. This suggests that, for the weather conditions in London, IX-SAASHPs can be a promising choice for SH and HW. It is interesting to note that, using the same area of solar collector and TES tank volume, the parallel system has a lower yearly *SF* (29%) than the dual-source system (39.6%), but both systems share the similar SPF_{sys}, 4.5 and 4.4. This means that in the dual-source system, the electricity consumed by pumps balances the electricity saved by using solar energy. In addition, it should be noticed that, though the dual-source IX-SAASHPs always have a *COP* under 3.5 in previous studies [7], for the weather conditions in London, the dual-source system can be comparable to the parallel system. This suggests that the dual-source IX-SAASHP is of higher application potential in high altitude regions.

For all the three systems, the space heating takes account of around 67% of the total heat demand. This suggests that, although SH takes a shorter period of time, it is more important than HW in domestic heating sector. To make the domestic heating sector greener, advanced technologies in various aspects helping reduce the heat demand for space heating, such as low *U*-value materials and passive design, need to be developed.

In terms of heat provision, the HPs contribute to the most heat provision (around 83%) and also consume the most of the overall electricity consumption (around 85%). To increase heat provision and reduce operation cost, it is important to improve HP technologies for higher *COP* such as using high efficient compressor, suitable refrigerant and heat exchangers with enhanced heat transfer and optimised design.

6.5 Economic analyses

To evaluate the economic performance of IX-SAASHPs, under net-zero target in the UK, economic analyses are conducted for IX-SAASHPs, electric water heater and gas boiler, as well as electric heater and gas boiler boosted SHW systems.

For economic analyses, the total energy consumption of the heating systems, Q_{tot}, is calculated by Eq. (8):

$$Q_{tot} = (Q_{sh} + Q_{hw} - Q_{ce})/\eta \quad (8)$$

where Q_{ce} is the clean energy (extracted from solar and ambient air sources) used by the heating system and η is the efficiency of the electric water heater and gas boiler.

The payback period, P_{pb}, is defined on the basis of electric water heater by Eq. (9):

$$P_{pb} = C_i / C_{spy} \quad (9)$$

where C_i is the initial cost difference and C_{spy} is the cost saving per year calculated by Eq.(10) and Eq.(11), respectively.

$$C_i = C_{i0} - C_{ieh} \quad (10)$$

$$C_{spy} = C_{o0} - C_{oeh} \quad (11)$$

where C_{i0} and C_{o0} are the initial and operation costs of the heating system, respectively, C_{ieh} and C_{oeh} are the initial and operation costs of the electric water heater.

The efficiencies of the electric water heater and gas boiler are taken from [24] to be 0.95 and 0.85, respectively. The electric water heater and gas boiler have a TES tank of 300 L. For the SHW systems, the sizes of the solar collector and outdoor TES tank are taken to be the same as those of the dual-source IX-SAASHP and therefore both systems have the same amount of solar thermal energy collected i.e. ca. 4.71 MWh. The heat provisions of the three heating systems for SH and HW over the year is ca. 11.19 MWh. It is noted that, for the serial system, the heat provision of ca. 10.82 MWh is insufficient to meet the requirement of thermal comfort sometimes and the rest heat needed is assumed to be provided by the auxiliary electric heaters with an efficiency of 0.95 for the purpose of economic analysis of the heating systems.

The current energy prices are taken from E.On Energy (a UK energy suppler) to be £212.17 per MWh for electricity and £ 41.18 per MWh for gas (prices in April 2021) [25]. According to the “balanced pathway” scenario for net zero emission of greenhouse gases by 2050 in the UK, the electricity generation costs via nuclear and gas with carbon capture and storage will be £85 and £80 per MWh and the sales of gas boilers will be phased out by 2033 [2]. Wind and solar will provide 80% of electricity generation with a cost of £43 per MWh by 2035. Therefore, the electricity price is expected to be £51.4 per MWh by 2035. The prices of the components of the heating systems are obtained from an online market where the flat plate solar collector price is around £30 per m^2, water tank price is £290 per 100 L, and a pump with a head of 15 m and a capacity of 15 L/min is around £10 [26]. All the three heating systems have a capacity of 8 kW. The systems are estimated to be easy to connect to current space heating and water heater. The installation costs are assumed to be 3 hours for SHW system and 6 hours for SAASHPs with a cost of 80 per hour [27].

The results of economic analysis for 2021 and 2035 are listed in tables 8 and 9. As the electricity price will decrease by 75% by 2035, the payback period will be 4 times as that today. Though the gas boiler is the cheapest one today, they are expected to be phased out by 2033. The gas boiler boosted SHW is the second cheapest one and has a similar payback period to the parallel IX-SAASHP. This suggests that the parallel IX-SAASHP can be a good alternative for replacing gas boiler boosted SHW from now on. The payback period of the electric heater boosted SHW is almost 1.5 times as that of the parallel IX-SAASHP. The serial IX-SAASHP has the longest payback period due to its high initial cost. In general, IX-SAASHPs can save more operation cost than electric water heater and electric heater boosted SHW. Furthermore, since the initial cost can be partly covered by the UK Green Homes Grant [28], the parallel and dual-source IX-SAASHPs are of high potential value of applications in the UK.

Table 8: Results of economic analysis for electric heater, SHW and IX-SAASHP heating systems (2021)

		Electric water heater	**Gas boiler**	**Electric heater boosted SHW**	**Gas boiler boosted SHW**	**Serial IX-SAASHP**	**Dual-source IX-SAASHP**	**Parallel IX-SAASHP**
Heat provision per year, MWh		11.19	11.19	11.19	11.19	10.82 + 0.37	11.19	11.19
Efficiency/performance		0.95	0.85	0.95	0.85	*SPF*=5.5, 0.95	*SPF*=4.4	*SPF*=4.5
Energy consumption per year, MWh		11.8	13.2	7.2	8.0	2.1	2.2	2.2
Initial cost, £	collector	0	0	540	540	1350	540	540
	tanks	870	870	2320	2320	9570	2320	2320
	Heater/HP	60	15	60	15	460+60	1085	330
	pumps	0	0	20	20	30	30	30
	Installation	0	0	240	240	480	480	480
	total	930	885	3020	2975	11630	4135	3380
Operation cost, £		2499.1	542.1	1447.2	313.9	443.1	475.9	463.9
Cost saving per year, £		-	1957.0	1051.92	2185.2	2056.1	2023.2	2035.2
Payback period, year		-	-	2.1	1.0	5.4	1.7	1.4

Table 9: Results of economic analysis for electric heater, SHW and IX-SAASHP heating systems (2035)

		Electric water heater	**Electric heater boosted SHW**	**Serial IX-SAASHP**	**Dual-source IX-SAASHP**	**Parallel IX-SAASHP**
Heat provision per year, MWh		11.19	11.19	10.82 + 0.37	11.19	11.49
Efficiency/performance		0.95	0.95	*SPF*=5.5, 0.95	*SPF*=4.4	*SPF*=4.5
Energy consumption per year, MWh		11.8	7.2	2.1	2.2	2.2
Initial cost, £	collector	0	540	1350	540	540
	tanks	870	2320	9570	2320	2320
	Heater/HP	60	60	460+60	1085	330
	pumps	0	20	30	30	30

Installation	0	240	480	480	480
total	930	3180	11950	4455	3700
Operation cost, £	606.0	367.9	107.2	115.4	112.5
Cost saving per year, £	-	254.8	498.1	490.1	493.0
Payback period, year	-	8.8	22.1	7.2	5.6

7. Conclusions

In this work, TRNSYS has been used to simulate the operation performances of serial, parallel and dual-source IX-SAASHPs for SH and HW in London. The economic analysis has also been conducted to forecast the market of the IX-SAASHPs under the energy scheme predicted for net-zero carbon emission by 2050 in the UK. The following conclusions can be drawn:

1. All the three IX-SAASHPs can achieve a yearly SPF_{sys} higher than 4.4, suggesting their potential to be applied for domestic heating under weather conditions in high latitude regions.
2. The heat provision of the serial IX-SAASHP is limited by the availability of solar irradiance. Since the solar energy is the sole heat source of the serial system, it requires large sizes of the solar collector and TES tanks, resulting in high installation cost and longer payback period.
3. The parallel IX-SAASHP has the simplest pipe connection and control function. It shows the highest SPF_{sys} and the most stable operation performance.
4. The dual-source IX-SAASHP shows much lower cost than the serial system and similar operation performance to the parallel system.
5. The parallel IX-SAASHP has the lowest payback period of 5.3 year and the dual-source IX-SAASHP has a payback period of 6.9 years.

Acknowledgements

The authors gratefully acknowledge the financial supports from the Joint PhD Studentship of China Scholarship Council (CSC) and Queen Mary University of London.

Nomenclature

C_i	initial cost difference
C_{i0}	initial cost of the studied system
C_{ieh}	initial cost of the electrical water heater
C_{o0}	operation cost of the studied system
C_{oeh}	operation cost of the electrical water heater.
COP	coefficient of performance
C_{spy}	cost saving per year
HC	heating capacity

P_{pb}	payback period
$Q_{\text{ASHP, con}}$	thermal energy obtained at the condenser of air source heat pump
Q_{ce}	clean energy used in the system
$Q_{\text{HP,con}}$	thermal energy obtained at the condenser of a heat pump
Q_{HW}	thermal energy for hot water
Q_{SH}	thermal energy for space heating
Q_{su}	solar energy used
Q_{sup}	thermal energy supply
Q_{TES}	thermal energy storage
SF	solar fraction
SPF_{HP}	seasonal performance factor of the heat pump
SPF_{sys}	seasonal performance factor of the system
T_{amb}	ambient air temperature
T_{room}	room air temperature
T_{HWS}	outlet temperature of hot water tank
W_{ASHP}	electricity consumed by the air source heat pump
W_{HP}	electricity consumed by a heat pump
W_{pump}	electricity consumed by all the pumps
W_{SWHP}	electricity consumed by the solar water heat pump
W_{tot}	total electricity consumed

Greek Letter

η	efficiency of electric heater and gas boiler systems

Abbreviation

ASHP	air source heat pump
DX-SAASHP	direct expansion solar-assisted sir source heat pump
HP	heat pump
HW	hot water
HWS	hot water storage
IX-SAASHP	indirect expansion solar-assisted air source heat pump
PCM	phase change material

SAASHP	solar-assisted air source heat pump
SC	space cooling
SFH	single family house
SH	space heating
SHW	solar hot water
SWHP	heat pump used hot water from solar collector as heat source
TES	thermal energy storage
TRNSYS	TRaNsient SYstem Simulation program

References

[1] Department for Business, Energy & Industrial Strategy, Energy consumption in the UK, 2018

[2] Committee on Climate Change, The Sixth Carbon Budget -- The UK's path to Net Zero, 2020, https://www.theccc.org.uk/publication/sixth-carbon-budget/

[3] Long JB, Xia KM, Zhong HH, Lu HL, A YG, Study on energy-saving operation of a combined heating system of solar hot water and air source heat pump, Energy Convers Manage 2021; 220: 113624.

[4] Kim T, Choi BI, Han YS, Do KH, A comparative investigation of solar-assisted heat pumps with solar thermal collectors for a hot water supply system, Energy Convers Manage 2018; 172: 472-484.

[5] Dongellini M, Naldi C, Morini GL, Influence of sizing strategy and control rules on the energy saving potential of heat pump hybrid systems in a residential building, Energy Convers Manage 2021; 235: 114022.

[6] Chargui R, Awani S, Determining of the optimal design of a closed loop solar dual source heat pump system coupled with a residential building application, Energy Convers Manage 2017; 147: 40-54.

[7] Yang LW, Xu RJ, Hua N, Xia Y, Zhou WB, Yang T, Belyayev Ye, Wang HS, Review of the advances in solar-assisted air source heat pumps for the domestic sector, Energy Convers Manage 2021; 247: 114710.

[8] Freeman TL, Mitchell JW, Audit TE, Performance of combined solar-heat pump systems, Solar Energy 1979; 22: 125-135.

[9] Fraga C, Mermoud F, Hollmuller P, Pampaloni E, Lachal B, Large solar driven heat pump system for a multifamily building: Long term in-situ monitoring, Solar Energy 2015; 114: 427–439.

[10] Ji J, Cai JY, Huang WZ, Feng Y, Experimental study on the performance of solar-assisted multi-functional heat pump based on enthalpy difference lab with solar simulator, Renew Energy 2015; 75: 381-388.

[11] Cai JY, Ji J, Wang YY, Huang WZ, Numerical simulation and experimental validation of indirect expansion solar-assisted multi-functional heat pump, Renew Energy 2016; 93: 280-290.
[12] Poppi S, Bales C, Heinz A, Hengel F, Chèze D, Mojic I, Cialani C, Analysis of system improvements in solar thermal and air source heat pump combisystems, Appl Energy 2016; 173: 606–623.
[13] Liu Y, Ma J, Zhou GH, Zhang C, Wan WL, Performance of a solar air composite heat source heat pump system, Renew Energy 2016; 87: 1053-1058.
[14] Ran SY, Li XT, Xu W, Wang BL, A solar-air hybrid source heat pump for space heating and domestic hot water, Solar Energy 2020; 199: 347-359.
[15] Kutlu C, Zhang YN, Elmer T, Su YH, Riffat S. A simulation study on performance improvement of solar assisted heat pump hot water system by novel controllable crystallization of supercooled PCMs. Renew Energy 2020; 152: 601-612.
[16] Yerdesh Y, Abdulina Z, Aliuly A, Belyayev Y, Mohanraj M, Kaltayev A. Numerical simulation on solar collector and cascade heat pump combi water heating systems in Kazakhstan climates. Renew Energy 2020; 145: 1222-1234.
[17] Treichel C, Cruickshank CA. Analysis of a coupled air-based solar collector and heat pump water heater in Canada and the United States. IEA SHC Int Conf on Solar Heating and Cooling for Buildings and Industry 2019.
[18] Treichel C, Cruickshank CA. Energy analysis of heat pump water heaters coupled with air-based solar thermal collectors in Canada and the United States. Energy 2021; 221: 119801.
[19] Treichel C, Cruickshank CA. Greenhouse gas emissions analysis of heat pump water heaters coupled with air-based solar thermal collectors in Canada and the United States. Energy Buildings 2021; 231: 110594.
[20] Ma JL, Fung AS, Brands M, Juan N, Moyeed OMA. Performance analysis of indirect-expansion solar assisted heat pump using CO2 as refrigerant for space heating in cold climate. Solar Energy 2020; 208: 195-205.
[21] Dott R, Haller MY, Ruschenburg J, Ochs F, Bony J, The Reference Framework for System Simulations of the IEA SHC Task 44 / HPP Annex 38—Part B: Buildings and Space Heat Load, A technical report of subtask C—Report C1 Part B, International Energy Agency, 2013.
[22] World Health Organization, LEGIONELLA and the prevention of legionellosis, 2007.
[23] Charted Institute of Plumbing and Heating Engineering, https://www.ciphe.org.uk/consumer/safe-water-campaign/hot-water-scalds/, [accessed on April 22nd, 2021].
[24] Li H, Yang HX, Potential application of solar thermal systems for hot water production in Hong Kong, Appl Energy 2009; 86: 175–180.
[25] E.ON Energy, https://www.eonenergy.com/for-your-home/products-and-services/best-deal-for-you/quote, [accessed on April 9th, 2021].

[26] https://www.made-in-china.com, [accessed on April 2nd, 2021].
[27] Plumber Costs: 2021 Call Out Charges & Hourly Prices UK, https://tradesmencosts.co.uk/plumbers/, [accessed on October 11th, 2021].
[28] Green Homes Grant: make energy improvements to your home, https://www.gov.uk/guidance/apply-for-the-green-homes-grant-scheme, [accessed on October 11th, 2021].