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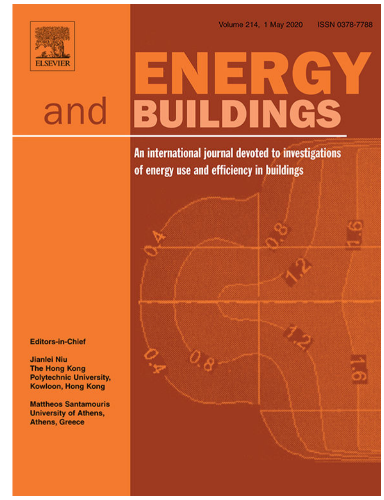

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Study on waste heat recoveries and energy saving in combined energy system of ice and swimming halls in Finland

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Abstract

Ice and swimming halls annually consume lots of energy and produce significant amount of potential waste heat in Finland. In this paper, utilization of four possible waste heat sources (ice refrigeration, dehumidification of air, Gray water and exhaust air) is studied by simulating combined energy system of ice and swimming halls locating in Helsinki. Four cases were simulated including the reference case, one case with waste heat recovery and two cases with both waste heat recovery and two different exhaust air heat pumps. In addition, thermal energy storage tanks are used to store the excess waste heat from the ice hall, while the high temperature exhaust air heat pumps can raise the waste heat temperatures for all heat demands. The results show that up to 99% of the purchased district heat can be replaced by the waste heat in the ice hall at the cost of only 9% purchased electricity increase. The combined utilization of excess heat transferred from the ice hall and the waste heat from the swimming hall can result in 72% reduction of purchased district heat and 37% electricity demand increase in the swimming hall. In the combined energy system of the studied ice and swimming hall, altogether 77% waste heat is utilized, bringing in 82% purchased district heat decrease and 25% electricity increase, while the total consumed energy reduced by 42%. In addition, the total annual energy cost savings reach 133 k€ (-29%), while the saving of the energy cost of the combined system can make up the maximum cost of the profitable investment. During three repayment periods (7, 10 and 15 years), the energy cost savings and maximum cost of profitable investment for the ice hall alone and combined ice and swimming halls are between 510 k€ and 970 k€ and between 700 k€ and 1 580 k€, respectively.

Keywords: Waste heat recovery, Ice hall, Swimming hall, Dynamic building energy simulation,

Energy saving

1. Introduction

Building sector take responsibility to approximate 40% of total energy use [1, 2] and around 36% of related CO_2 emission in Europe [1]. Large amount of CO_2 emission has caused a series of environmental problems, e.g. global warming and the imbalance of the nature [3]. Thus, energy conservation should be taken into consideration to improve energy performance and minimize the environmental impacts [4]. The European Commission has expressed its position and sets series of goals to improve energy efficiency and mitigate climate change. According to the European Commission 2014 [5], three goals are supposed to be achieved by 2030 compared to 1990: (1) 40% overall CO_2 emission should be reduced; (2) renewable energy use accounts for 27% of final energy consumption; and (3) the energy efficiency should be improved by 27%. In 2018, The commission has also proposed the goal of achieving a climate neutral Europe by 2050 [6]. Building sector, as a potential great energy consumption source, can greatly reduce energy use and mitigate CO_2 emissions by improving energy efficiency and replacing fossil fuels by renewable energy sources [7, 8].

Ice and swimming halls belong to building sector and they are also significant energy consumers and CO_2 emission producers. Much electricity is annually consumed by ice and swimming halls on ice refrigeration and pool water pumping & saunas, respectively [9, 10]. Considering the occupants' thermal comfort, swimming halls are also required to support enough heat to keep the indoor air and pool water warm enough compared to ice halls. In Finland, there are 280 swimming halls and 220 ice halls, taking responsibility for more than 1.2% of annual building energy consumption [11]. According to Ministry of the Environment of Finland in 2017 [12], ice and swimming halls are classified into building class 9 with special indoor air conditions and high energy consumption. Although the energy use level is high in ice and swimming halls, Finnish building code has set requirements only for heat losses of envelope, infiltration and ventilation without requirements for primary or purchased energy consumption levels [12].

Much excess heats in the ice and swimming halls are wasted if not re-utilized. The usual waste heat recovery is achieved by transferring waste heat to a medium (E.g. water). In ice halls, the heat losses mainly happened in the process of ice refrigeration, Gray water and air dehumidification, while Gray water and exhaust air are mainly carrier of heat loss in swimming halls. Researchers have studied the utilization of waste heat in the energy systems combining adjacent ice and swimming halls. Kuyumcu et al. [13] utilized the refrigeration waste heat in an ice rink and stored it in a thermal energy storage (TES) tank to provide heat for a swimming pool. They concluded that the optimal performance for a semi-Olympic size swimming pool (625 m^2) system can be achieved by using the waste heat of an ice rink of 475 m^2. In addition, the electricity use of the system is notably affected by the temperature of a TES. Linhartová and Jelínek [14] used a heat pump (HP) to utilize the waste heat from low temperature condensing process in an ice hockey hall. The results show that a maximum of 30% of waste heat can be utilized during a low temperature condensing process. In addition, Lautiainen et al. [15] also studied the energy balance between ice and swimming halls by utilizing and transferring waste heat from ice refrigeration to the nearby swimming hall. The results show that 1 210 MWh waste heat is produced, and 254 MWh of it can be used for a nearby swimming hall.

According to Zhai et al. [7], energy efficiency improvement is regarded to be an energy conservation method, while utilization of waste heat is an approach to improve energy efficiency [16]. There are many researches on the waste heat recovery in ice and swimming halls, while the major focus is on the waste heat utilization of the ice refrigeration. In addition, the International Ice Hockey Federation (IIHF) recommends that the ice refrigeration waste heat recovery should be implemented into new ice halls [17]. However, many other waste heat sources in the ice and swimming halls could be utilized to reduce energy consumption as well. In ice halls, the other possible sources for waste heat recovery are condensing water during dehumidification and Gray water, while the possible waste heat recovery sources in swimming halls are exhaust air and sewage water [18, 19]. The Environmental Product Declaration (EPD) 2009 states that the waste heat in ice and swimming halls is low temperature heat sources. The low temperature waste heat can be used to low temperature heat demands (E.g. space heating, under-floor heating and pool water heating), while it can also be used for high temperature heat demands (E.g. DHW) after being pre-heated [20]. But, in the process of pre-heating, extra electricity is consumed by a HP to increase the temperature level of waste heat suitable for high-temperature heat demands. Thus, the electricity consumption of HP should be taken into consideration and minimized during the waste heat recovery.

Considering all previous researches, none of them did a comprehensive study on diversified waste heat recoveries in combined energy system of ice and swimming halls. Thus, the novelty of this paper is to comprehensively consider four possible waste heat sources and analyse their effects on the energy performance and potential energy and cost savings in the combined energy system of ice and swimming halls. The possible waste heat sources analysed in this paper includes the heat losses from ice refrigeration, Gray water and condensing water in ice hall and exhaust air and gray water in swimming halls.

2. Methodology

2.1 Structure of the simulation study

The research process was divided into two parts: dynamic building energy simulations and the spreadsheet computation program for post-processing. The methodology of this study is shown in **Fig. 1**. Firstly, IDA Indoor Climate and Energy (ICE) tool [21] was used to establish the simulation models, while the input data for the simulation models were set based on the data from the studied ice and swimming halls in Helsinki as well as hourly energy prices including taxes and transfer prices for electricity [22] and district heat described more detailed in [23] and hourly weather data. Then, the hourly energy fluxes from the simulations were post-processed in Microsoft Excel 2016 to analyse the utilization of waste heat. Finally, the total annual energy cost savings and the maximum cost of profitable investment were calculated.

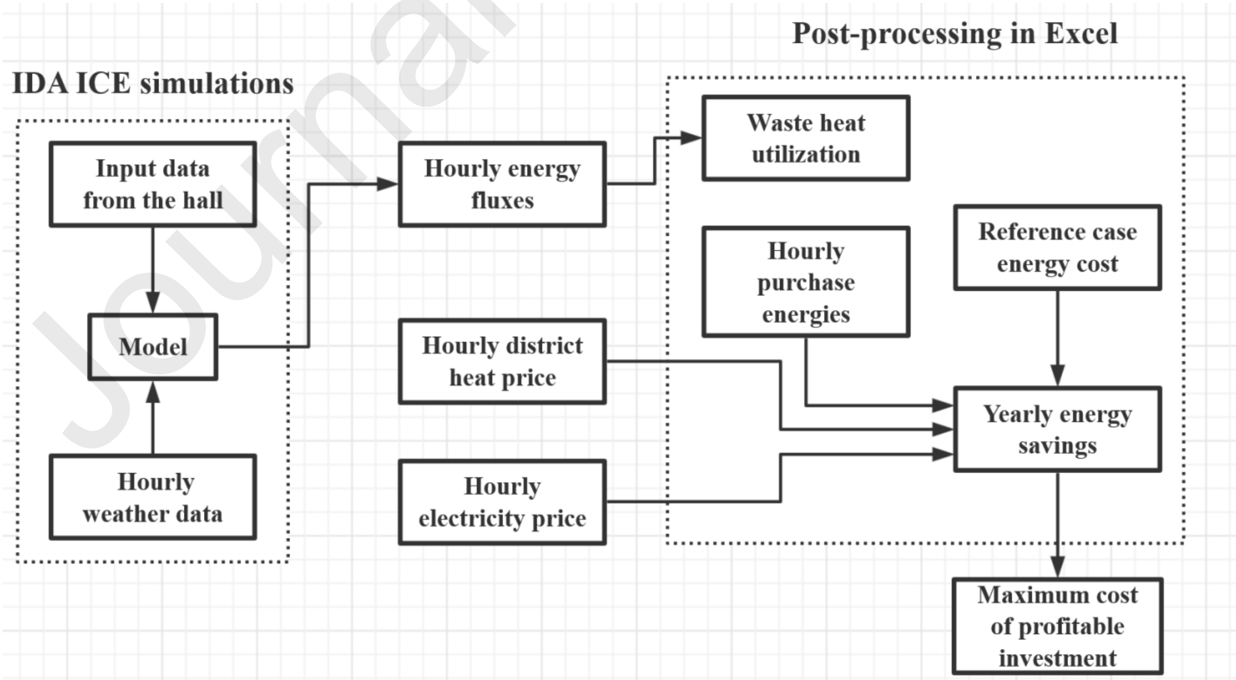

Fig. 1. Methodology as a logical diagram.

2.2 IDA-ICE simulation tool

Dynamic building simulation tool IDA-ICE [21], which has been validated in many studies e.g. [24-26], was used in this study. This software is suitable for modelling of HVAC-systems, internal heat gains, outdoor climate etc. and provides simultaneous dynamic simulation of heat transfer and mass flows. The ice rink and pool extensions of IDA-ICE which allows the modelling of ice and water surfaces in a zone, were used in the study. The ice rink and pool models account for both mass and heat transfer between the ice or water surfaces and the zone. Cooling demand of the ice and heating demand of the pool water to reach and maintain chosen setpoint temperatures are simulated in the extensions. For ice formation, the phase-change process is simulated and the continuous refreshment of pool water is also considered. For ice rinks, two pipe layers are modeled, one for freezing the ice and another below the ice layer to heat the ground to prevent frost propagation.

2.3 Modelling of technical systems

The simulation results were calculated on the spreadsheet post-processing to analyse the waste heat recovery efficiency in combined building energy systems of ice and swimming halls. In waste heat recovery system, the temperature levels and temperature differences between sub-systems were taken into consideration as well as the mismatch of heat demands and available excess heats. **Fig. 2** shows the heat fluxes between the system and sub-systems in the ice and swimming halls, respectively. The energy systems of halls are interconnected by the excess heat from the ice hall, while this part of excess heat is stored in a low temperature TES, and then transferred to the swimming hall and finally re-utilized in the swimming hall. However, the excess heat from the swimming hall is sent out of the combined ice and swimming halls system.

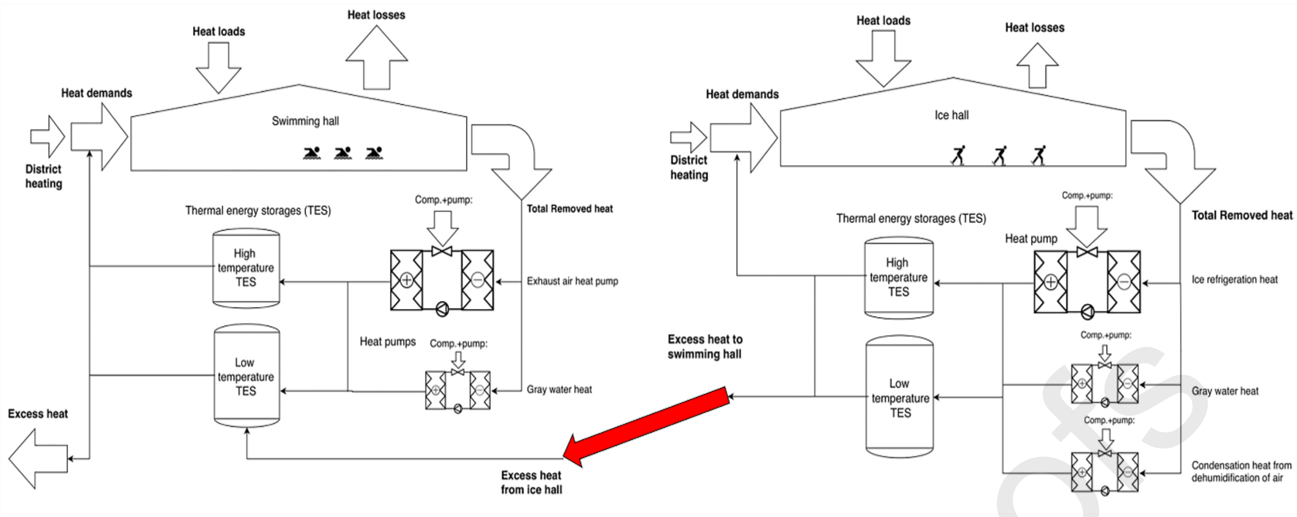

Fig. 2. The heat fluxes analysed in the swimming hall (Left) and ice hall (Right).

As there is mismatch time between the available waste heat and the heat demands, short-term TESs are required to avoid the mismatch and promise to store and re-utilize the waste heat in each time step. This mismatch would limit the waste heat utilization to some degrees, but it can be eliminated with the short-term TES. In addition, the short-term TES can also ensure the valid assumption of full waste heat utilization for each time step. Short-term TES tanks with two-zone moving boundary were used to avoid time mismatch between the heat demands and the available waste excess heat and store the waste heat for short time. The energy balance (heat input and output) determines the boundary height of the cold and heated water in the tank model [27]. The temperatures and properties of the TES tank are listed in **Table 1**. The set point temperatures of TES tanks were chosen so that the amount of utilized waste heat is maximized. The discharge time of the selected TES tank is 30 minutes in this paper.

Table 1 The set point temperatures and properties of different TES tanks.

TES	Temperature [°C]	Capacity [kWh]	Size [m^3]
Swimming hall TES 1	+34	75	2.5
Swimming hall TES2	+55	100	4.2
Ice hall TES1	+33	51	1.8
Ice hall TES2	+55	39	1.5
Total	--	265	9.9

HPs were used for different waste heat sources to increase their temperatures to the suitable levels. The preheating by HPs was used to increase the waste heat temperature to the system working temperatures. In this paper, superheat heat exchangers were used in the refrigeration heat recovery in the ice hall and exhaust air heat pump (EAHP) in the swimming hall, while the superheat temperature and portion were set to +100°C and 15%. The COPs of condensing dehumidification and Gray water HP were 3.0 and 3.9, respectively in this study. Calculation of the COPs is described in detailed in section (3.4.2) in Lindroos [11].

2.4 Weather data

A test reference year (TRY) which describes the current climatic conditions of southern Finland was used as weather data for the simulations [28]. The TRY consists of hourly outdoor temperature, relative humidity, wind speed and direction as well as solar radiation data on direct normal surface and diffuse horizontal surface. **Fig. 3** shows the TRY temperature (Between -20 and +30 °C) and relative humidity (From 30 to 100%) [29].

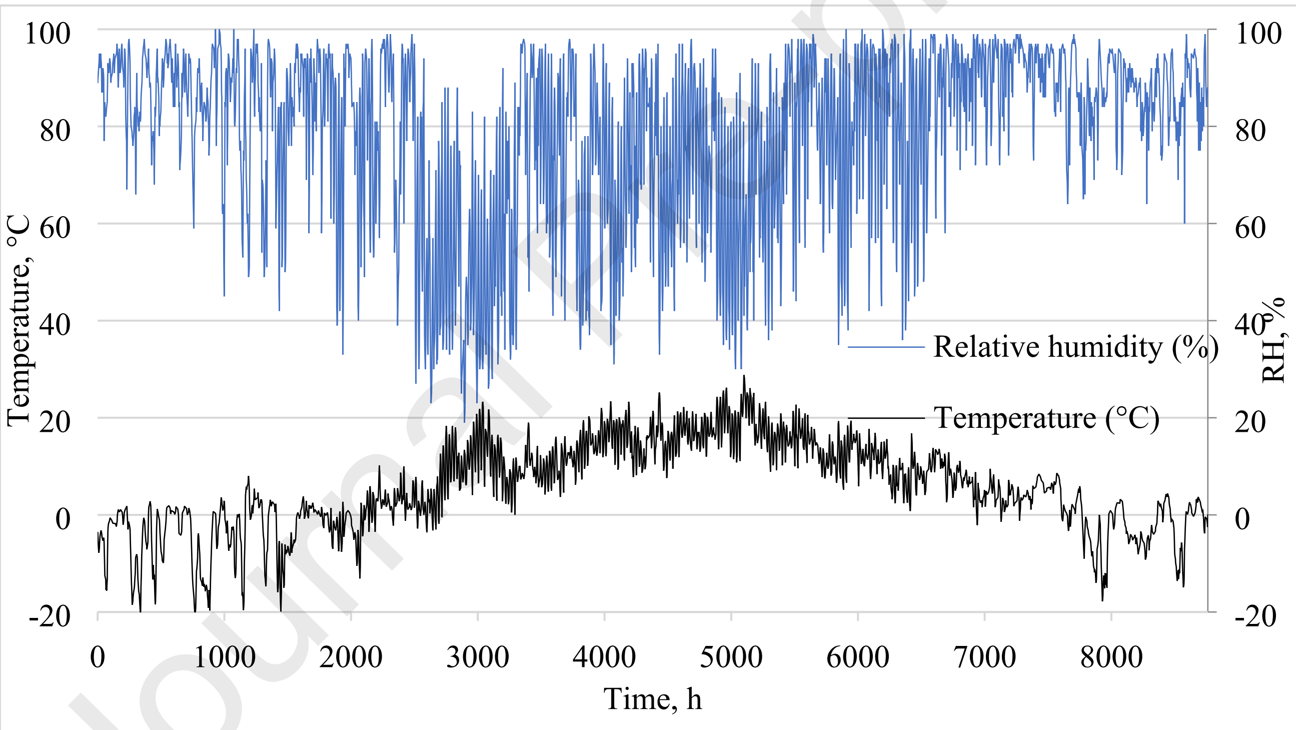

Fig. 3. TRY temperature and relative humidity (FMI, 2012).

2.5 Energy prices and maximum profitable investment

The maximum costs of the profitable investments analysed in this paper are equal to the total energy cost savings during the repayment period resulting from the investments. Many influencing factors were taken into consideration when calculating the maximum profitable investment, including the energy cost savings for each case, the inflation of energy prices, nominal interest and repayment period. The repayment period here refers to the assumed minimum lifecycle of the implemented system. The real interest rate of energy price and total discount yield can be calculated via **Eq. (1)-(2)**, respectively [30]. The real interest rate of energy price (1%), escalation of energy price (2%) and three repayment periods (7, 10 and 15 years) were used in the analysis. The maximum cost of profitable investments is calculated by **Eq. (3)**, which was equal to the total energy cost saving, namely the product between the total discount yield and the annual energy costs savings.

$$r_e = \frac{i - f_e}{1 + f_e} \quad (1)$$

$$a_n'' = \frac{1 - (1 + r_e)^{-n}}{r_e} \quad (2)$$

$$S_{inv} = a_n'' \cdot S_{E,a} \quad (3)$$

where r_e represents the annual real interest rate of energy price [%]; i is the annual nominal interest rate [%]; f_e is the annual escalation of energy prices [%]; a_n'' is the total discount yield [a]; n is the repayment period [a]; S_{inv} is the maximum cost of profitable investment [€]; $S_{E,a}$ represents the annual energy cost savings [€/a].

3. Building description

3.1 Ice hall

3.1.1 Building properties

The studied ice hall is in a sports center in Helsinki. The ice hall has a net floor area of 6 674 m^2 with two ice rinks and 1 000 seats, regarded as a training hall. **Fig. 5** shows the model geometry and heights of the halls.

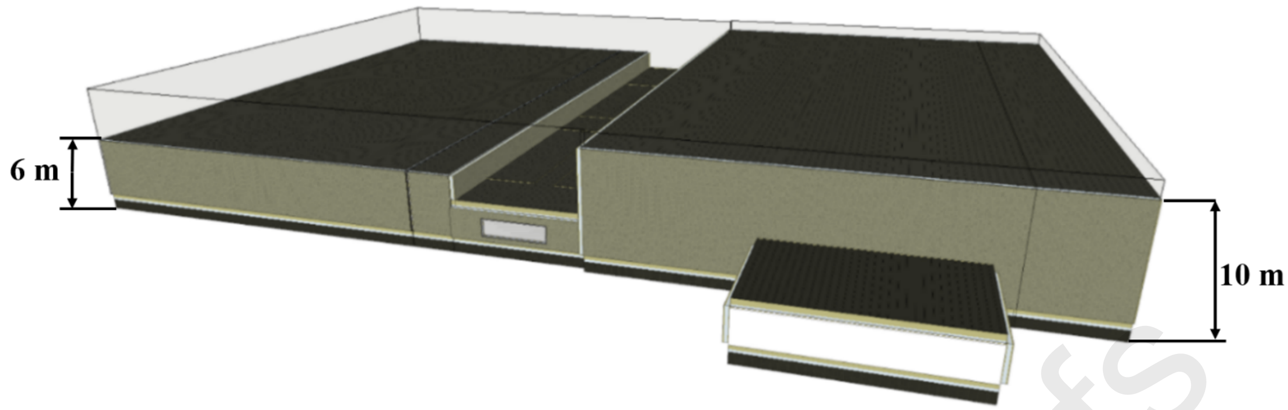

Fig. 4. The IDA-ICE model geometry of studied ice hall.

The ground and envelope areas of the ice hall are 6 741 m^2 and 16 671 m^2, while the total volume of the ice hall is 48 780 m^3. The ratio of window and envelope areas is 0.10%, while the ratio of envelope area to volume is 0.3417 m^2/m^3. **Table 2** shows the envelope parameters for the ice hall model. The envelope parameters set in the model are based on Hemmilä and Laitinen [18], Partanen [31] and Ministry of the Environment [32]. Based on the measurements by Toomla et al. [33], the average infiltration rate of the hall (0.03 1/h) was used in the simulation.

Table 2 Properties of the envelope of the ice hall.

	Structure	Location	U-value [W/(m^2K)]
Envelope	Base slab	Ice rink hall/Warm space	0.16
	Ceiling	Ice rink	0.28
		Warm space	0.09
	External walls	Ice rink hall	0.28
		Warm space	0.17
	Internal walls	Ice rink/Warm space	0.4
		Warm space/Warm space	0.62
Additional thermal bridge conductance	Thermal bridge conductance	Value/ W/(mK)	
	Ceiling / External wall	0.08	
	Base slab / External wall	0.24	
	External wall / External wall	0.06	
	External window and door	0.03	

3.1.2 Technical systems

Two ice rinks of the studied ice hall are identical and they were simulated with properties and set points of the ice rink cooling system and ice resurfacing process shown in **Table 3**. The utilization of refrigeration waste heat and ice resurfacing heat load were calculated by post-processing. Furthermore, there are two air handling units (AHUs) used in the ice hall model, including an AHU system with condensing dehumidification and indoor air recycling for the ice rink spaces with spectator stands and a separate AHU for the warm spaces e.g. locker room. Condensing dehumidification cools the supply air to temperature of 0°C and the AHU uses recycling air when dehumidification and heating are needed. Ventilation air flow rates of the ice rinks spaces are controlled by variable air volume (VAV) control system based on CO_2 concentration and air flow rates of warm spaces are controlled according to occupancy schedules. The properties of the ventilation system are listed in **Table 4**. Heating set point temperature of the ice rink spaces and warm spaces like locker rooms are 6 and 21 °C. The design temperatures for the heating system used in the ice hall simulations are listed in **Table 5.**

Table 3 Properties and set points of the ice rinks.

Cooling of ice rinks	Values	Ice rinks	Values
Ice temperature set point	-3 °C	Ice layer thickness	0.03 m
Chiller total cooling capacity	400 kW	Ice resurfacing	
Coolant	Freezium	- Frequency	45 times per week
Coolant freezing point	-35 °C	-Hot water	
Cooling power	450 W/m²	¤Consumption	450 litres per run
Supply coolant temperature	-12 °C	¤Temperature	+32 °C
Return coolant temperature	-9 °C		
Pump efficiency	0.8		
Pump max pressure	3 000 Pa		

Table 4 Properties of ventilation system.

Space group	Floor area [m²]	Minimum outdoor airflow [dm³/s/m³]	Maximum outdoor airflow [dm³/s/m³]	Heat recovery efficiency [%]
Ice rinks	5624	0.8	6.1	75
Locker room	426	0.3	3.0	6
Warm spaces	625	0.3	3.0	6

Table 5 The design temperatures for the heating system.

Heating systems	Inlet water temperature/return water temperature [°C]
Water radiator heating	50/40
Ground heating	14/7
Domestic hot water heating	55/8
Ice resurfacing hot water heating	32/9

3.1.3 Usage of the hall

The open period for the ice hall is from 7.00 to 22.30 on the workdays and Sunday and from 13.00 to 22.30 for Saturday. The ice hall was simulated using the occupancy rates listed in **Table 6** and the used activity levels of the occupants were 3.0, 2.0 and 1.8 MET for ice rink spaces, locker rooms and other warm spaces, respectively. Heat gains from lighting were set to 5W/m² in ice rink spaces and 12 W/m² in other spaces.

Table 6 The occupancy of two ice rinks in the ice hall model.

Ick rick space	Occupants	Frequency	Time	Duration
With big spectator stand	48 players 250 spectators	Day Week	Open times Sunday 17.00 - 19.00	Open times 2 hours

	750 spectators	2 months	Sunday 17.00 - 19.00	2 hours
With small spectator stand	48 players	Day	Opening times	Open times
	62 spectators	Week	Saturday 13.00 - 15.00	2 hours
	125 spectators	Week	Sunday 13.00 - 15.00	2 hours

3.2 Swimming hall

3.2.1 Building properties

The studied swimming hall locates in the same sports center as the ice hall presented in section 3.1. The net floor, ground and envelope areas of the swimming hall are 7 982 m^2, 4 047 m^2 and 13 705 m^2, respectively, while the volume of the swimming hall model is around 53 463 m^3. The window to envelope ratio is 8.90%, while envelope area per volume is 0.2563 m^2/m^3. **Fig. 5** shows the model of the studied swimming hall.

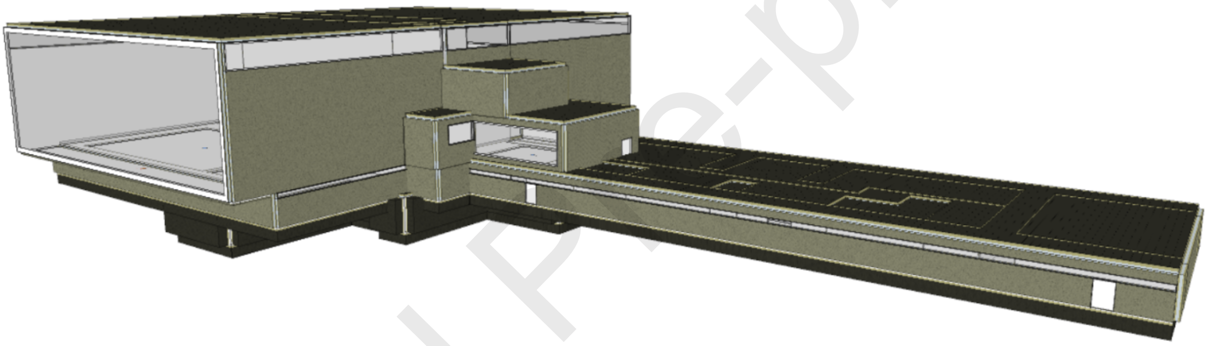

Fig. 5. The model geometry of the studied swimming hall.

The U-values of the structures used in the simulation are listed in **Table 7**. The U-value of windows has significant effect on heat losses through the envelope due to a relatively large proportion of window areas to the envelope in the swimming hall. The additional thermal bridge conductance of the swimming hall model is the same that of the ice hall model (Shown in **Table 2**) [32]. The swimming hall was simulated using average annual infiltration rate of 0.04 1/h [33]

Table 7 U-values for different structure in the swimming hall model [32].

Structure	Location	U-value [W/(m^2K)]
Windows	All spaces	1.0
Base slab	All spaces	0.24
Ceiling	All spaces	0.2
External wall	All spaces	0.23
Internal wall	Pool spaces	0.47
	All other spaces	0.8

3.2.2 Technical systems

Altogether three swimming pools are in the swimming hall, whose pool areas are 400 m^2 (big pool), 112 m^2 (children's pool) and 63 m^2 (young children's pool). The average depths are proportional to pool areas, which are 2.8 m, 1.4 m and 0.75 m, respectively. The pool water temperatures were set to 26.5 °C for big pool and children's pool, while that for young children's pool of 28.0 °C. Evaporation coefficients used in the simulation for big and children's (1.0) and young children's pool (1.5) were chosen according to ASHRAE (2003). The design heating power per pool surface area was 200 W/m^2 and the design supply water temperature +37.0 °C.

The same AHU serves the big and children's pool spaces, while young children's pool space has its own AHU. The AHUs of the pool spaces use recycling of indoor air to increase the relative humidity (RH) levels of pool spaces up to 50% and VAV control of the AHUs control the air flow rates according to RH to maintain the RH levels of the pool spaces between 50% to 57%.

Separate VAV controlled AHU serves the shower and other spaces where the air flow rates are controlled according to CO_2 levels of the spaces. **Table 8** shows the heating set point temperatures and properties of the ventilation system.

Table 8 Heating set point temperatures and properties of the ventilation system.

Space group of AHU	Net surface area [m2]	Heating setpoint of indoor air [°C]	Min. outdoor airflow [$dm^3/s/m^2$]	Max. outdoor airflow [$dm^3/s/m^2$]	Heat recovery efficiency [%]
Big pools	1 144	28	2.0	4.0	60
Young children's pool	231	30	2.0	4.0	60
Showers	411	24	3.3	6.7	60
Other spaces	6 196	18	0.5	2.6	60

The set-point of DHW heating is +55 °C for the swimming hall, while the temperature of incoming cold water for energy calculation is set to +8 °C. Based on Hemmilä and Laitinen [18], the average tap water temperature was assumed to +39 °C, while the average DHW usage is set to 51 m^3/day. **Table 9** shows the design working temperatures for heating systems in the swimming hall model.

Table 9 Design temperatures of heating systems in the swimming hall.

Heating system	Places	Inlet water temperature/return water temperature [°C]

Water radiator heating	All spaces except showers	50/30
Underfloor heating	Pool spaces and showers	34/30
Domestic hot water heating	Showers	55/8
Pool water heating	Pool spaces	40/27

3.2.3 Usage of the hall

The annual opening period for the swimming hall is from the 14 of July to the 31 of May. The swimming hall opens from 7.00 to 22.30 at workdays. **Table 10** shows the usage schedule of the studied swimming hall. The lighting is at full power from 16.00 to 22.30 and at half power during other open times. The fully occupied period for the swimming hall spectator stand appears once per two months between 18 and 21 on Sundays. In addition, the spectator stand has an occupancy rate of 10% in the other Sundays between 18 and 21, while the spectator stand is not in use during the rest time. The opening time of saunas is consistent with that of the swimming hall.

Table 10 Usage schedule of the studied swimming hall.

Occupants	Time		Usage
Lighting	16.00-22.30 during open times		Full power
	7.00-16.00 during open times		Half power
	Closing time		Off
Occupancy and DHW usage	Workdays	7.00 to 16.00 &21.30 to 22.30	25% usage
		16.00 to 21.30	75% usage
	Weekends & holidays	7.00 to 9.00 & 21.30 to 22.30	25% usage
		9.00 to 10.00	50% usage
		20.30 to 21.30	75% usage
		10.00 to 20.30	100% usage
Spectator stand	Once per 2 months from 18.00 to 21.00 on Sundays		Fully occupied (300 persons)
	18.00-21.00 during other Sundays		10% usage (30 persons)
	Rest of the time		Closed

Note: Open times: Every workday from 7.00 to 22.30 between 14 of July and 31 of May

4. Combined ice and swimming halls and solutions for waste heat recovery

Fig. 6 shows the schematic map of the ice hall and waste heat recovery systems as well as the temperature levels of the waste heats. The waste heat sources in the ice hall are ice refrigeration, condensing water from dehumidification and Gray water. During the ice rink cooling process, the heat loads of compressor electricity and ice are turned into heat, and then a condenser is used to transfer the heat from the coolant to the water, while the utilization of heat received from the ice rink cooling process is called ice refrigeration heat recovery. The heat released from the condensation of air moisture by the gas into liquid is the condensing heat, which can be recovered during air condensing dehumidification process. Washing and shower water drained into the sewers become the heat source of Gray water heat recovery. There are also other DHW usages, e.g. pool water changing, pool filter flushing, pool resupply water and resurfacing water, but they are not drained into sewers; Thus, they are not the sources of gray water heat recovery. Although the temperature level of heat from the Gray water is too low to be directly used in heat demands with high temperature requirement, the heat temperature in the Gray water heat recovery is still higher than that in refrigeration or condensing heat recovery. The Gray water heat recovery can be utilized fully in both ice and swimming halls if the temperature is increased with HP to temperature of low-temperature TES and it is prioritized over other lower temperature waste heat sources.

The heat transformation process is shown via big arrows of energy flux and thin arrows representing liquid flow rates. **Fig. 6** also shows the temperatures of all the heating and waste heat processing systems. Ice refrigeration process produces both high temperature superheat and low temperature latent heat, and the superheat is transferred to high temperature TES 2 and the latent heat to the low temperature TES 1. In addition, the low temperature TES 1 receives +38 °C water from all three waste heat sources. High temperature TES 2 provides high temperature water to the only receiver, DHW heating. District heat is purchased only for the supply air heating.

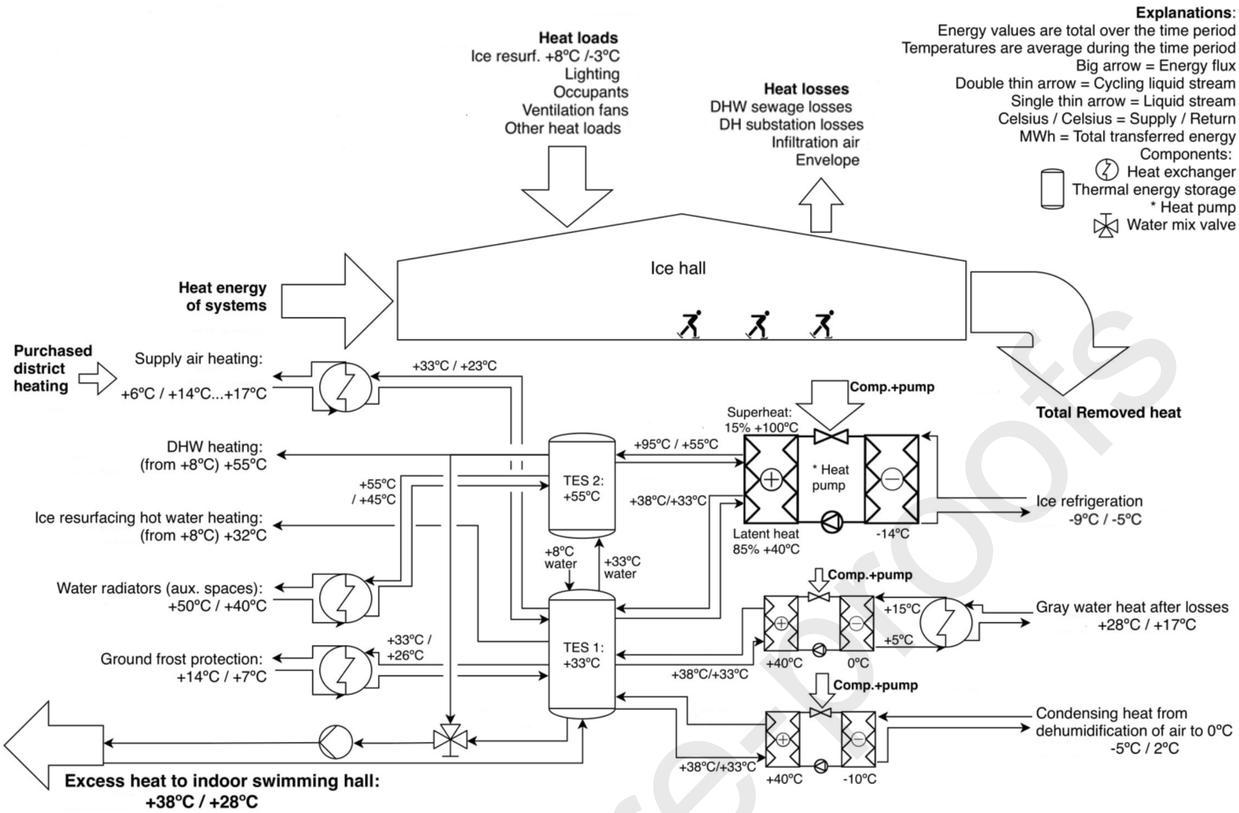

Fig. 6. Schematic map of location and direction of all the heat fluxes in an ice hall with waste heat recovery as well as temperatures of all the heating and waste heat processing systems.

There is much excess waste heat available from the refrigeration process alone in the ice hall, while the heat demand of the swimming hall is at a high level. Thus, the excess waste heat in the ice hall could be transferred to a neighboring swimming hall, and then reduce the energy use and improve the energy efficiency in the combined energy system. The amount of waste heat received from refrigeration heat recovery is affected by the number of ice rinks. The total heat demand of big ice halls (more than 4 000 m^2 per ice rink) cannot be fully met by the waste heat received from refrigeration and thus no excess heat is available for other buildings under this condition. However, small ice halls and some specific ice halls with multiple ice rinks typically produces excess waste heat. Thus, the excess waste heat from small ice halls can be transferred e.g. to the swimming halls, but there is no need for the waste heat transformation from swimming hall to the ice hall.

Fig. 7 shows the schematic map of the swimming hall and waste heat recovery systems as well as the temperature levels of the waste heats, while it shows the temperature level of EAHP corresponding to high temperature EAHP case. In the swimming hall, the waste heat sources are exhaust air, Gray water and the excess heat from the ice hall. The exhaust air in swimming hall is warm with high moisture and therefore has high potential of heat recovery. This part of waste heat can be recovered by exhaust air heat pumps to meet all heat demands. Depending on the case, the EAHP cools the exhaust air to a temperature of +5 or +10 °C and raises the condensation heat to a temperature of +40 or +60 °C. In the high temperature EAHP case, the low temperature TES 1 receives +38 ℃ water from Gray water heat recovery, while the high temperature TES 2 receives +59 ℃ waster from exhaust air heat recovery. In the low temperature EAHP case, TES 2 receives +40 ℃ waste heat from EAHP and district heat is used to increase temperature level of TES 2 to required level. Pool water heating is supplied with waste heat as the last heat demand after the other heat demands. At last, the excess waste heat from the swimming hall is transferred out of the combined energy system, and could be utilized nearby, E.g. heating for outdoor football field or outdoor swimming pools.

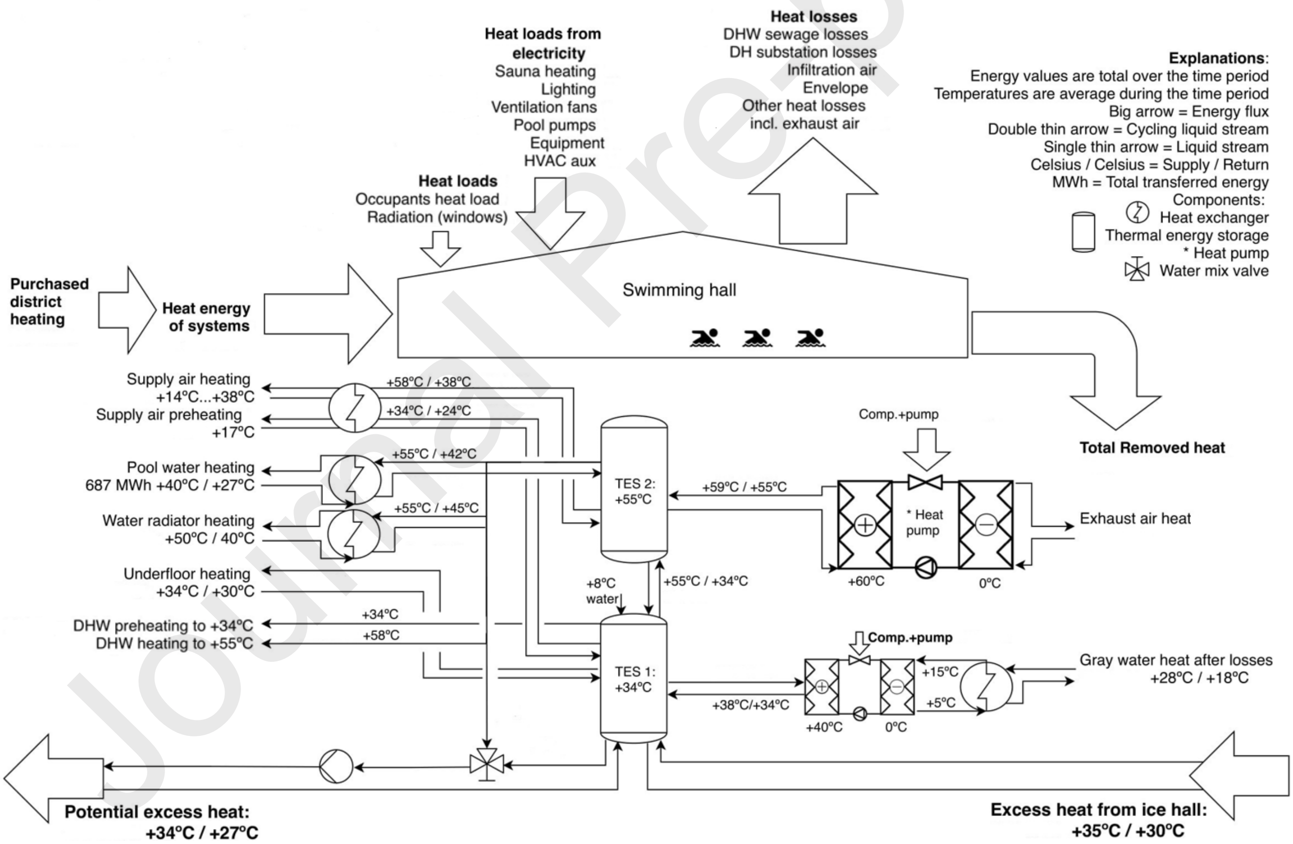

Fig. 7. Schematic map of location and direction of all the heat fluxes in a swimming hall with waste heat recovery as well as temperatures of all the hating and waste heat processing systems.

5. Results

5.1 Studied cases

Table 11 shows different analysed cases of this paper. Altogether 4 cases were analysed, including reference Case 1 without waste heat recovery, Case 2 with three waste heat recovery options excluding EAHP and Cases 3-4 with all the studied waste heat recovery options and low or high temperature EAHPs. Case 1 describes separate halls with individual energy systems while the halls are combined by the energy systems in the other cases (Cases 2-4).

Table 11 Cases description.

Case number	Hall systems	WHR	RHR	CHR	GWHR	EAHP	Design temperature of EAHP [°C]
1	Individual	--	--	--	--	--	--
2	Combined	×	IH	IH	IH&SH	--	--
3	Combined	×	IH	IH	IH&SH	SH	+5/+40
4	Combined	×	IH	IH	IH&SH	SH	+10/+60

Notation: IH = ice hall, SH = swimming hall, WHR = waster heat recovery, RHR = refrigeration heat recovery, CHR = condensation heat recovery, GWHR = Gray water heat recovery, EAHP = exhaust air heat pump.

5.2 Annual energies of cases

Table 12 summarizes the breakdown of annual energies of ice and swimming halls in Cases 1-4 including waste heat, heat energies supplied by the heating and ventilation systems and purchased energies.

5.2.1 Annual energies of the separate halls in reference Case 1

The energy systems of the ice and swimming halls are separated in the reference Case 1 and the waste heat recovery systems are not used. In the ice hall, the total purchased district heat and electricity for the ice hall is 1 614MWh/a and 1 007 MWh/a, respectively. Ice refrigeration HP is the biggest waste heat producer of 1 593 MWh/a, while extra 221 MWh/a heat is from the air dehumidification HP. Supply air heating (1 265 MWh/a) accounts for the largest portion (81%) of the heat energy of systems (1 566 MWh/a). In addition, heating energy is also used in space heating, DHW heating, ice resurfacing water heating and ground frost protection. Ice refrigeration HP (578 MWh/a) consumes the largest portion (57%) of the total electricity use (1 007 MWh/a). The total purchased district heat and electricity for the reference swimming hall is 2 717 MWh/a and 1 404 MWh/a, without waste heat recovery by EAHP and Gray water HP and without utilization of waste heat transfer from the ice hall.

DHW heating ranks the first of 947 MWh/a (36%) in terms of heat energy of system, followed by Pool water heating of 649 MWh/a (25%), while next comes supply air heating of 596 MWh/a (23%). The electricity is totally used for lighting, equipment, sauna& HVAC aux. The total purchased district heat and electricity for ice and swimming halls is 4 331 and 2 411 MWh/a, respectively. **Table 12** shows the methods to calculate the utilization efficiency of waste heat in the ice hall only, in the swimming hall only and in the combined halls. The utilization efficiency of waste heat in the ice hall is calculated by the ratio of utilized waste heat in the ice hall to total available waste heat in the ice hall. In addition, the utilization efficiency of waste heat in the swimming hall is calculated by the ratio of utilized waste heat from the swimming hall plus transferred waste heat from the ice hall to the sum of total available waste heat in the swimming hall and transferred waste heat, while the total utilization efficiency of waste heat in combined ice and swimming halls is the ratio of total utilized waste from both of the halls to the total available waste heat in the halls.

Table 12 Calculation of the utilization efficiency of waste heat in the ice hall only, in the swimming hall only and in the combined halls

Calculation of utilization efficiency of waste heat	Numerator	Denominator
Ice hall only	Utilized waste heat in IH	Total available waste heat in IH
Swimming hall only	Utilized waste heat from SH + transferred waste heat from IH	Total available waste heat in the SH + transferred waste heat
Combined halls (Total)	Total utilized waste from both halls	Total available waste heat in the halls

Notation: IH = ice hall; SH = swimming hall

5.2.2 Annual energies of the combined ice hall in cases 2-4

According to **Table 13**, the annual energies in the ice hall in cases 2-4 are the same. Compared to the reference case, the purchased district heat in Cases 2-4 decreases extremely from 1 614 MWh/a to 22 MWh/a by 99%, achieving the self-balance of heat energy supply. The total electricity consumption increases only by around 9% to 1 093 MWh/a, while the total purchased energy of the ice hall decreased by 57% to 1 115 MWh/a. The heat energy of systems for Case 1 and Cases 2-4 in the ice hall keeps the same due to the same demand side. Except the waste heat used to the ice hall, there is still 950 MWh/a excess heat transferred to the swimming hall. The waste heat from ice refrigeration (1 595 MWh/a) is 7 times bigger than that from condensing water (221 MWh/a) during air dehumidification and 25 times bigger than that in Gray water (64 MWh/a). The utilization efficiency of waste heat in the ice hall in cases 2-4 is 68%.

5.2.3 Annual energies of the combined swimming hall in Case 2

According to **Table 13**, in addition to the waste heat utilization from ice hall, swimming hall can utilize the waste heat from itself through exhaust air and Gray water waste heat recovery. In this case, the only source of waste heat in the swimming hall is Gray water (188 MWh/a) as well as the excess waste heat (950 MWh/a) from the ice hall. Compared to the reference Case 1 in the swimming hall, the purchased district heat decreased from 2 717 MWh/a to 1 997 MWh/a by 26%, while the purchased electricity increased by only 4%. The heat energy of heating systems in the swimming hall are the same in Cases 1 and 2, since they share the same demand side. Altogether 720 MWh/a waste heat is utilized, of which 77% is from the excess heat (557 MWh/a) in the ice hall. The utilization efficiency of waste heat in the swimming hall in case is 63%, while the total utilization efficiency of waste heat in the ice and swimming halls is 66%.

For the combined energy system of ice and swimming halls Case 2, the total purchased district heat decreased by 53% due to the waste heat utilization, while the total purchased electricity increased only by 6% because the only additional electricity user is the Gray water HP. Thus, the total energy saving is 32% (2 170 MWh/a) compared to the reference case. In addition, there are still 458 MWh/a potential excess heat could be used elsewhere.

5.2.4 Annual energies of the combined swimming hall in Case 3

In Case 3, the exhaust air of swimming hall is cooled to +5℃, while the condensation heat is raised to +40 ℃ in the EAHP. Compared to the reference swimming hall Case 1, purchased district heat is reduced from 2 717 MWh/a to 1 509 MWh/a by 44%, while electricity use increased by 50% to 2 107 MWh/a in Case 3. The total utilized waste heat in the swimming hall Case 3 is 1 240 MWh/a, of which 31% comes from the excess heat in the ice hall and 69% comes from its excess self-heat. Compared to Case 2 without EAHP, the total utilized waste heat increased by 520 MWh/a, but just accounting for around 23% of the total produced waste heat (2 267 MWh/a) by the EAHP. The utilization efficiency of waste heat in the swimming hall case 3 is 46%, while the total utilization efficiency of waste heat in the ice and swimming halls is 56%.

For the combined energy system of ice and swimming halls in Case 3, the total reduction of the purchased district heat reaches 65%. The use of lower temperature EAHP also increases the electricity consumption by 33%, but stores a huge amount of excess heat (2 267 MWh/a). The low temperature of the waste heat from the TES cannot meet the requirement of high temperature heat demands of the swimming hall. Thus, to improve WHR efficiency, high temperature EAHP is recommended and used in Case 4.

5.2.5 Annual energies of the combined swimming hall in Case 4

This high condensation temperature EAHP can supply all the heat demands for the swimming hall and raise the temperature of the exhaust air cooling to +10 °C. There is altogether 2 259 MWh/a waste heat available in the swimming hall, including 1 121 MWh/a high temperature heat produced by EAHP, 188 MWh/a low temperature heat from Gray water HP as well as 950 MWh/a excess waste heat from the ice hall. Compared to the reference Case 1, 72% decrease of purchased district heat is achieved at the cost of only 36% increase of electricity demand. Altogether 1 973 MWh/a waste heat is utilized, of which only 28% is the excess heat from the ice hall. All heat demands are mostly covered by the waste heat utilization except of the pool water heating using the waste heat in the last. Only 41% of the heat demands of pool water heating is supplied by waste heat. The utilization efficiency of waste heat in the swimming hall in case is 87%, while the total utilization efficiency of waste heat in the ice and swimming halls is 77%.

For the combined energy system of ice and swimming halls Case 4, compared to the reference case, 82% of total purchased district heat is reduced, while only 25% additional electricity need be consumed. There is still a moderate amount of total potential excess heat (827 MWh/a).

Table 13 The summary of the annual energies of the cases.

Annual energies of the cases, MWh/a	1. IH+SH	2. (WHR)	3. (WHR & LT EAHP)	4. (WHR & HT EAHP)
Waste heat				
Ice hall:				
Available from:				
- Ice refrigeration HP	1 593	1 595	1 595	1 595
- Gray water HP	0	64	64	64

- Air dehumidification HP	221	221	221	221
-Total	1 814	2 359	2 359	2 359
Utilized in ice hall	0	1 603	1 603	1 603
Swimming hall:				
Available from:				
- Ice hall (transferred)	0	950	950	950
- EAHP	0	0	1 576	1 121
- Gray water HP	0	188	188	188
-Total	0	1 138	2 717	2 259
Utilized ice hall waste heat	0	557	385	558
Utilized swimming hall waste heat	0	163	855	1 415
Total utilized waste heat	0	720	1 240	1 973
Excess waste heat from swimming hall	0	-458	-2 267	-827
Heat energies supplied by heating and ventilation systems				
Ice hall:				
- Space heating	22	22	22	22
- Supply air heating	1 265	1 265	1 265	1 265
- DHW heating	185	185	185	185
- Ice resurfacing water heating	41	41	41	41
- Ground frost protection	52	52	52	52
- Total	1 566	1 566	1 566	1 566
Swimming hall:				
- Space heating	444	444	447	447
- Supply air heating	596	596	605	604
- DHW heating	947	947	947	947
- Pool water heating	649	649	667	666
- Total	2 635	2 635	2 667	2 665
Purchased energy:				
Electricity:				
Ice hall:				
- Ice refrigeration HP	578	578	578	578
- Gray water HP	0	16	16	16
- Air dehumidification HP	73	73	73	73
- Lighting, equipment & HVAC aux.	356	426	426	426
- Total	1 007	1 093	1 093	1 093
Swimming hall:				
- EAHP	0	0	450	320
- Gray water HP	0	49	49	49
-Lighting, equipment, sauna& HVAC aux	1 404	1 413	1 608	1 552
- Total	1 404	1 462	2 107	1 921
Total:	2 411	2 555	3 200	3 014
District heat:				
- Ice hall	1614	22	22	22
- Swimming hall	2 717	1 997	1 509	773

- Total	4 331	2 019	1 531	795

Notation: IH = ice hall, SH = swimming hall, WHR = waster heat recovery, EAHP = exhaust air heat pump, LT = low temperature, HT = high temperature.

5.3 Annual energy comparison and cost investment analysis

Table 14 shows the absolute and relative changes of annual energies of Cases 2 and 4 compared to the reference Cases 1. As mentioned in section 5.2.5, in case that the temperature of waste heat from the low temperature EAHP cannot meet the requirement of high temperature heat demands of the swimming hall, high temperature EAHP is recommended and used in Case 4 to improve WHR efficiency. Under this circumstance, case 3 with low temperature EAHP is excluded in the annual energy comparison and cost investment analysis.

Compared to the reference swimming hall case, 26% of purchased district heat is reduced in the swimming hall Case 2 with WHR, while the corresponding saving in Case 4 with WHR and high temperature EAHP reaches 72%. However, the use of EAHP in case 4 also increases the electricity consumption by 37% compared to the reference swimming hall case. The waste heat recovery in the ice hall almost consumes no additional electricity due to the mandatory ice refrigeration and air dehumidification process. In both Cases 2 and 4, near no purchased district heat is needed due to the utilization of waste heat. For the total district heat and electricity use in both halls, Case 2 achieves 32% reduction, while Case 4 reaches 43% reduction compared to the reference cases.

Table 14 The absolute (rounded to tens) and relative changes of annual energies of Cases 2 and 4 compared to the reference Cases 1.

Case		2 [Δ MWh/a]	2 [Δ %]	4 [Δ MWh/a]	4 [Δ %]
Swimming hall	DH	-720	-26 %	-1 940	-72 %
	EL	+60	+4 %	+450	+37 %
	Tot	-660	-16 %	-1 430	-35 %
Ice hall	DH	-1 590	-99 %	-1 590	-99 %
	EL	+90	+9 %	+90	+9 %
	Tot	-1 510	-57 %	-1 500	-57 %
Swimming and ice halls	DH	-2 310	-53 %	-3 540	-82 %
	EL	+140	+6 %	+610	+25 %
	Tot	-2 170	-32 %	-2 930	-43 %

DH = District heat; EL = Electricity; Tot = Total DH + EL;
'+' = an increase compared to the reference cases; '-' = a decrease compared to the reference cases.

Table 15 shows the annual energy costs for the ice and swimming halls in Cases 1, 2 and 4, including annual district heat, electricity and total energy costs. The total energy costs of the reference Cases 1_{IH} and 1_{SH} is 463 k€ with summer breaks. **Table 15** also shows the absolute and relative changes in annual energy costs. The positive and negative values mean the increase and decrease compared to the reference cases, respectively. Compared to the reference Case 1_{IH}, the energy cost for the ice hall alone decreased by around 45% in both Cases 2 and 4. In addition, the energy saving of WHR in the ice hall achieved around 97% (81 k€). The purchased district heat is almost entirely replaced by the heat from waste heat utilization in the ice hall. Compared to the reference case 1_{SH}, the district heat energy cost in the swimming hall reduced by 35 k€ (35%) and 97 k€ (62%) in Cases 2 and 4, respectively, while the electricity costs increases by 5 k€ (+4%) and 45 k€ (+45%) in Cases 2 and 4, respectively. For the combined energy use of the ice and swimming halls, compared to the reference Cases 1_{IH} and $_{SH}$, district heat energy costs decrease by 123 k€ (50%) and 186 k€ (75%) in Cases 2 and 4, respectively. The total energy costs of the combined energy system in the ice and swimming halls decrease by 112 k€ (-24%) and 133 k€ (-29%) in Cases 2 and 4, respectively.

Table 15 The annual energy costs for the ice and swimming halls in Cases 1, 2 and 4.

Case		Annual energy costs/ k€			Absolute and relative changes in annual energy costs			
		1	2	4	2 [Δ k€]	2 [Δ %]	4 [Δk€]	4 [Δ %]
SH	DH	155	120	58	-35	-23 %	-97	-62 %
	EL	127	132	172	+5	+4 %	+45	+36 %
	Tot	282	252	231	-30	-11 %	-51	-18 %
IH	DH	92	4	2	-88	-96 %	-90	-98 %
	EL	89	95	97	+6	+7 %	+8	+9 %
	Tot	181	99	100	-82	-45 %	-81	-45 %
SH+ IH	DH	247	123	60	-123	-50 %	-186	-75 %
	EL	216	227	270	+11	+5 %	+54	+25 %
	Tot	463	351	330	-112	-24 %	-133	-29 %

SH = Swimming hall; IH = Ice hall; DH = District heat; EL = Electricity; Tot = Total DH + EL.

Table 16 shows the total cost savings and the maximum cost of profitable investment with three repayment periods. For the ice hall alone, the total cost savings vary from 0.51 and 0.97 million euros mainly based on the repayment period. For the combined ice and swimming halls, the total cost savings range between 0.7 and 1.58 million euros depending on the used measures and repayment period.

Table 16 The total energy cost savings and the maximum cost of profitable investment during three repayment periods.

Case [Δ k€]		2	4
IH	7 a	510	510
	10 a	700	690
	15 a	970	970
SH+IH	7 a	700	820
	10 a	950	1 130
	15 a	1 330	1 580

6. Discussion

By 2018, the total numbers of ice and swimming halls in Finland are 220 and 280, respectively [11]. The new ice halls are built for an average of five halls per year in Finland, while many ice halls locating in Helsinki need to be renovated over the next few years [10]. According to Jyväskylä University [34], two new swimming halls on average were built every year in the past 10 years. Thus, demands of new construction and renovation of ice and swimming halls in Finland create the opportunities for the waste heat recovery to achieve energy saving and thereby a reduction of CO_2 emissions in ice and swimming halls.

The utilized waste heat from the ice refrigeration in the ice hall can almost replace the required purchased district heat, while the electricity consumption increases marginally. The ice refrigeration waste heat recovery should be set as a regulation for new ice hall, since it can reduce the energy use by half with relatively small investment cost.

Not only can the waste heat from the ice hall be utilized in the ice hall, but also a portion of them can further utilized to support underfloor heating or preheating of DHW or supply air heating in a nearby swimming hall. In addition, the swimming hall itself has many potential waste heat sources (exhaust air and Gray water), which can be utilized to reduce the heating demands in the swimming hall. The utilized waste heat in both ice and swimming halls has low temperatures, which should be preheated with a HP close to +60 °C for all the heat demands in the swimming hall. Heat demands of a swimming hall are big enough to make all the waste heat sources from ice and swimming halls fully utilized. The total energy consumption in the studied swimming hall decreased by 43% based on the waste heat utilization of both ice and swimming halls. Thus, the waste heat utilization is recommended to the combined energy systems of the neighbour ice and swimming halls.

After utilizing the waste heat in the combined energy system of ice and swimming halls in Helsinki, range of unutilized excess heat is between 459 and 2 267 MWh/a depending on the case. On the premise of being equipped with a long-term TES for clustering excess heat in summer breaks, the excess heat can supply the operating heat demands of a modern building with the area ranging from 15 000 to 74 000 m^2 depending on the case and average heat demand of 39 kWh/m^2/a.

The effect of studied measures on CO_2 emissions of electricity and district heat can be estimated by using Finland's average CO_2 emission factors which are 141 kg-CO_2/MWh for electricity and 154 kg-CO_2/MWh for district heating according to [35]. Although the total annual electricity consumption of the combined halls increases, for example 25% in case 4 compared to case 1, where waste heat recovery is not utilized (see Table 14), total annual CO_2 emissions due to electricity and district heat consumption decreases from 1007 tons CO_2/a to 547 tons CO_2/a. If this CO_2 emission reduction of 460 tons CO_2/a could be achieved for example in 100 ice and swimming halls in Finland by combining them and using the studied measures of case 4, it would bring 46 ktons CO_2/a emission reduction.

Utilization of waste heat should be taken into consideration in the planning phase of the sport parks. During this planning phase, the ice and swimming halls should be placed closer to give possibility to easily transfer waste heat between the halls and utilize it effectively. Implementation of the waste heat recovery solutions in existing ice and swimming halls requires that they already are sufficiently close to each other. But even if they are close enough, it is typical in practice that resources are reserved only for a refurbishment of a single hall which is in greater need of refurbishment and there are no resources left to connect the energy systems of the halls and to update the energy systems of both of the halls. Therefore, refurbishment projects of the sport parks should be carried out as regional projects, so that the utilization of waste heat could be maximized in whole area instead of focusing on refurbishment of a single building at a time.

The results and system solutions presented in this paper can be utilized in a design process of new and existing ice and swimming halls, which will be renovated. The results and solutions can be generalized for similar techno-economic conditions in different climatic conditions.

7. Conclusions

In this paper, all the possible waste heat sources were applied and analysed to improve the energy performance and potential energy and cost saving in ice and swimming halls. The possible waste heat sources analysed in this paper includes the heat losses from ice refrigeration, Gray sewage water and condensing water in ice halls and exhaust air and Gray sewage water in swimming halls. The conclusions are as follows:

1. In the ice hall locating in Helsinki, the application of ice refrigeration, condensing and Gray water recoveries can save altogether 81 k€ energy cost every year, accounting for 45% energy costs of the ice hall. In addition, the utilization efficiency of waste heat in the ice hall is 68%, while up to 99% of heat demand can be supplied by waste heat at the cost of electricity demand increasing by only 9%. Thus, almost zero district heat is purchased, while the ice hall can be self-sufficient in terms of heat.

2. In the swimming hall locating in Helsinki, the maximum energy saving is altogether 35% in the combination of the reduction of 72% purchased district heat and the increase of 37% purchased electricity. The maximum utilized waste heat in the swimming hall is altogether 1 973 MWh/a, including 558 MWh/a utilized waste heat from the ice hall and 1 415 MWh/a utilized heat from the swimming hall, achieving the maximum annual energy saving of 51 k€ in the swimming hall. The maximum utilization efficiency of waste heat from the swimming hall is 87%, while the maximum total utilization efficiency of waste heat from both ice and swimming halls is 77%.

3. In the combined energy system of the ice and swimming halls, the purchased heat decreases by 82%, while the purchased electricity increases by 25%. Thus, the total energy consumption decreases by 43%. The total annual energy cost in the combined ice and swimming halls decreases by 133 k€ with all the studied waste heat recovery methods. The maximum total waste heat utilization efficiency is up to 77% (3 576 MWh/a). The utilized waste heat from EAHP accounts for the biggest portion, because only this part of waste heat has high temperature and can meet the requirement of high temperature demands in the swimming hall.

4. The total saving of the energy cost of the combined system can make up the maximum cost of the profitable investment. During three repayment periods (7, 10 and 15 years), the energy cost savings and maximum cost of profitable investment for the ice hall alone and combined ice and swimming halls are between 510 k€ and 970 k€ and between 700 k€ and 1 580 k€, respectively.

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Highlights：

Four waste heat recoveries are applied in the combined ice (IH) and swimming halls (SH).

Up to 99% of heat demand can be supplied by waste heat in IH, saving annual 81 k€ energy cost.

Utilizing waste from both IH and SH can save 35% energy in the SH every year.

In the combined IH and SH, the total annual energy cost saving is 133 k€.

The max energy cost savings for IH alone and combined IH and SH is 970 k€ and 1580 k€.

Auther statement:

Xiaolei yuan: Conceptualization, Writing - Original Draft, Formal analysis, Methodology
Leo Lindroos: Methodology, Software, Conceptualization
Juha Jokisalo: Writing - Review & Editing, Supervision, Data Curation, Resources
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