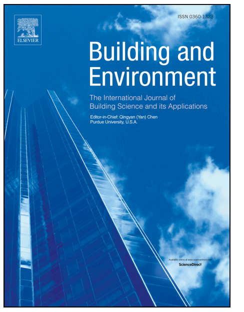

Heating energy-saving potentials in HVAC system of swimming halls: A review

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Heating energy-saving potentials in HVAC system of swimming halls: A review

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Abstract

Swimming halls (SHs), which belong to special building sector, are easily overlooked as significant energy users and carbon producers. The demands of heat (e.g., pool water heating, domestic hot water, space and supply air heating) and electricity (e.g., Saunas, pool pumping and ventilation) in SHs are both very high, which indicates the high energy saving potentials. This paper comprehensively introduced and summarized the energy-saving potentials mainly for the heating system in SHs. After briefly introducing the global energy and building energy backgrounds, the energy system of SHs was firstly introduced, including its energy use and breakdown, ventilation demand, and heat losses. Then, renewable and sustainable energy sources applied in SHs were reviewed, especially solar energy application in terms of individual solar-assisted heating and hybrid solar-assisted heat pump systems, while geothermal and biomass and other energy applications were also introduced briefly. Furthermore, building energy management (BEM) strategies were introduced and summarized comprehensively, including waste heat utilization, prediction of energy demand and consumption, control and optimization of HVAC system, and demand response potentials of both electricity and district heat. In the discussion part, the recommendations of high-efficient or energy-saving technologies in SHs were given as well as the future development. Finally, suggestions were given for achieving energy efficiency and carbon reduction in SHs via using renewable energy sources (especially solar energy), optimizing the energy and HVAC systems, possible waste heat recoveries, and applying demand response of energy. In addition, establishing feasible and comprehensive energy indexes to evaluate energy use in SHs is also essential in the future.

Keywords: Swimming halls; Heating energy system, Energy efficiency and saving; Solar energy utilization; Waste heat recovery, Demand response

Nomenclature

Abbreviations

ANN	Artificial neural network
BEM	Building energy management
CFD	Computational fluid dynamics
CLI	California Legislative Information
Cond.	Condenser
Comp.	Compressor
CWP	Circulating water pump
DC	Data center
DHW	Domestic hot water
DR	Demand response
ESO	Early switch-off
EPD	Environmental Product Declaration
Evap.	Evaporator
FINVAC	Finnish association of HVAC societies
GHEs	Ground heat exchangers
GSHP	Ground source heat pump
HVAC	Heating, ventilation and air-conditioning
HP	Heat pump
HVAC	Heating, ventilation and air-conditioning
IEA	International Energy Agency
IH	Ice hall
ISP	Indoor swimming pool
MPC	Model predictive control
PAH	Pool air heating
PID	Proportional integral derivative
PV	Photovoltaic
PVT-SAHP	PV/thermal solar-assisted HP
PWH	Pool water heating
SAHP	Solar-assisted HP
SH	Swimming hall
SE	Solar energy
TV	Throttle valve
W-SAHP	Water solar-assisted HP

List of symbols

A_s	Surface area of conduction to ground [m^2];
A_p	Pool surface area [m^2];
B_p	Empirical evaporation coefficient [m/h];
c_w	Water specific heat capacity [kJ/K];
g	Gravitational acceleration, [m/s^2];
h	Space height, [m];
h_{cv}	Convective heat transfer coefficient [$W/(m^2 \cdot K)$];

k	Thermal conductivity [W/(m·K)];
k_s	Soil specific heat;
L_c/L_s	Poll characteristic length;
m_{rf}	Mass flowrate of the refilling fresh water
$p_{v,sat}$	Vapor pressure of saturated air at the temperature of pool water [Pa];
p_a	Air vapor pressure [Pa];
p_{atm}	Atmospheric pressure, [Pa];
q_{wm}	Evaporating water mass flow [kg/s]
Q_s	Dimensionless conduction heat rate;
Q_e	Evaporative heat loss [kWh];
Q_{cv}	Convective heat loss [kWh];
Q_{cd}	Conductive heat loss [kWh];
Q_r	Radiative heat loss [kWh];
Q_{rw}	Refilling water heat loss [kJ];
R	Gas constant of water vapor [J/(kg·K)];
Ra	Rayleigh number;
$R_{sp,da}$	Specific gas constant for dry air, [J/(kg·K)];
S	Stack-effect caused pressure difference, [Pa];
T_a	Ambient air temperature [K];
T_p	Pool water surface temperature [K];
T_s	Soil temperature [K];
T_{out}	Outdoor air temperature, [K];
T_{in}	Indoor air temperature, [K];
T_{sur}	Ambient upper surface temperature [K];
T_{aw}	Air average temperature (on water surface layer) [K]
ε_w	Water emissivity;
σ_s	Stefan-Boltzmann constant (5.67×10^{-11} kW/(m^2);
ρ_{out}	Outdoor air density, [kg/m^3];
ρ_{in}	Indoor air density, [kg/m^3];

1. Introduction

The rapid depletion and low-utilization efficiency of global non-renewable resources has caused the problems of energy shortage, higher energy prices and corresponding climate change concerns (e.g., global warming and urban heat island effects) [1, 2]. In 2014, European Union has reacted to the energy shortage and environment-related concerns for achieving three main goals by 2030 [3], which are 40% carbon emission reduction, 27% increase of renewable energy share, and 27% increase of energy efficiency, compared with the level in 1990 [3]. In addition, European Union in 2018 has also claimed a proposal of achieving climate neutral Europe by 2050 [4]. Thus, energy conservation has become an urgent problem and also a hotspot in the global energy industry.

Among all the high energy consumption fields, building sectors consume more than 40% of the total global primary energy, which have surpassed that in industrial transportation sectors, and have become the largest energy user throughout the world [5-7]. Thus, building sectors undoubtedly greatly influence the global energy use, carbon emission and clean energy transition [8], while improving the energy efficiency and using renewable energy in buildings are regarded as the most effective approaches to achieve energy conservation, and alleviate global energy shortage [7]. Considering current available energy conservation strategies, it is predicted by the International Energy Agency (IEA) Efficient World Strategy report that building sectors in 2040 would achieve more than 40% energy saving than that in 2013 [9, 10]. IEA has claimed that heating and cooling system is responsible for approximate 16% of total energy use in moderate and warm climate zones, whose figure is approximate the half in cold climate zones [10]. Thus, high-efficient energy utilization in heating, ventilation and air-conditioning (HVAC) system is an indispensable part of global energy conservation, and could be somehow the dominant position.

Sport facilities belong to special building sector, and they also consume significant amount of energy and produce many carbon emissions [11]. According to EUROSTAT energy statistics 2019, sport facilities are responsible for more than 8% of the total building energy use in Europe [12]. Among all the sport facilities in Europe, swimming halls (SHs) are the second most popular sport facilities [13-14], and they own a high potential for efficient-energy use actions [15]. Apart from the common energy demands for all types of sport facilities (e.g., lighting, domestic hot water (DHW) supply, and space heating and cooling), SHs have other special energy demands (e.g., pool water heating, space heating and dehumidification energy use) [11, 15]. Different from the outdoor swimming pools mainly used in summer time, indoor swimming facilities can meet people's swimming demands all the year, which are not much influenced by the climate conditions [16]. Energy use of outdoor swimming pools is mainly affected by the outdoor weather conditions, but that of indoor swimming facilities is not the same, which is mainly determined by the heating supply facilities (e.g., space heating, supply air heating, DHW heating, pool water heating) [17-18] and electricity demands for saunas and dehumidification of ventilation system [18-19]. Heating supply is to ensure both comfortable water temperature, and indoor thermal comfort levels, while dehumidification process is to adjust high humidity caused by inevitable water evaporation to an occupants' acceptable level [20]. Therefore, the energy consumption of SHs should be much larger than that of outdoor swimming pools. According to the international center for energy and environmental technology (ICEET) [21], the energy used in an indoor swimming pool (ISP) is approximate 3 times than that in an outdoor swimming pool with the same size. Thus, the energy use in SHs is relatively higher than that in other sport facilities and outdoor swimming pools, which means much bigger energy-saving potentials.

In Finland, there are 280 SHs for 5.5 million persons, which altogether with the ice halls account for 1.2% of annual total building energy use [22]. The number of swimming pools in Norway is more than 850, which is much larger compared with its population size of 5 million persons [17, 23]. The energy cost in sports facilities generally accounts for approximate 30% of the overall operating and maintenance fees, while that in SHs usually accounts for a much higher proportion [24]. Although SHs are just a very small proportion in building sectors, they do occupy relatively considerable building energy use, and their energy cost accounts for quite large part of overall operating and maintenance fees [25]. However, it seems the energy use level and energy-saving potentials in SHs have not attracted enough attention. In Finland, the Ministry of the Environment sets no energy use limitation for the SHs, but its energy certificate (E-value) is needed to be calculated in the design phase. The E-value should be compared to get the SHs with higher energy use, but still no specific limitation is set for the E-value [26]. Compared with other building sectors, the researches on energy system in SHs are relatively few, owing to lack of corresponding energy regulations and the insufficient building scale/number [27]. The first batch of studies on improving energy efficiency in SHs started from 1960s, while until 2020 Li et al [16] firstly reviewed the all-time researches on energy system in both indoor and outdoor swimming pools. Besides, there is no other comprehensive review related to the energy system of swimming pool facilities.

However, there are many distinctions on the energy systems between indoor SHs and outdoor swimming pools [16, 17]. Thus, this paper could be the first review paper, whose focus is on reviewing and summarizing the current energy saving potentials in indoor SHs only. In this paper, all-time energy-saving strategies in SHs, from 1960s to 2021, will be comprehensively presented and reviewed. The structure of the rest of the paper is described as follows. The second section introduces the energy system of SHs, including its energy use and breakdown, ventilation demand and heat loss conditions. Then, section 3 describes some renewable energy sources (e.g., solar, geothermal and biomass energy) applied in SHs, and mainly focuses on the solar-assisted (SA) heating systems (e.g., individual SA heat pump (SAHP) and hybrid SAHP systems), and their operation performance optimization. In section 4, energy management strategies are represented and summarized, including waste heat utilization, energy demand and consumption prediction, HVAC system control and optimization, and demand response of both electricity and heat. In the discussion part, the recommendations of high-efficient or energy-saving technologies in SHs are given as well as the future development. Renewable energy sources, especially solar energy, are recommended in SHs, while HVAC system prediction and optimization is also suggested to improve energy efficiency. In addition, it is recommended to apply possible waste heat recoveries and demand response of both electricity and heat in SHs. **Fig. 1** shows the diagram of main contents reviewed and summarized in this paper.

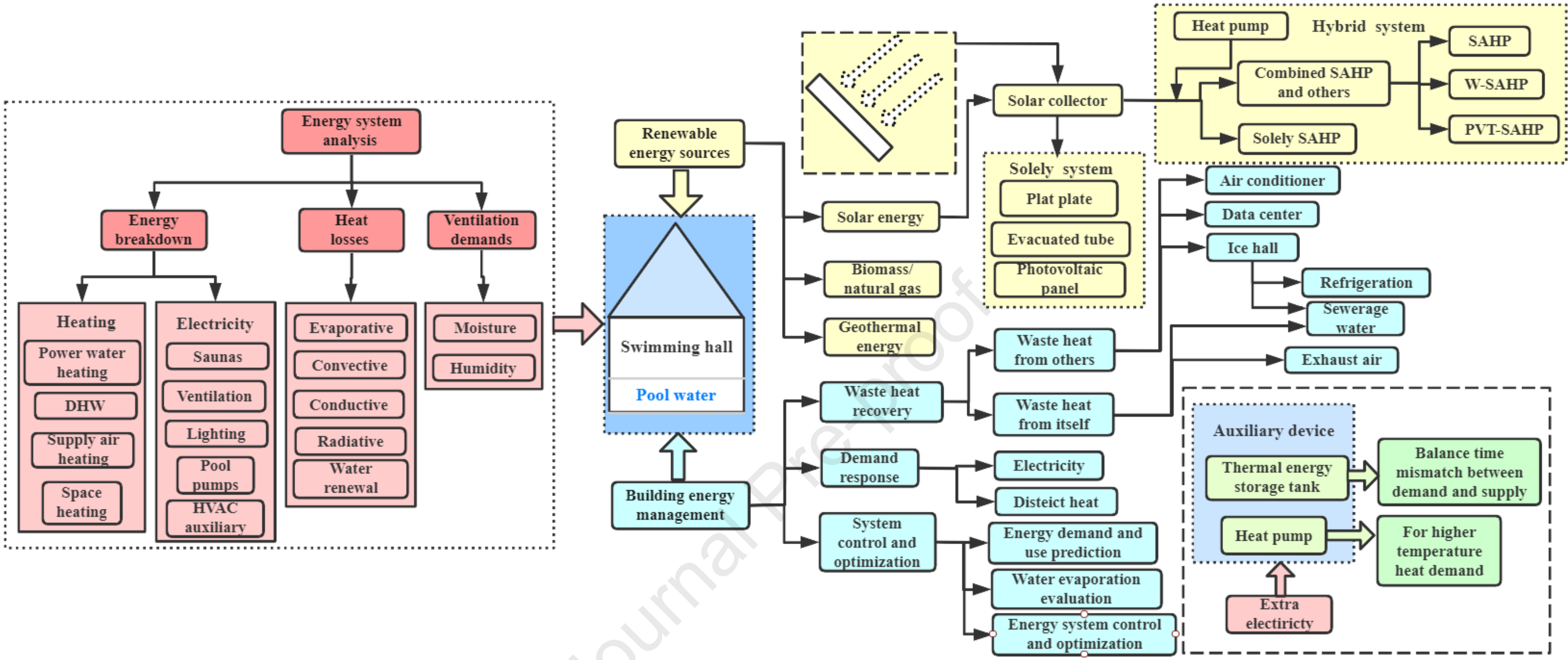

Fig. 1. The schematic diagram of main contents reviewed and summarized in this paper.

2. Energy system of SHs

2.1. Energy use and breakdown

According to the California Legislative Information (CLI), swimming pool is defined as "any structure intended for swimming or recreational bathing that contains water over 18 inches deep" [28], while SHs are the buildings with swimming pools as well as other support facilities (e.g., bathroom and sanitary units, saunas (Nordic region), spectator stand, technical spaces) [29].

Hemmilä and Laitinen [22] classified the SHs in Finland based on the pool surface area in 2018, and got the average energy use per gross floor area, as shown in **Fig. 2**. Public SHs often close down for approximate one month in summer time for maintenance; Thus, those consumptions in **Fig. 2** are for altogether 11 months in practice. It is relatively difficult to achieve high building energy performance in cold climate zones (e.g., Nordic countries), due to large air temperature differences between indoors and outdoors. In addition to the huge heat losses, SHs also have huge moisture load in pool water areas compared with ordinary building types [29]. The high moisture load will lead to the condensation moisture and mold concentrations within the SHs, but can be prevented via indoor air heating above the pool water and air dehumidification at the cost of extra high energy consumption [27, 30].

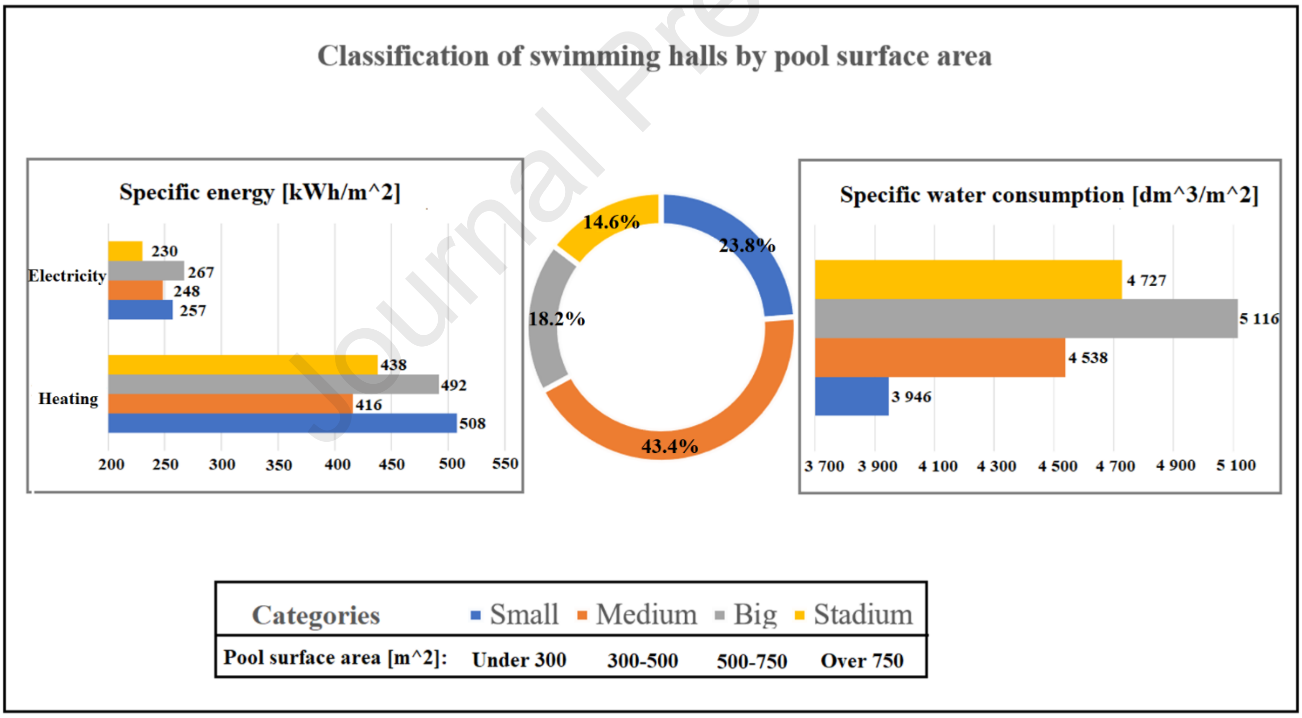

Fig. 2. Energy use of swimming halls classified by pool surface area [21]

The pool water temperature is recommended to be maintained in the range between 22 and 28 °C due to thermal comfort requirement [31, 32]. In addition, Environmental Product Declaration (EPD) has recommended design pool water temperature for big pools should be kept from 26 to 28 °C [33], while the indoor air temperature is recommended to be 1.5-2.5 °C higher than the pool surface temperature [33, 34]. Nowadays, due to the enhanced comfort requirement, pool water temperature will be normally set to 28 °C. The temperature difference between pool water and indoor air can limit evaporation, and thus reduce water heat loss and improve occupants' thermal comfort. Indoor air humidity is also recommended by the EPD [33] in the range from 45 to 60%, because indoor air humidity over 60% will cause microorganism growth, while that below 45% will increase the heat loss of pool water from evaporation, and thus decrease energy efficiency.

The energy consumption in the SHs consists of two parts, heating and electricity use. To be specific, the average heating energy use per gross floor area accounts for approximate 66% of the total SH energy use in Finland, while average electricity use accounts for the remaining 34% [22]. **Fig. 3** shows the energy use breakdown of SHs in Finland. It shows that the largest heat consumers in SHs are DHW supply and pool water heating, while the largest electricity consumers are saunas and pool pumps. Apart from the shower and washing DHW supply, DHW also serves the pool water changing, pool water resupply and filter flushing, which altogether are responsible for 38% of total heating energy use, while the indoor air heating, composed of supply air heating and space heating, is right behind (34% of total heating energy use). Supply air heating represents heating who is carried out by an air handling unit, which heats the ventilation supply air and blown to the rooms, while space heating means heating which is carried out in rooms (e.g., water radiators, floor heating). The big heating demands of pool water and supply air are mainly caused by the evaporation from pool water to the air. Due to the evaporation, the heat losses from pool water and indoor air are approximately 77% and 23%, respectively [32]. Evaporating water absorbs heat not only from the pool water but also from the pool air, which increase the supply air heat demand; and thus, decreasing the temperature difference between pool water and pool air can decrease evaporation and heat losses.

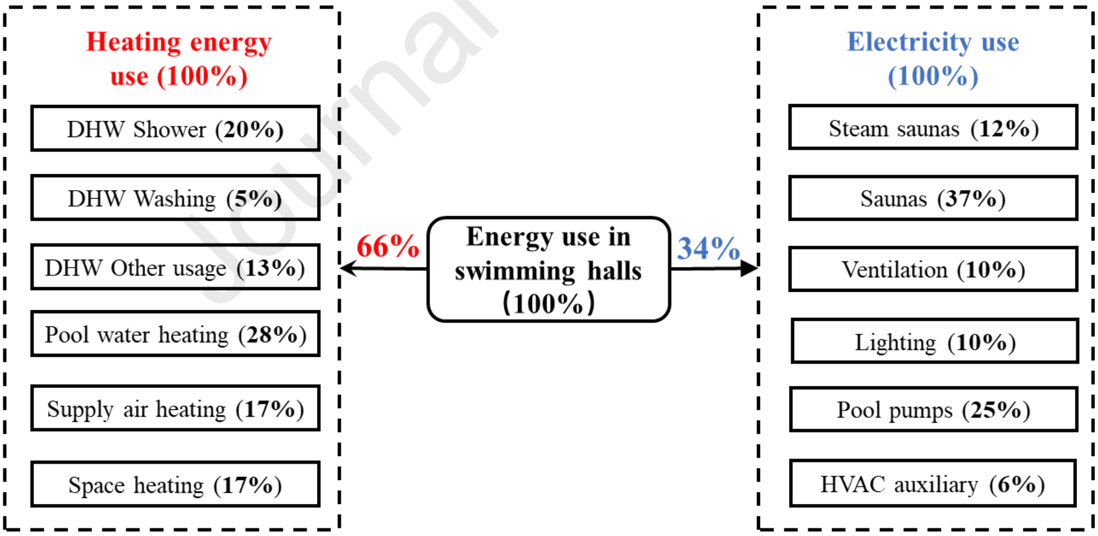

Fig. 3. The breakdown of energy usage of SHs in Finland

In addition, due to multiple big saunas use and their high use frequency, saunas along with steam saunas rank the first (49%) in terms of electricity consumption, which are followed by the pool pumps electricity use (25%). The active and frequent use of sauna facilities increases the energy use due to high saunas door opening rate, and causes the heat from the stove transferred from the water to the exhaust air [27]. High energy use of the pool pumps is for the pool water recycling, while the water will be pumped to the heat exchangers and the filters to keep the water warm and clean enough, respectively. Due to the requirements of humidity and temperature levels in SHs, ventilation energy use is also high (10%), while the specific ventilation demand in the halls will be introduced in the following **sub-section 2.2.**

2.2. Ventilation demands regarding moisture and humidity controls

Ventilation can adjust both the indoor air moisture and the humidity of outdoor air entering the room, which will affect the indoor air quality and thermal comfort, respectively, while it also largely influences the heating and electricity use in buildings [35]. Compared with space heating, the ventilation rate requirement for supply air heating is bigger, leading to the electricity increase of ventilation fans [12]. Finnish association of HVAC societies (FINVAC) [36] formulated ventilation guidelines for different types of Finnish buildings, and categorized exercise buildings and SHs into their own ventilation group. In this group, the ventilation rate is determined by the occupancy and moisture load instead of floor surface area.

2.2.1 Moisture concerns

FINVAC also mentions indoor air moisture content is decisive factor for ventilation control, while the biggest moisture load in SHs comes from the pool evaporation, which determines the biggest airflow rate of ventilation [37]. Vapor pressure difference, between indoor air and saturated air at the pool water temperature, leads to the pool evaporation phenomenon, which is described as **Eq. 1**. As the temperature setpoints are not the same for separate zones, different ventilation or heating supply equipment should be considered (e.g., air handling units (AHU), heating distribution system and recommended displacement ventilation for the pool edge) [33].

$$Q_e = A_p \cdot \frac{B_p}{R \cdot T_a} \cdot \left(p_{v,sat} - p_a\right) \quad \textbf{(1)}$$

Where Q_e represents the mass flow of evaporating water, [kg/h]; A_p is the pool surface area, [m^2]; B_p is the empirical evaporation coefficient, [m/h]; R is water vapor gas constant, [J/(kg·K)]; T_a is the air average temperature on the water surface layer, [K]; $p_{v,sat}$ is the vapor pressure of saturated air at the temperature of pool water, [Pa]; p_a is the air vapor pressure [Pa].

As mentioned above that the vapor pressure difference will cause the pool water evaporation, and evaporation process will accelerate the gathering of moistures. Moisture gains can increase the indoor air humidity and deteriorate the facilities' moisture condition in the halls, and thus should be effectively removed by the ventilation system [29]. Moisture control by ventilation is important in SHs, as it affects both the indoor air quality, thermal comfort as well as energy use. EPD [33] mentioned that it was prohibited to discharge humid indoor air through the building envelope to the outdoor environment directly; Thus, under-pressure ventilation is essential for the humid pool spaces. In general, SHs belong to high-rise spaces, whose air pressure is much higher on the top than that on the bottom (namely stack effect, caused by the difference between indoor and outdoor air temperature). The over-pressure phenomenon in the top part of the pool space caused by stack effect can be relieved by the under-pressure ventilation compensation. However, this compensation may be not enough under the circumstance of too cold outdoor weather or seriously insufficient off-time ventilation. The stack-effect caused pressure difference can be calculated via **Eq. 2** [33].

$$S = (\rho_{out} - \rho_{in}) \cdot g \cdot h = \left(\frac{1}{T_{out}} - \frac{1}{T_{in}}\right) \cdot \frac{p_{atm}}{R_{sp,da}} \cdot g \cdot h \quad \textbf{(2)}$$

Where S represents the stack-effect caused pressure difference [Pa]; ρ_{out} is outdoor air density [kg/m^3]; ρ_{in} is the indoor air density [kg/m^3]; T_{out} is the outdoor air temperature [K]; T_{in} is the indoor air temperature [K]; p_{atm} is atmospheric pressure [Pa]; $R_{sp,da}$ is the specific gas constant for dry air [J/(kg·K)]; g is the gravitational acceleration [m/s^2]; h is the space height [m].

2.2.2. Humidity concerns

Humidity adjustment is essential as one of the important factors for thermal comfort, and can be also realized by ventilation [37, 38]. The evaporation process of pool water will absorb heat from air, and drop the indoor air temperature, while the evaporation and energy demand can be reduced by rising the relative humidity appropriately, which has been proved in Yli-Rosti's research [39]. ASHRAE handbook has recommended the relative humidity range as 50-60% concerning the swimmers' comfort and energy use [40]. However, the phenomenon of condensation and microorganism growth may happen on the cool surfaces of pool spaces when the relative humidity is too high [33, 35]. Marín et al. [41] mentioned that comprehensively considering the associated energy use and comfort level requirement, the Spanish standards for the maximum relative humidity is set to 65%. In Finland, dehumidification process is not compulsory in SHs, but it can be fulfilled by outdoor airflow increase as a passive method [42]. However, positive dehumidification can be achieved by applying heat pump (HP) system, which can reduce ventilation and overall energy consumption during dehumidifying [37].

2.3. Heat losses and gains

SHs consume much energy (e.g., heating energy and electricity energy use), and heating is needed in pool area year around to maintain the set room air temperature. In addition, heat loss must occur during different heating supply modes as well as possible heat gains. The category of heat losses in the SHs has been studied and summarized by some researchers e.g., Douglass [43], Li et al. [16], Lindroos [27], Jordaan et al. [44], which includes evaporative, convective, conductive, radiative and water renewal heat losses. **Table 1** shows the detailed description of those possible heat losses within SHs. The star symbol '★' represents the heat loss level, while the more the number of stars, the larger the heat loss level. The main heat gain in the SHs is the solar, however the solar energy is absorbed by the building envelope, and the pool water cannot directly obtain the solar energy. Thus, heat gain in SHs can be neglected [16, 44].

Table 1. Heat losses in SHs.

Heat loss	Grade	Definition/Cause	Equations		Sources
Evaporative	★★★★	State conversion of pool water from liquid to gas	$Q_e = A_p \cdot \frac{B_p}{R \cdot T_a} \cdot (p_{v,sat} - p_a)$	**Eq. 1**	EPD 2009 [33]
Convective	★★★	Temperature difference between the water surface and ambient air	$Q_{cv} = h_{cv} \cdot A_p \cdot (T_p - T_a)$;	**Eq. 3**	Lam and Chan, 2001 [46] Incropera et al. 2006 [47]
			$h_{cv} = \frac{k \cdot (0.14 \cdot Ra^{1/3})}{L_c}$	**Eq. 4**	Winterton 1999 [48] Bergman et al. 2011 [49]
Conductive	★★	Temperature difference between pool water and	$Q_{cd} = \frac{1}{2L_s} \cdot Q_s \cdot k_s \cdot (T_p - T_s)$	**Eq. 5**	Govaer and Zami 1981[50]

		soil			
Radiative	★	Long-wave radiation caused heat transfer between pool water and the environment	$Q_r = 0.0057A_p \cdot \varepsilon_w \cdot\cdot \left((T_p)^4 - (T_{sur})^4\right)$	**Eq.6**	Bergman et al. 2011 [49] Marín et al. 2019 [41] Howell et al. 2015 [51]
Refilling water/ water renewal	★★★	Temperature difference between pool water and refilling fresh water/ water renewal	$Q_{rw} = c_w \cdot m_{rf} \cdot \left(T_p - T_{rf}\right)$	**Eq. 7**	Buonomano et al. 2015 [52] Chow et al. 2012 [53]

Notations: $Q_e =$ Evaporative heat loss; $Q_{cv} =$ Convective heat loss; Q_{cd}= Conductive heat loss; $Q_r =$ Radiative heat loss; Q_{rw}= Refilling water heat loss; $A_p =$ Pool surface area; $B_p =$ Empirical evaporation coefficient; $R =$ Gas constant of water vapor; T_a= Ambient air temperature; $p_{v,sat} =$ Vapor pressure of saturated air at the temperature of pool water; $p_a =$ Air vapor pressure; $h_{cv} =$ Convective heat transfer coefficient; $T_p =$ Water surface temperature; $k =$ thermal conductivity; $Ra =$ Rayleigh number; $L_c = L_s =$ Poll characteristic length; $Q_s =$ Dimensionless conduction heat rate; k_s= Soil specific heat; $A_s =$ Surface area of conduction to ground; $T_s =$ Soil temperature; $\varepsilon_w =$ Water emissivity; $\sigma_s =$ Stefan-Boltzmann constant (5.67×10^{-11} kW/(m^2); $T_{sur} =$ Ambient upper surface temperature; $c_w =$ Water specific heat capacity; $m_{rf} =$ Mass flowrate of the refilling fresh water.

3. Renewable energy sources

To solve the global primary energy crisis, more renewable energy sources should be developed and widely used. In 2015, the share of renewable energy use in the total global energy use sector was 25%, while it is predicted to rise to approximate 63% by 2050 [54]. Alternative renewable energy sources have been widely used in all kinds of buildings [55], including solar [56-58], biomass [59-60], geothermal [61-64] energies, etc.

3.1. Solar energy utilization

In recent years, solar energy has been widely investigated and applied in various fields due to the characteristics of universality, harmlessness, massiveness and permanence [65], while solar energy is also applicable and widely used in SHs, which can be fulfilled by solar collectors. A thermal solar collector belongs to the type of special heat exchanger, transforming solar radiation into heat. Based on whether there is vacuum space, solar collector is divided into two types, flat plate and evacuated tube collectors. In addition, photovoltaic (PV) solar panel can also fulfill solar energy utilization [44]. Due to the introduction of high-efficient solar collectors, solar energy began to be exclusively used for the heating of SHs as an indirect solar energy utilization [66], while many researchers used solar thermal collectors as an indirect solar energy converter in SHs.

3.1.1. Solar collector applications from 1980s

In 1983, Brambley and Wells [67] proposed applying solar collectors into the heating system of SHs, and analyzed its economic performance compared with the conventional system with low-price fuels (e.g., coal and gas). They did not recommend to use solar collectors due to too long payback period (around 10 years). But with more researchers' study on solar energy applied in SHs, the viewpoints of Brambley and Wells [67] have been challenged and reversed. In 1989, Singh et al. [66] firstly connected an indoor swimming pool with panel collectors under active operation mode, and transiently analyzed its performance considering the evaporative heat losses from the surface of the pool water. They found that the use of solar collectors can achieve the desired ISP temperature by the active method in harsh climate. In 1991, Tiwari and Sharma [68] further investigated the SHs with solar collectors and other heat exchangers, and proposed the corresponding analytical expression regarding convection and evaporation losses. Furthermore, Croy and Peuser in 1994 [69] studied and compared the visitors' behaviors and reactions to conventionally heated and solely solar-heated swimming pools. They found that the ambient temperature would affect the number of visitors and pool water temperature, while the number of visitors had no relationship with the pool heating method. However, according to the existing literature, few researchers have conducted in-depth research in the indirect solar energy application in SHs during the period from 1995 to 2010.

3.1.2. Proposal of solar assisted HP system and its extension

However, since 2012, indirect solar energy in swimming pools returned to the researchers' field of vision. They began to study solar assisted HP (SAHP) system in SHs, and combined SAHP system with other systems. Chow et al. [53] introduced a new design of SAHP system for ISP space and pool water heating, while **Fig. 4** shows the simplified system diagram of the indirect SAHP system in ISPs. They found that the studied SAHP system can meet the heating demand in SH well, while the temperatures of pool water and pool space air can be maintained at 32 and 29 °C, respectively during the operating period. In addition, the heating system has a COP of 4.5 with up to 79% global fractional energy saving factor in November, while its economical payback period was less than 5 years.

Later in the same year, Tagliafico et al. [70] proposed an approach to analyze and assess the energy saving of a water solar assisted HP (W-SAHP) system for pool water heating in SHs. The W-SAHP system was equipped with a commercial water-to-water HP as well as unglazed flat plate solar collectors. **Fig. 5**. shows the simplified schema of the W-SAHP system for the pool water heating. They finally formulated an equation to estimate the energy savings, and found that W-SAHP could ensure the primary energy saving index to a minimum of 35%, while this figure could be close to 50% in mild-climate towns. In addition, Bai et al. [71] proposed and applied a hybrid PV/thermal SAHP (PVT-SAHP) system for water heating demand in a sports center. PV/thermal system differs from the general solar thermal system, as these two systems converts solar energy into electricity for heating and direct heating through solar collectors, respectively. **Fig. 6** shows the schematic diagram of the indirect PVT-SAHP system, where R1 and R2 represent on-off differential controllers. They found that the system energy demand could be met by the PVT-SAHP system, while the temperature of hot water supply could be reheated to 40 °C. In addition, the PV/thermal collectors' overall efficiency could reach to 76% in Hong Kong, but the payback period was relatively long (10.5 years).

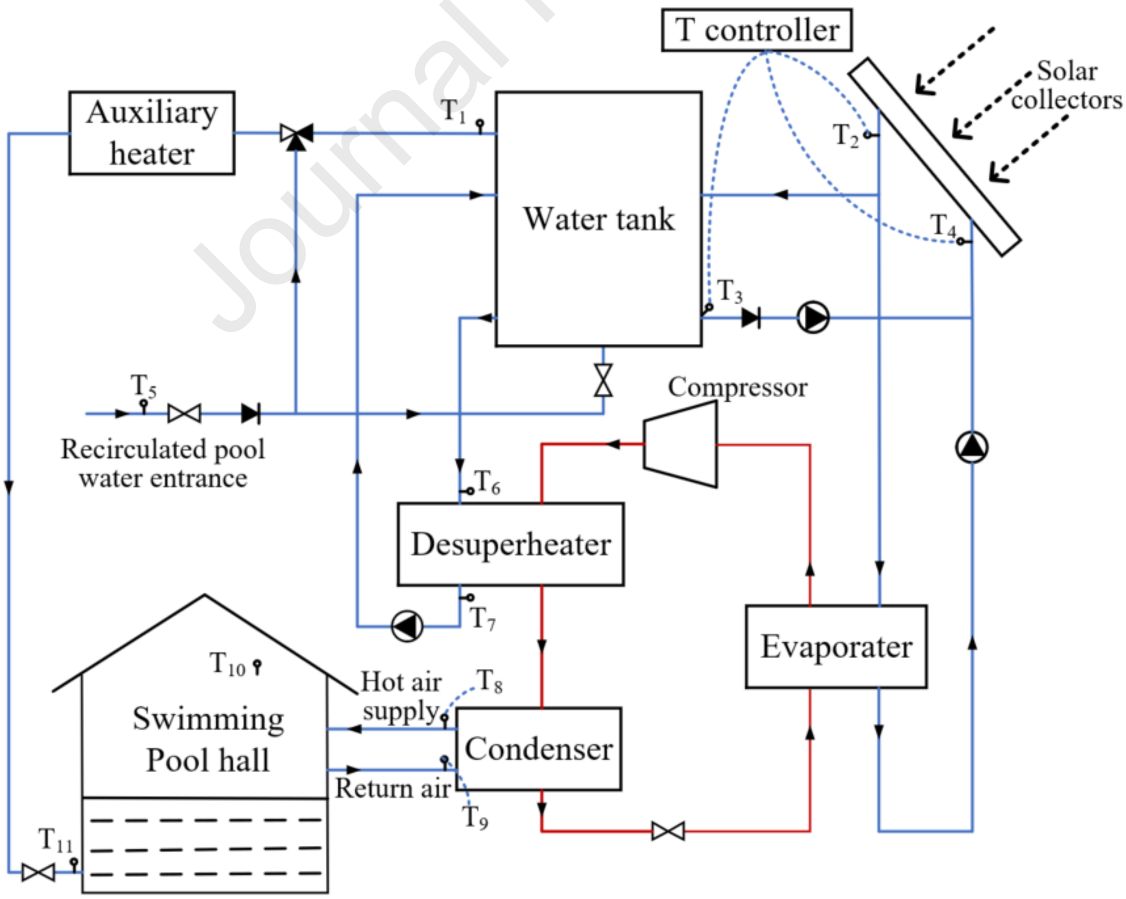

Fig. 4. Simplified system diagram of the indirect SAHP system [53].

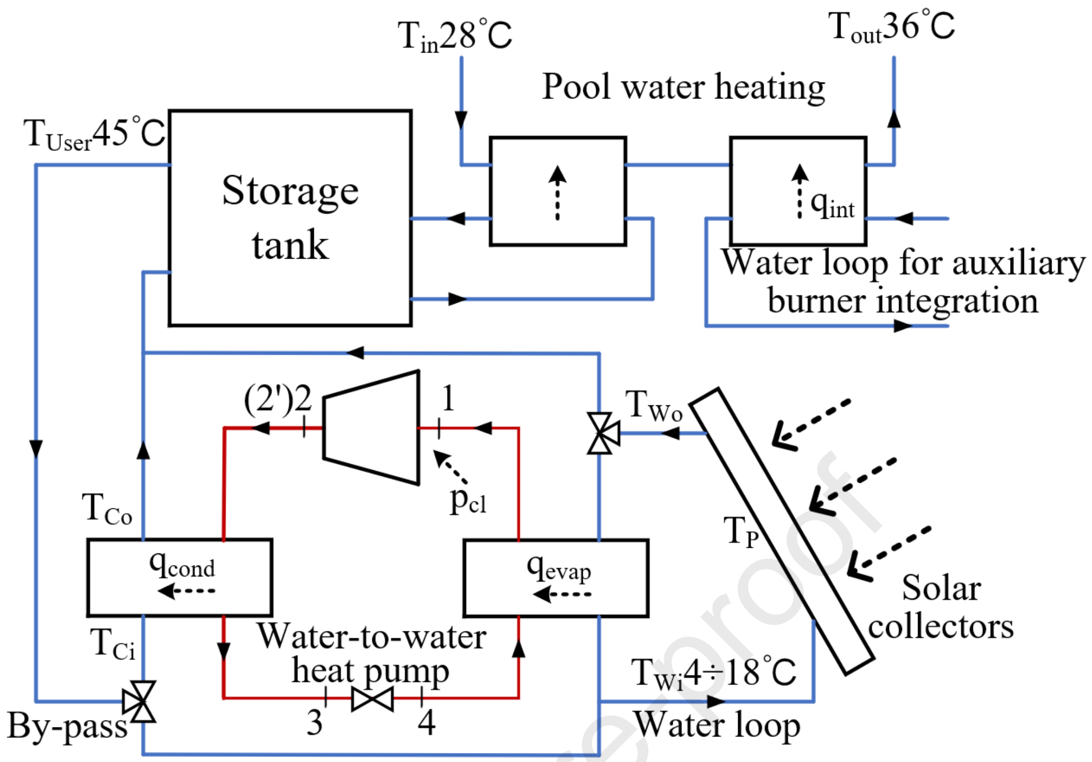

Fig. 5. Simplified schema of W-SAHP system for the pool water heating [70].

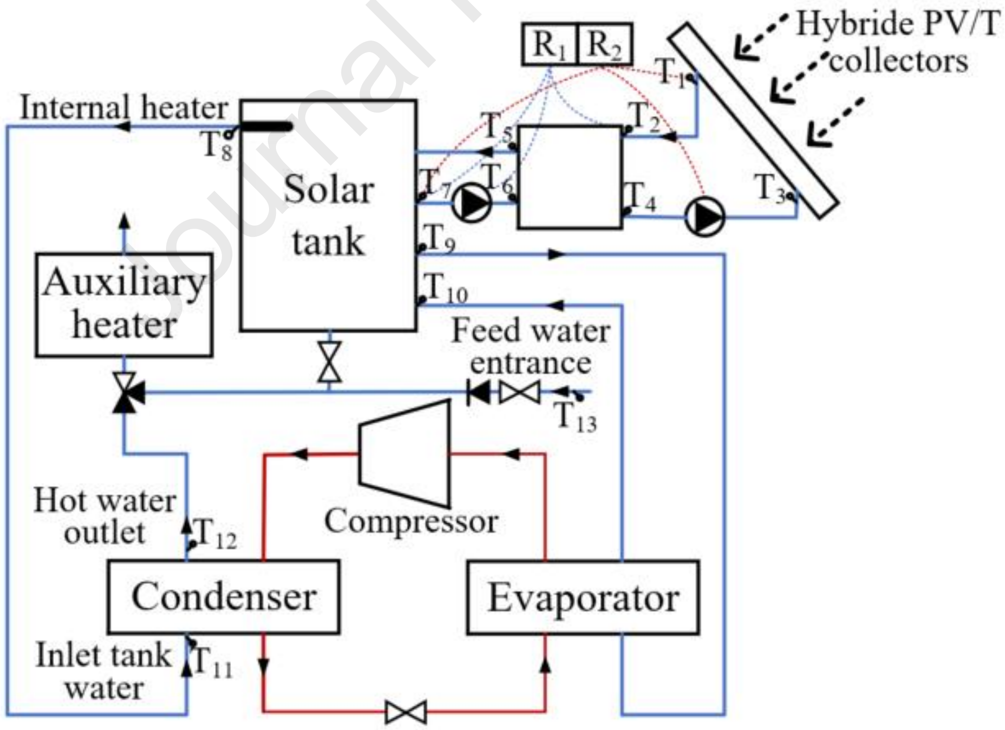

Fig. 6. Schematic diagram of the indirect PVT-SAHP system [71].

3.1.3. System optimization and further development

After putting forward SAHP or other hybrid SAHP systems, researchers began to investigate the factors to affect the operation performance of these systems. Kincay et al. [72] studied and analyzed the solar energy utilization in SHs in terms of its technical and economic performance, and then determined the optimum solar collector surface area in various locations. They found that the total yearly energy from solar energy could make up for the total heat losses between 30.5% and 47% in different locations, while the solar energy use could save 7%-16.2% total annual energy costs varying from locations. Then, Bataineh [73] transiently analyzed an ISP model with a SAHP system for pool water heating, which was connected to solar evacuated tube collectors, and they drew the conclusions that the primary energy saving for both pool water and DHW was positively correlated with the collector area. The collector areas equaled to 53%, 40% and 26.6% of pool surface could result in 100%, 87% and 59% primary energy savings, respectively. Based on its economic analysis, the lowest energy production cost of $ 0.011/kWh could be achieved by utilizing the solar evacuated tube collector with area of 200 m^2.

Buonomano et al. [52] numerically and thermo-economically analyzed the technical feasibility and energy performance of a PV/thermal (PVT) collector heating system for an indoor-outdoor swimming pool. Compared with Bai et al. [71], Buonomano et al. [52] has considered the behavior of thermal swimming pool and its heat demand. They claimed that none of research focused on the pool water heating supply by adopting PVT collectors in SHs. They found that the thermal energy demand in swimming pool was significantly affected by the adopted model. In addition, the optimal swimming pool energy performance could be achieved when the PVT collector field area was in the optimal range between 200 and 300 m^2.

3.2. Other renewable energy sources

Apart from the solar energy, other renewable and sustainable energies (biomass, geothermal energy, etc.) also can be used in the energy system of SHs. Geothermal energy has the characteristics of high stability and big capacity, which is considered as a promising renewable energy. Geothermal energy has been studied and applied in outdoor swimming pools by many researchers [65, 74-78], while it is also applicable in SHs, normally as ground source HP (GSHP) application. **Fig. 7** shows the working principle of GSHP system and its application in SHs [79]. The GSHP system consists of underground exchange system (including ground heat exchangers to exchange heat from the soil), and above ground system (including GSHP units, circulating water pumps, other heat exchangers, end devices, etc.) [79]. Barbato et al. [80] investigated and analyzed the feasibility of applying geothermal energy system for ISPs in Italy. In the geothermal energy system, some parameters have been considered, including site geological and hydro-geological characteristics, geothermal plant characteristics and the energy conversion system. They concluded that the economic performance of the system was satisfactory, and the payback period was approximate 15.4 years under the present fiscal incentives and rules, which is within an acceptable level in terms of full load operation life of the machine.

1 **Table 2** Summary of characteristics and performance of individual and hybrid ASHP system

Year	Researchers/ references	System type	Research focus	Solar collector type	Heat source	Heating supply	Finding and conclusions
1994	Croy and Peuser [69]	Solely solar-heated system	Analysis --Heating performance	Flat plate	SE	Pool water	● Ambient temperature would affect the number of visitors and pool water temperature; ● Visitor number had no relationship with the pool heating method.
2012	Chow et al. [53]	Individual SAHP	Analysis -- Heating performance -- Energy saving	Flat plate	SE	Pool water Space air	● Heating energy demand in SHs is met well; ● Maintain temperatures of pool water and pool space air at 32 and 29 °C; ● COP of heating system: 4.5; ● Up to 79% global fractional energy saving factor in November; ● Economical payback period is less than 5 years.
2012	Tagliafico et al. [70]	Hybrid W-SAHP	Analysis -- Energy saving	Flat plate	--SE --Water energy	Pool water	● An equation is formulated to estimate the energy savings; ● Primary energy saving index can be ensured to a minimum of 35%; ● Primary energy saving index is close to 50% in mild-climate towns.
2012	Bai et al. [71]	Hybrid PVT-SAHP	Analysis -- Heating performance -- Energy efficiency -- Payback period	Evacuated tube	SE	Pool water DHW supply	● Meet the system energy demand; ● The temperature of hot water supply can be reheated to 40 °C; ● The overall efficiency of PV/thermal collectors can reach to 76% in Hong Kong; ● The payback period is relatively long (10.52 years).
2012	Kincay et al. [72]	Individual SAHP	Optimization --Surface area	Flat plate	SE	Pool water	● Total yearly energy from solar energy can make up for the total losses between 30.5% and 47% in different locations; ● Save 7%-16.2% total annual energy costs varying from locations.
2015	Bataineh	Individual	Optimization	Flat plate	SE	Pool water	● Collector area positively affects primary energy

	[73]	SAHP	--Surface area				saving for both pool water and DHW; ● 53% collector area causes 100% primary energy saving; ● 40% collector area causes 87% primary energy saving; ● 26.6% collector area causes 59% primary energy saving; ● Lowest energy production cost of 0.011/kWh can be achieved by utilizing the solar evacuated tube collector with area of 200 m^2.
2015	Buonomano et al. [52]	Hybrid PVT-SAHP	Optimization --Adopted model type --Field area	Flat plate	SE	Pool water	● Adopted model affects thermal energy demand significantly, ● Optimal energy performance occurs when the PVT collector field area is between 200 and 300 m^2.

Notations: SAHP= Solar-assisted HP; W-SAHP= Water solar-assisted HP; PVT-SAHP= PV/thermal solar-assisted HP; SE= Solar energy; DHW= Domestic hot water

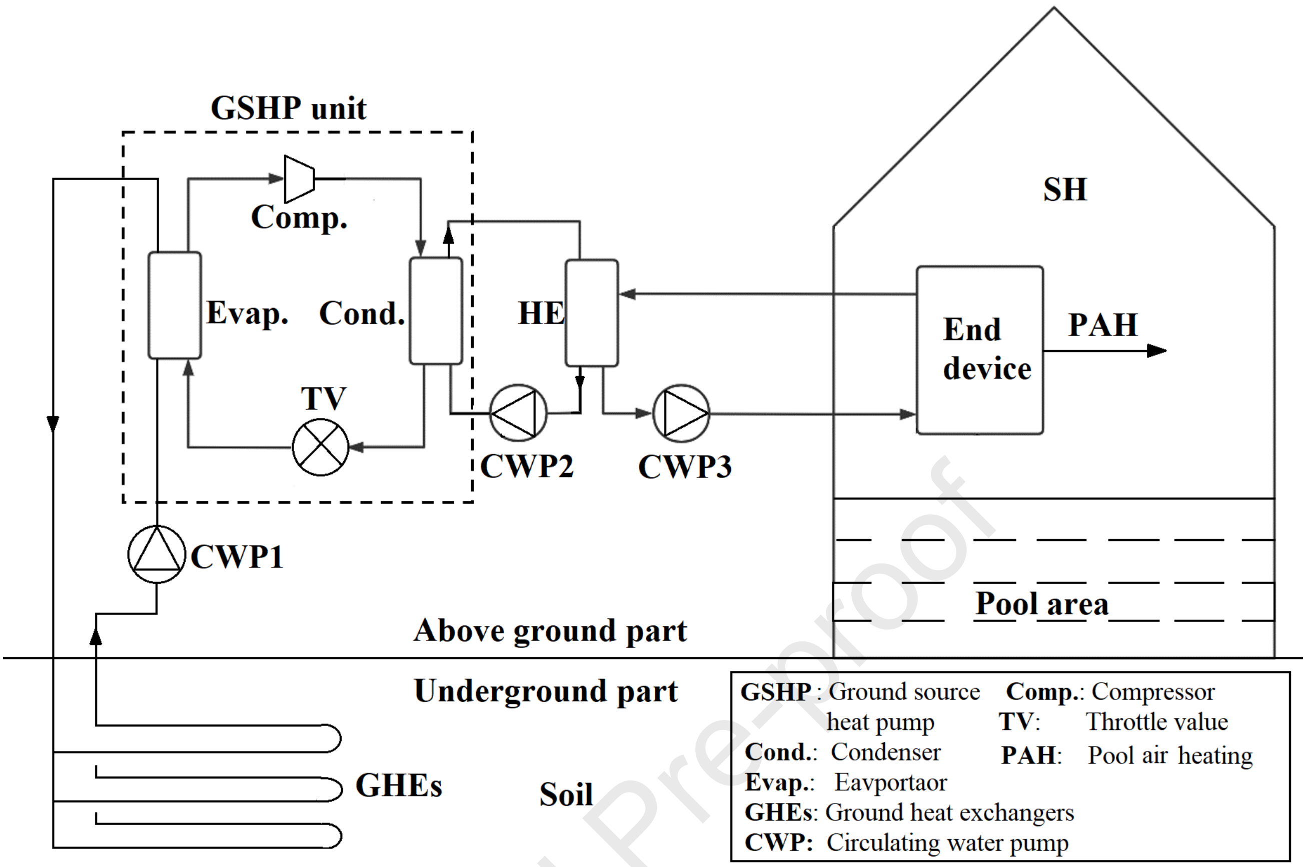

Fig. 7. Working principle of the GSHP. [79]

In addition, biomass heaters can replace the existing oil heaters to eliminate the oil consumption and reduce pollution [75]. The biomass heater can cover exclusively the reduced heat loads of swimming pools. At present, there are few researches focusing on sole biomass application in SHs. Delmastro et al. [81] tried to connect a woody biomass cogeneration plant to the district heating network and electricity grid to achieve sustainable built environment in Italy. Although the produced heat and electricity was sold to the ISP, it did not directly use biomass heat in the pool. This part of energy sold to the grid can also be used to other places with energy demands. Apart from this biomass application in ISP, the other researches focused on the performance comparison of biomass heater and other heating options. Angeles [82] proposed and applied four alternative energy sources (e.g., natural gas, biomass, combined system of solar collector and natural gas or biomass) to supply sanitary hot water and heat ISPs. The aim of their research was to find out the most suitable one with the best financial viability, performed by net present value (NPV). They proposed a hypothetical business case, and calculated the initial investment and operating costs during 20 years' period of each energy scheme. The results showed that biomass installation could achieve best financial viability.

4. Building energy management and utilization

Building energy management systems (BEMS) is defined as using one or more strategies and methods to improve building performance, efficiency and energy utilization [83]. This technology is aimed to manage and rationally use existing utilized energy and possible energy sources in buildings, and improve the energy efficiency at the cost of no or less energy [84]. Building energy management along with energy utilization can be feasible methods to improve building energy efficiency [85-86]. BEM and energy utilization methods have been widely used in commercial and residential buildings, including waste heat utilization [87-89], HVAC system control and optimization [90-93], demand response [94-96] and others.

4.1. Waste heat utilization

Waste heat utilization is one of operable strategies to improve energy efficiency and achieve energy saving. The implement of waste heat recovery process is always with heat exchangers or heat pumps to transfer the waste heat. Waste heat belongs to the low temperature heat source, which can just be directly used into low temperature heat demands (e.g., pool water heating and under-floor heating), while waste heat can also be used for high temperature heat demands (e.g., space heating and DHW supply), after pre-heating [11, 27]. Under this circumstance, pre-heating process requires a HP to increase the waste heat temperature for higher temperature demands at the cost of extra electricity use.

4.1.1. Waste heat source from nearby ice hall or SH itself

Waste heat recovery in SHs is divided into two parts, namely 'waste heat utilization from other system to the SHs', and 'self-waste heat reuse for itself'. The heat demand of SHs is large and diversified due to the demand of pool water heating, supply air heating, space heating and DHW. Thus, it is common to use the waste heat of other heat systems into SHs. Ice halls, as the same kind of sports building as SHs, also have high energy use and potential of waste heat utilization. In addition, the SHs and ice halls are usually built nearby in Nordic countries. Thus, utilizing waste heat from the ice halls to the neighboring SHs is feasible, and has been studied by many researchers.

In 2016, Kuyumcu et al. [97] firstly proposed utilizing refrigeration waste heat from the ice rink chiller in Gaziantep, Turkey, and then Kuyumcu et al. [32] improved the system for storing the heat into an underground thermal storage (TES) tank and transferring the stored heat for heat supply in the SHs. **Fig. 8** shows the schematical map and difference between original proposed waste heat recovery system [97], and optimized system with an under-floor TES tank [32]. The capacity of TES tank was 300 m^3, which was big enough to avoid the hourly mismatch between waste heat and heat demands. They drew the conclusion that the heat demand of a semi-Olympic size swimming pool of 625 m^2 could be met by the waste heat utilization from an ice rink of 475 m^2 in terms of the optimum thermal performance and energy demand. In their study, all the utilized waste heat from refrigeration process was assumed totally to be stored in the TES tank, and then transferred to the SHs. However, under this circumstance, the relationship between the sizes of ice halls and SHs would be an optimization problem. In addition, they also found that the water temperature in the TES tank greatly affected the chiller cooling performance and HP heating performance, which indicated the significant impact of TES temperature on the system electricity use.

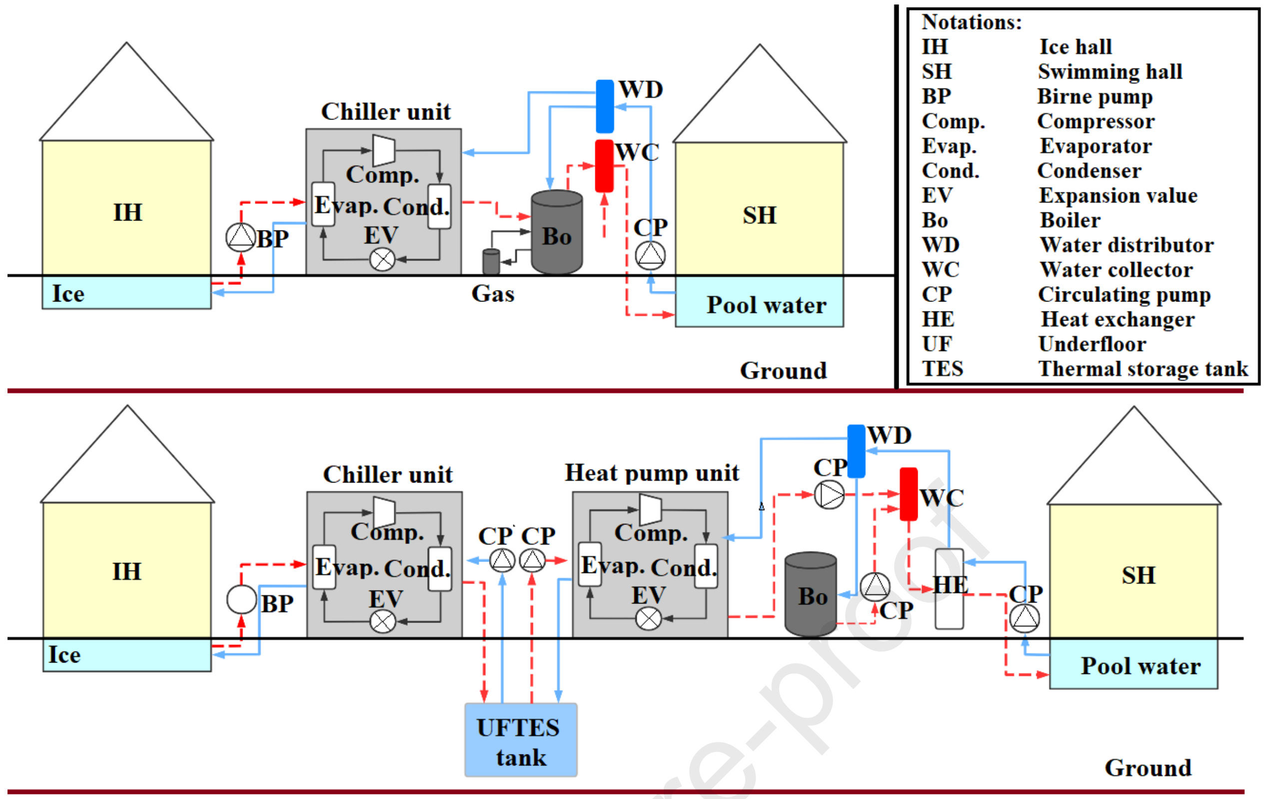

Fig. 8. The schematical map and difference between original proposed waste heat recovery system (Top) [97], and optimized system with an under-floor TES tank (Bottom) [32].

In addition, Linhartová and Jelínek in 2017 [98] also investigated the possible waste heat utilization from ice hall to a neighboring SH. They found there was a time mismatch between the energy delivery and demands, which caused the low utilization rate of refrigeration waste heat (19%) in ice hall. The excess waste heat was used for DHW, pool water heating and space heating in a neighboring SH, but the utilization rate was still low due to the time mismatch between the delivery and demand. Thus, it indicated that TES tank could be used in the combined energy systems to balance the mismatch, and could increase the system operation profitability. Then in 2018, Lautiainen [99] applied TES tank in the combined energy systems of ice hall and SH, and studied the feasibility of waste heat utilization in ice hall and transferring to the SH. The waste heat source was also from the ice refrigeration process, and they drew the simple conclusion that the refrigeration process could produce approximate 1 210 MWh waste heat, of which 254 MWh could be used for a neighboring SH.

Later in 2020, Yuan et al. [11] comprehensively studied the possible waste heat recoveries in neighbored ice hall and SH. Different from the previous studies [31, 98, 99], which only considered refrigeration waste heat utilization, Yuan et al. [11] proposed utilizing waste heat from both the refrigeration process and sewerage water for ice halls, and delivering excess waste heat to the a nearby SH. In addition, the SH itself has big potential for waste heat utilization from exhaust air and sewerage water. The warm exhaust air with high moisture has high heat recovery potential, which can meet all-level heat demands after being preheated by an exhaust air HP. In addition, sewerage water drained into the sewers is sufficient and with much waste heat, while sewerage water refers to the used washing, shower and saunas water, which can be recovered by heat exchangers. There are also other water sources with waste heat (e.g., DHW, refilling water, pool filter flushing), but they are not drained into the sewers, and thus don't belong to the sewerage water heat recovery. In their study, SH would use the excess waste heat from the ice hall and reutilized waste heat from exhaust air and sewerage water within itself. **Fig. 9** shows the schematic diagram of the waste heat recovery system in combined swimming and ice halls. They used TES tanks to balance the mismatch between the energy delivery and demands. The results showed that the SH could utilize altogether annually 1 973 MWh waste heat, including 558 MWh excess heat from the ice hall and 1 415 MWh utilized heat from itself. In addition, this SH achieved 51 k€ energy saving per year.

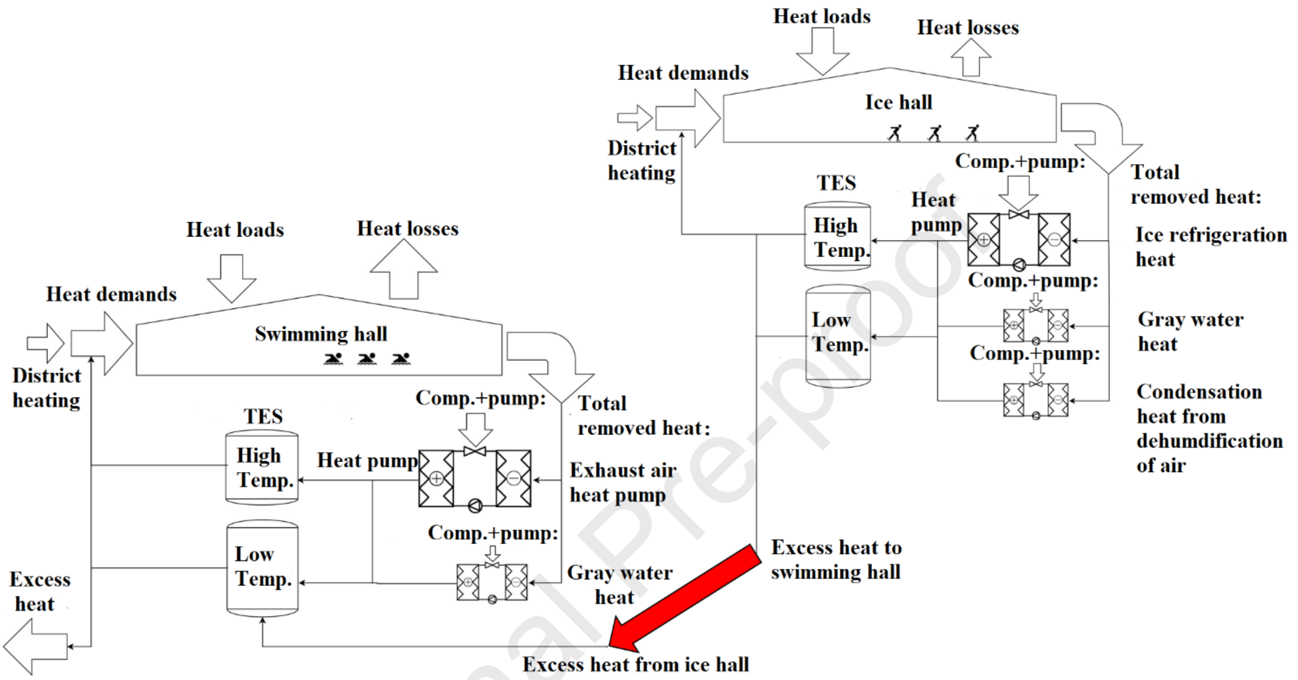

Fig. 9. The schematic diagram of the waste heat recovery system in combined swimming and ice halls [11]

4.1.2. Waste heat source from other energy systems

In addition to waste heat recovery from the ice and SHs, researchers also studied and applied other possible waste heat into the SH, e.g., waste heat from data centers and air-conditioners. Harrington and Modera [100] tried to utilize the waste heat from air conditioners to the swimming pools, and they found waste heat utilization of air conditioner can realized 25-30% reduction of cooling electricity demand and 30-35% peak demand for a single-family residential building. In addition, it was preliminary analyzed that approximate 30-45% cooling cost could be saved by air-conditioner waste heat recovery.

Furthermore, Oró et al. [101] built up a combined energy system of a liquid cooled data center and an ISP, and economically analyzed the combined energy system with heat exchangers. In the combined system, the waste heat generated by the liquid-cooled data center was utilized and transferred to the ISPs, while the cold water from the pool was used for data center cooling. **Fig. 10** shows the schematic diagram of connecting between the energy system of data center and that of ISP. They concluded that the combined energy system could reduce the operational expenses and make a profit by selling excess heat from data center, while the operational expenses of ISP could be reduced by 18%.

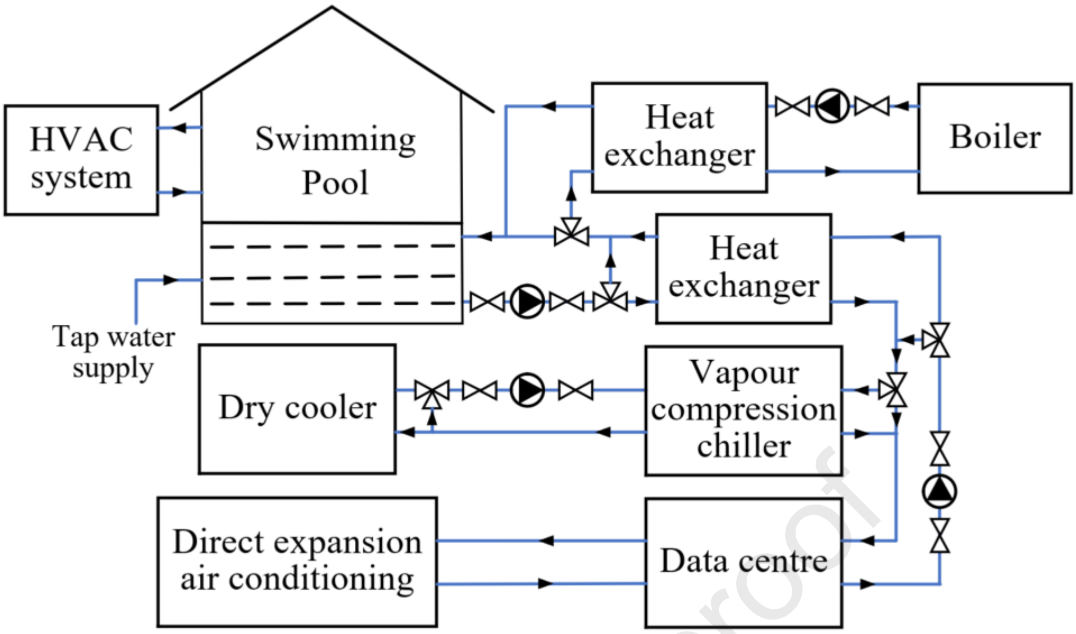

Fig. 10. Schematic diagram of the utilization of data center waste heat into swimming pool [101]

Table 3. Summary of waste heat recovery in SH energy system

Year	Researchers	Waste source	Utilized waste heat source	TES tank	HP	Finding (Energy or economic saving)
2013	Harrington and Modera [100]	Air conditioner	Geothermal panels	Pool as heat sink	√	For a single-family residential building: ● 25-30% reduction of cooling electricity demand; ● 30-35% reduction of peak demand; ● 30-45% cooling cost saving.
2016	Kuyumcu et al. [97]	IH	Refrigeration	×	× (Boiler)	● Higher system COP can be achieved by higher chiller unit, causing low waste heat utilization; ● Selecting the chiller unit based on the SH energy demand; ● The ideal ceiling emissivity value is 40%; ● At least 600 m^2 can meet the energy demand of an Olympic-sized SH (1250 m^2).
2016	Kuyumcu et al. [32]	IH	Refrigeration	√	√	● Optimum performance for a system with a semi-Olympic size SH can be met by a 475 m^2 ice rink.
2017	Linhartová and Jelínek [98]	IH	Refrigeration	×	√	● Low utilization rate of refrigeration (19%); ● Mismatch between energy delivery and demand; ● TES tank is recommended.
2018	Lautiainen [99]	IH	Refrigeration	√	√	● Around 1 210 MWh waste heat can be produced, while 254 MWH can be used for nearby SH
2018	Oró et al. [101]	Liquid-cooled data center	Heat of chips	×	√	● Operational expenses in DC; ● Can make a profit by selling excess heat in DC; ● 18% Operational expenses reduction of SH.
2020	Yuan et al. [11]	IH (Excess heat from IH) SH	Refrigeration Sewerage water Exhaust air Sewerage water	√	√	● Maximum utilization efficiency of waste heat from SH: 87%; ● Annually 1 973 MWh waste heat used in SH, including 558 MWh from IH and 1 415 MWh from itself; ● 51 k€ energy saving per year for SH.

Notations: SH= Swimming hall; IH= Ice hall; DC= data center

4.2. Energy system prediction and optimization

4.2.1. Energy demand and consumption prediction

The energy demand in SHs is much higher due to various water heating and air heating demands, but can be improved by reasonable energy demand allocation. Thus, estimating and predicting energy demand and consumption may contribute to improve energy performance and saving.

Marín et al. [35] built up a dynamic simulation model to estimate the thermal energy demand in an ISP by empirical validation. They defined an innovative and specific model to characterize an ISP with high accurate dynamic energy behavior, and validated it through a two-stage procedure, i.e., stage 1 (establishing a full-monitoring system to compare the recording data with simulation results), and stage 2 (using actual operating data from 4 other swimming pool to validate the model performance). They found that the proposed model could, to some degrees, accurately estimated the thermal energy demand with an average error of -1.8%. They concluded that the energy demand of SHs increased by 9.5% when the pool water temperature increased by 1℃, while the results also showed that the energy demand was, to some degrees, affected by the indoor air temperature and humidity. Different from estimating the energy demand by Marín et al. [35], Yuce et al. [13] applied artificial neural network (ANN) to directly predict energy consumption and occupant thermal comfort in SHs. As many uncertain factors would directly or indirectly affect the energy use and thermal comfort, it was difficult to establish the mathematic relationship between its inputs and outputs. Thus, they applied Levenberg–Marquardt ANN based prediction method to elicit the relationship, and finally achieved low error rate. **Fig. 11** shows the topology of ANN for HVAC system in ISP proposed by Yuce et al. [13].

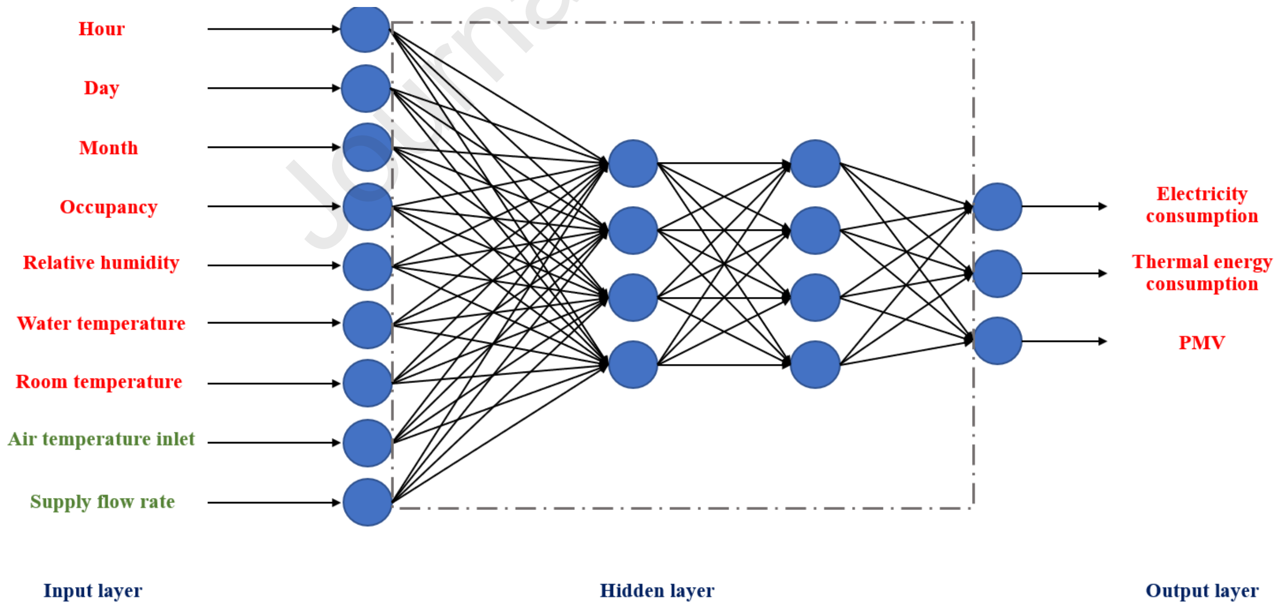

Fig. 11. Topology of ANN for HVAC system in ISP [13]

4.2.2. Water evaporation evaluation and optimization

As mentioned above in **Sections 2.2** and **2.3**, water evaporation will cause significant heat loss [33, 44], and moisture concerns [37, 41], while moisture control and dehumidification are normally achieved by ventilation with extra electricity input. Thus, many researchers put their efforts to analyze and predict the evaporation condition for its better control and utilization, and achieve optimized indoor air quality, thermal comfort and energy saving.

Shah [102] tried to find out reliable methods to predict the water evaporation in ISPs, and claimed reliable evaporation prediction method was critical to sizing of air-conditioning equipment and energy use calculation. Two innovative correlations were proposed based on physical phenomena and purely empirical analysis, respectively. The results showed, compared with actual data, correlation based on purely empirical (a mean deviation of 16.2%) performed better than that on physical phenomena analysis (a mean deviation of 26.2%) in terms of pool water evaporation. The proposed correlations could be regarded as reliable methods for evaporation prediction in ISPs, which could be applied to actual design and analysis. Then, Asdrubali [103] built up a scale model for pool water evaporation evaluation in ISPs, and controlled the environmental variables (e.g., pool water temperature, air temperature, air velocity and relative humidity) in the purposely designed experimental apparatus to study their effects on water evaporation rate. They concluded that the proposed evaporation prediction model performed in line with existing models.

In addition, Blázquez et al. [104] put forward a new and practical method based on computational fluid dynamics (CFD) to estimate the water evaporation rate in ISPs. The evaporation rate was used to achieve an energy performance balance between ventilation and dehumidification systems. **Fig. 12** shows its fluid domain and boundary conditions at the air-water interface, considering three assumptions: 1. Equal air and pool water temperatures; 2. Water vapour concentration equals to air saturation humidity at pool water temperature; 3. Free slip wall condition (no shear stress). Altogether 233 simulations with different flow conditions were simulated and validated by three different test chambers and an actual swimming pool. They concluded the proposed method was feasible and reliable with a small relative error (3%) and total mean relative error.

Ciuman and Lipska [29] also proposed experimentally a validated CFD numerical model to study the air, heat and moisture flow in ISP. They claimed eliminating the moisture from the pool water surface was the key to ensure appropriate thermal-moisture conditions. They experimentally investigated the effects of air variables on the thermal-moisture conditions during various periods of the whole year, and used these data to determine the boundary conditions to establish improved numerical models with the method modelling moisture emission from the surface of the water. They concluded the simulation results based on the improved model agreed well with the experimental and predicted results.

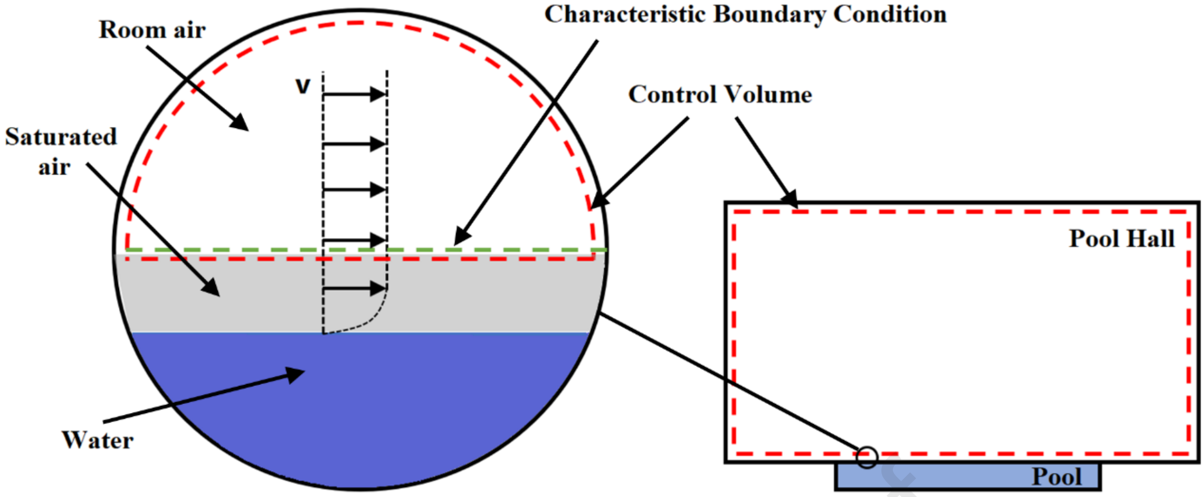

Fig. 12. Fluid domain and boundary conditions at the air-water interface [104]

Apart from evaporation prediction to improve thermal/humid environment, HP can help to dehumidify pool air, and then reduce the active ventilation demand and fans' electricity use [105]. Westerlund and Dahl [106] applied an open absorption HP in the ISP heating system to dehumidification and decrease ventilation electricity use. The dehumidification process was achieved by the absorber operation. They concluded that the open absorption HP could be economically applied in ISPs with 4-5 years payback period. In addition, applying the open absorption HP in ISPs for remodification task has also been studied by some other researchers [107, 108]. According to Sun et al. [37], HP could be adapted to a HP dehumidifier as it could achieve latent heat recovery from the indoor air with high humidity, and heat supply for the pool water and pool air. **Fig. 13** shows the schematic diagram of the proposed HP dehumidifier ISP heating system proposed by Sun et al [37]. They applied the proposed HP dehumidifier in an ISP, and compared its dehumidification and thermal performance with a conventional dehumidifier. They drew the conclusion that under the circumstance of over 18.6 kJ/kg outdoor air specific enthalpy, only the HP dehumidifier could meet the pool water heating demand without auxiliary pool heater. In addition, the HP dehumidifier performed better than the conventional dehumidifiers in terms of energy and energy cost saving, and its dynamic payback period was around 1.1 years.

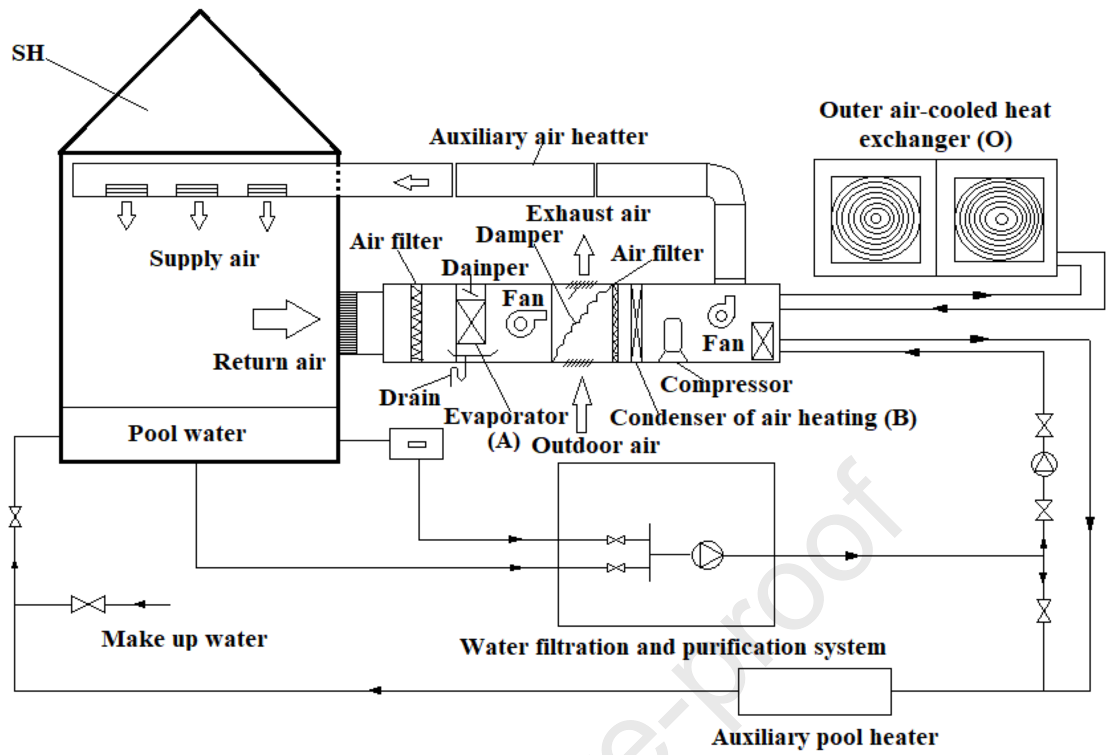

Fig. 13. HP dehumidifier application in the heating system of ISP [37]

4.2.3. Energy system control and optimization

Apart from energy demand and consumption prediction and evaporation concerns, control and optimization of HVAC system in SHs can be adopted to achieve high energy efficiency and saving. In 2007, Lee and Kung [105] used particle swarm algorithm to optimize the HP system in ISP for energy cost reduction. They took both continuous parameters (e.g., heat conductance of heat exchangers and mass flow of outdoor air) and discrete parameters (e.g., compressor and boiler types) into consideration as the optimized parameters. Through a case study, they found the proposed optimized algorithm could be successfully used in heating system optimization, and achieved optimized outdoor air flow and heating design. Then in 2016, Ribeiro et al. [34] proposed an innovative building energy management (BEM) method to optimize the HVAC control in ISP. The new BEM approach, using ESP-r simulation model to analyze the energy use [109-111], could be easily adopted to different kinds of pools, and could reduce their energy use significantly. When applied to the case building, the optimized HVAC system could achieve 7.14% energy cost saving in Portland. They believed the proposed method emphasized the role of BEM approaches on the energy saving strategies for ISPs.

In addition, Marín et al. [41] developed a model predictive control (MPC) strategy based on an early switch-off (ESO), and applied it in a heating system of ISP to improve its energy efficiency. The proposed control strategy has been adjusted by TRNSYS dynamic simulation process, and carried out in actual SH in Spain. They concluded that, compared with a proportional integral derivative (PID) controller, the proposed ESO-based MPC strategy can reduce the energy demand by 18.76% and fuel use by 42.64% in ISPs on the premise of acceptable thermal level in line with international swimming pool standards.

4.3. Demand response potentials

Huge energy demands (e.g., electricity and heat demands) promise the demand response (DR) potentials in SHs. The definition of DR is "changes in electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" [112]. DR belongs to BEM, which devotes to energy supply side management to achieve high-efficient energy use and saving. DR has been widely investigated and applied in building energy system to change their load profiles, while fast DR strategies prove to achieve quick and high-efficient response to the grid request and power demand reduction [113].

The current researches on DR are mainly on the electricity grid, and electricity DR has been widely investigated in all kinds of buildings [114]. DR has also been applied and investigated in SHs. Ribeiro et al. [115] proposed to apply contract-based demand response in SH to optimize the building electricity demand. Control strategies, carried out by building thermal simulation and a theoretical formula for the HVAC and pumping systems respectively, decreased the peak-time electricity demand, and responded to the system emergency signal. The results showed the power demand decreased by 7.0% and 20.9% for the HVAC and pumping systems, respectively. In addition, under the circumstance of emergency grid situation, the maximum electricity demand reduction could reach 24.5% and 42.9%, respectively. Thus, the authors concluded DR can be used and with a promising application prospect in SHs.

According to Finnish Energy 2018, district heat demand in residential and service buildings shared the biggest Finnish energy market of 46.1% in 2015, which ranks the first followed by the electricity demand of 18.2% [116], and that proportion of district heat demand was still high (approximate 12%) in the energy market of European Union [117]. Thus, SHs, serving as big district heat consumers, have significant potential of district heat. Yuan et al. [19] firstly proposed applying DR control of heating in SH, and were also the first to put forward applying DR of district heat in SH for pool water and pool space air heating. A rule-based DR control algorithm was put forward for district heating in the studied SH. **Fig. 14** shows the schema of the dynamic energy price algorithm decision making, input data and output data. The corresponding minimum percentages of expensive and cheap district heat prices can be classified by the algorithm. They concluded that the big pool and heat storing capacity of pool water made the district heating network more flexible. DR-based district heat control application can rise the average pool water temperature from 26.5°C (normal setpoint temperature) to 27.3°C, while the district heat cost reduced by 1.1%. In addition, the energy cost savings and maximum profitable investment cost were 10 000-20 000 € during 7-15 years' repayment period.

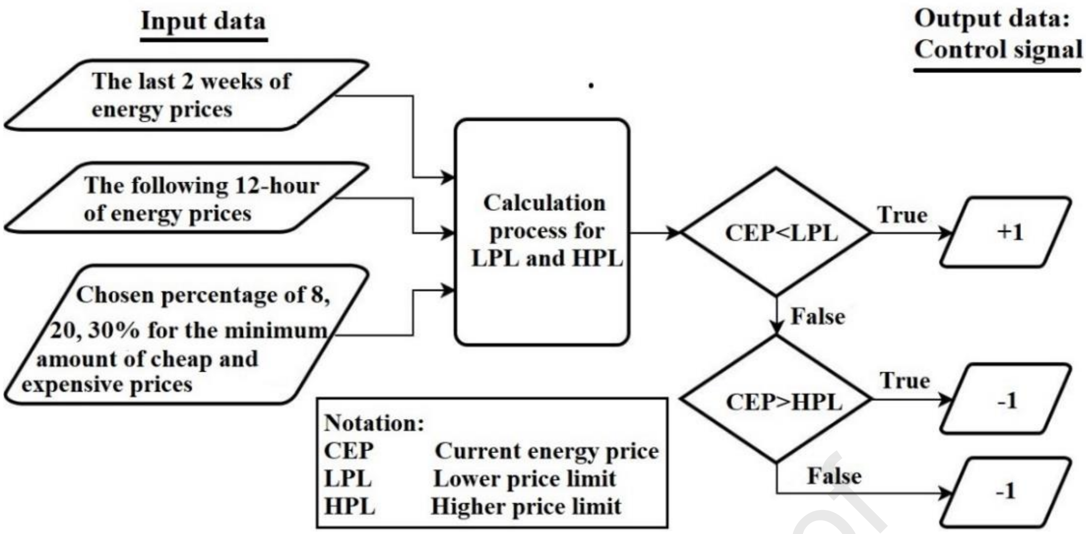

Fig. 14. Decision making, input data and output data of the dynamic energy price algorithm [19].

1 **Table 4.** Summary of BEMs in SHs

Year	Researchers/ references	Category	Measure	Finding (Performance and energy & energy cost saving)
2020	Marín et al. [35]	Energy demand estimation	Dynamic simulation model	● Accurately estimate the thermal energy demand; ● An Average error of -1.77%.
2014	Yuce et al. [13]	Energy consumption prediction	Levenberg–Marquardt ANN based prediction method	● Elicit the relationship between its inputs and outputs; ● Achieve the expected error rate.
2007	Lee and Kung [105]	HP system optimization	Particle swarm algorithm	● Successfully used in heating system optimization; ● Achieve optimized outdoor air flow and heating design.
2003	Shah [102]	Waste evaporation prediction	Correlations based on physical phenomena analysis and purely empirical	● Correlation based on purely empirical (16.2%) performed better than that on physical phenomena analysis (26.2%) (mean deviation); ● Reliable methods for evaporation prediction; ● Applicable to actual design and analysis.
2009	Asdrubali [103]	Waste evaporation evaluation	Scale model study	● The proposed evaporation prediction model performed in line with existing models.
2017	Blázquez et al. [104]	Waste evaporation estimation	CFD with three assumptions for boundary conditions at the air-water surface	● The proposed method was feasible and reliable; ● Small relative error (3%) and total mean relative error.
2018	Barbara [29]	Air, heat and moisture study	CFD and all-year experiment	● Simulation results based on the improved model agreed well with the experimental and predicted results.
1994	Westerlund and Dahl [106]	Dehumidification	Open absorption HP	● The dehumidification process is achieved by the absorber operation; ● Open absorption HP can be economically applied; ● Payback period: 4-5 years.
2011	Sun et al. [37]	Dehumidification	HP dehumidifier	Under the circumstance of over 18.6 kJ/kg outdoor air specific enthalpy: ● Only HP dehumidifier can meet the pool water heating demand; ● No auxiliary pool heater needed. Normally ● HP dehumidifier can achieve energy and energy cost saving,

				● Dynamic payback period: 1.1 years.
2016	Ribeiro et al. [34]	HVAC system optimization	ESP-r simulation model	● Easily adopted to different kinds of pool; ● Reduce 7.5% energy cost.
2019	Marín et al. [41]	Energy system control and optimization	ESO-based MPC strategy	Compared with a PID controller, ● Reduce the energy demand by 18.76%; ● Reduce fuel use by 42.64%; ● Promise acceptable thermal level in line with international swimming pool standards.
2014	Ribeiro et al. [115]	DR of electricity	Contract-based DR control of electricity	● Decrease power demand by 7.0% and 20.9% for the HVAC and pumping systems, respectively; ● In emergency grid situation, the maximum electricity demand reduction could reach 24.5% and 42.9%, respectively.
2021	Yuan et al. [19]	DR of heat	DR of district heat	● High flexibility of district heating network due to huge water and heat storing capacity of pool water; ● Rise the average pool water temperature from the normal setpoint of 26.5°C to 27.3°C; ● Reduce the district heat cost by 1.1%; ● Energy cost savings and maximum profitable investment cost were 10 000-20 000 € during 7-15 years' repayment period.

Notations: HVAC= Heating, ventilation and air-conditioning; DR= Demand response; ANN= Artificial neural network; ESO= Early switch-off; MPC= Model predictive control; PID= Proportional integral derivative

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5. Discussion

Over the past decades, an average of two new SHs have been built each year in Finland, while this figure would increase significantly when expanded to the Nordic countries and the whole world [118]. In addition, the heat demand in SHs is much high. Thus, significant potentials of energy-saving exist in the heating system design and operation of SHs. The common energy demands for conventional sports facilities (Ice hall, Gym, etc.) are electricity, space air heating and cooling, and DHW. However, SHs have other special energy demands, which are pool water heating, space heating, and dehumidification energy use.

5.1. Recommendations

5.1.1. Renewable energy application

To fulfill the high energy demand, renewable energy sources are recommended in SHs. Compared with biomass and geothermal energy applications, solar energy has been widely investigated, and has been relatively mature-used in SHs [65]. Thus, involving renewable energy applications in SHs, SAHP and hybrid SAHP (e.g., W-SAHP, PVT-SAHP) systems are predominately recommended in its heating system. It should be noted that HP can meet all heat demands, while TES tank is recommended to balance the mismatch period of the heat demand and supply in both short-term and long-term periods. In addition, the energy performance can be further improved by system optimization of corresponding SAHP system.

5.1.2. Energy system prediction and optimization

Apart from replacing the conventional energy consumption by renewable energy in SHs, reasonable energy system prediction and optimization can also achieve its energy conservation. Firstly, the energy demand and consumption can be improved by reasonable energy demand allocation. Energy demand and consumption prediction can contribute to energy performance improvement and energy saving [35]. In addition, as water evaporation largely affects both indoor air quality, thermal comfort and energy consumption caused by ventilation demands for dehumidification process [33, 41], water evaporation evaluation and optimization are also recommended. While HP is also recommended to achieve pool air dehumidification and reduction of active ventilation demand and electricity use of fans. Using reasonable control algorithms for the SH HVAC system can also achieve energy saving via system optimization. Furthermore, the huge energy claim of SHs causes its demand response potentials and application feasibility. Demand response of electricity and heat/district heat can both be achieved and recommended in SHs.

5.1.3. Waste heat unitization

Although SHs are big energy consumers, they are also ‘heat producers’. The produced heat here refers to the waste heat from them. This part of waste heat is considerable, and is recommended to be reutilized. The heat from the exhaust air and sewerage water in the SH is wasted, but has huge recovery potentials. Nowadays, the waste heat recoveries of exhaust air and sewerage water in SH has been studied and proved feasible [27], and thus are recommended. In addition, the waste heat sources from other places (e.g., ice halls, data centers) have also been investigated and proved feasible, and thus are also recommended if they were nearby the SHs.

5.2. Future development

At present, there is no very clear and systematic energy performance evaluation indexes in the SHs, so it is necessary to establish feasible and comprehensive energy indexes to evaluate energy use in the future. In addition, the application of renewable energy should be further investigated, especially inexhaustible solar energy. Compared with conventional energy, these renewable energies are more environmental-friendly and renewable. Depending on grid incentives, PV/thermal assisted HPs outperform the solar thermal HPs, which should be studied more deeply. However, further study should focus more on optimizing the energy system itself, as it can fundamentally achieve energy high-efficiency and saving.

Thus, in the future, appropriate control and optimization strategies on the energy system (e.g., energy prediction, HVAC system optimization and demand response) could be one of the research hotspots for energy saving in SHs. In addition, waste heat recovery can also be a feasible energy-saving plan considering its high heat losses, while heat recovery directly for the ventilation system is also applicable and recommended in SHs, which can make up air without the need of a heat pump. Considering its main heat losses, the waste heat sources in SHs can be from its evaporative, convective, conductive and water renewal processes. Waste heat sources from other nearby places, especially ice halls (huge waste heat potentials from ice refrigeration, condensing dehumidification and sewerage water) can also be reutilized and investigated in the future.

6. Conclusion

SHs, belonging to special building sector, are easily overlooked as significant energy users and carbon producers. Apart from the common energy demands in buildings (e.g., lighting, DHW supply, and space cooling and heating), SHs have other special energy demands (e.g., pool water heating, space heating and dehumidification energy use), which indicates much bigger energy-saving potentials. This paper presented a comprehensive review of heating energy-saving potentials in SHs. The conclusions and recommendations for the heating energy system in SHs are as follows:

1. Fundamentally speaking, optimization of demand-side system and heating supply-side system (e.g., HVAC) have big potentials to achieve energy savings. Optimizing demand-side system can be realized by predicting and optimizing energy demand and consumption in SHs, while optimizing supply-side system can be achieved by HVAC system operation optimization.
2. BEM can also achieve energy conservation, while waste heat recoveries, belonging to BEM strategies, can re-utilize waste heat and enhance energy efficiency. Various heat sources can be recycled in SHs, including the heat from the SHs themselves (e.g., waste heat sources from exhaust air and sewerage water) and the heat from adjacent buildings (e.g., ice halls and data centers).
3. Except of huge electricity demand, SHs also have huge heat demand. Thus, demand response potentials of electricity and heat or district heat are both remarkable in SHs.
4. The utilization of renewable energy represented by solar energy will meet the heating energy demand well in SHs, and will reduce the damage of primary energy to the environment.
5. Although SHs consume lots of energy and produce much carbon emissions, no feasible and

comprehensive energy indexes can be used to evaluate energy use in SHs up to now; Thus, energy indexes or systematic evaluation system should be established for SHs in the future, which will also help improve the heating energy efficiency.

CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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